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LANDFILL LEACHATE TREATMENT USING COAGULATION-ADSORPTION HYBRID PROCESS: A REVIEW

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Abstract. Landfill leachate treatment is a critical environmental issue. This effluent is composed various toxins and complex chemicals including heavy metals, organic pollutants, ammonium nitrogen, and xenobiotic compounds. Due to this complexity and variation in the chemical composition, conventional treatment methods such as biological treatment and membrane separation often struggle with stabilized leachate due to its low biodegradability and refractory organic content. The combination of treatment methods such as coagulation/flocculation as pretreatment followed by adsorption has shown promising results in removing a broad range of contaminants at a much lower overall cost using natural materials. This review provides an in-depth examination of landfill leachate characteristics, conventional and innovative treatment techniques and operational parameters affecting their efficiency, with a focus on the hybrid coagulation-adsorption process which has been found in many recent studies to achieve promising results, yielding COD removal efficiencies exceeding 80% and ammoniacal nitrogen removal above 90% through a synergistic effect, significantly outperforming either of the processes alone. This review also critically evaluates the performance of commonly used coagulants and adsorbents, examines key operational factors governing hybrid process efficiency, and highlights remaining challenges for future research.

Keywords: landfill leachate, treatment, coagulation, adsorption, coagulants, organic matter, ammonium nitrogen.

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1. Introduction

Landfills are considered the most common measure for MSW disposal (Kaza et al., 2018). Infiltration of rainfall through the different layers of MSW disposed of in landfills creates a highly toxic liquid called landfill leachate (Baettker et al., 2020; Gautam et al., 2019). This liquid is a highly complex, dark, and toxic effluent which consists of very high concentrations of organic matter, high Chemical Oxygen Demand (COD), elevated levels of ammonia and nitrogen, high salinity, and various toxic substances. The toxicity level of landfill leachate typically exceeds that found in domestic sewage by several orders of magnitude. The substantial pollution content of landfill leachate requires effective leachate treatment to ensure proper discharge and environmental management. The composition of landfill leachate can be clustered into four principal groups, namely dissolved organic matter, inorganic macro-components, heavy metals, and xenobiotic organic compounds (Abdel-Shafy et al., 2024). Considering the highly toxic nature of landfill leachate, highly efficient treatment methods are required. Conventional biological treatment processes are effective for young landfill leachate treat-

ment, while generally struggling with old (stabilized) leachate, which contains high concentrations of refractory humic and fulvic like substances, persistent ammonium, and toxic micropollutants (El-Saadony et al., 2023; Luo et al., 2020). Other conventional technologies applied for landfill leachate treatment include membrane technologies (Ye et al., 2023), Advanced oxidation processes (AOP) (Li et al., 2022), and adsorption (Xu et al., 2019). Physicochemical treatment methods such as coagulation/flocculation and adsorption methods are increasingly applied in landfill leachate treatment, either as a standalone or hybrid process (two stages process) (Sossou et al., 2024).

The Coagulation/flocculation process is considered one of the most effective and economical options for the treatment of landfill leachate. Coagulation excels in removing colloidal particles, suspended solids, nonbiodegradable organic compounds, and heavy metals. Metal salts such as aluminium and iron coagulants are commonly used in the coagulation process. Although the coagulation process is considered highly effective in reducing COD, colour and turbidity, coagulation alone is found to struggle with the removal of dissolved contaminants such as ammoniacal nitrogen (Sossou et al., 2024).

Adsorption, on the other hand, is known to be one of the simplest processes to remove stubborn dissolved contaminants, colours, and heavy metals. The efficiency of adsorption depends on the selected adsorbent (He et al., 2023). Various adsorbents have been investigated for landfill leachate treatment, including activated carbon, biochar, zeolites, and industrial byproducts, with ongoing research into low-cost and waste-derived materials supporting circular economy (El-Saadony et al., 2023). The high suspended solids and turbidity in landfill leachate can hinder the adsorption process when used alone, clogging filters and blocking adsorption columns; therefore, the use of adsorption in hybrid treatment processes is advised.

In the context of hybrid treatment processes, the hybrid coagulation-adsorption process has shown promising results for a highly efficient landfill leachate treatment method. In this hybrid system, the coagulation/flocculation process is used as a pretreatment stage to remove suspended solids, colloidal matter, and part of the organic load, improving the clarity of leachate, thus reducing the chance of fouling and clogging, the subsequent adsorption stage then removes stubborn and residual dissolved organic and inorganic pollutants (Narendra et al., 2024). Recent studies have reported that this hybrid process shows a significant synergistic effect, achieving an overall higher COD, colour, heavy metals, and ammonia nitrogen than either coagulation or adsorption processes alone. The use of natural or waste derived material further increases the benefits of this process either environmentally or economically (El-Saadony et al., 2023; Genethliou et al., 2023).

2. Characteristics of landfill leachate

Landfill leachate is an immensely toxic liquid to both fauna and flora (Lindamulla et al., 2022; Swar et al., 2023). Characteristics of landfill leachate depend heavily on different factors such as the landfill age, geographical location, and climate (Jagaba et al., 2021; Mohammad-pajooch et al., 2017). The composition of landfill leachate consists of high concentrations of refractory organic matter, ammoniacal nitrogen ($\text{NH}_4\text{-N}$), heavy metals, inorganic salts, and various suspended solids (Yuan et al., 2017).

Table 1 shows leachate characteristics and treatability based on the landfill's age; a landfill's leachate's certain parameters and toxicity differ significantly depending on its age.

Landfill leachate's treatability highly depends on its age, generally, landfill's age is categorized into three categories: young (<5 years), intermediate (5–10 years), Old (>10 years). Young leachate contains high Biological Oxygen Demand (BOD) levels which makes it suitable for biological treatment methods. As the landfill becomes older, biological treatment methods become inefficient, on the other hand, physio-chemical methods become more suitable for its treatment, especially in the removal of refractory pollutants (Aftab et al., 2019).

Table 1. Leachate characteristics and treatability based on the landfill's age (source: Sossou et al., 2024)

Parameters	Young	Medium	Old (Stabilized)
Age	0.5–5	5–10	>10
pH	<6.5	6.5–7.5	>7.5
BOD/COD	0.5–1.0	0.1–0.5	<0.1
Kjehdal nitrogen (g/L)	0.1–2	N/A	N/A
Phosphorus (mg/L)	17–24	–	–
Suspended solids (g/L)	2.3–8.9	–	~ 5.8
Heavy metals (mg/L)	>2	<2	<2
$\text{NH}_3\text{-N}$ (mg/L)	<400	–	>400

Landfill leachate contains a diverse mixture of contaminants. The composition and characteristics of landfill leachate depend heavily on the geographical region where it was collected from (Sackey et al., 2020). The dissolved organic matter (DOM) in leachate tends to be more saturated and less oxidized, resulting in higher levels of ammonium nitrogen and sulfur-containing compounds (Yuan et al., 2017). Landfill leachate also contains some metal ions, metalloid ions, antibiotics, endocrine disruptors, pesticides, pharmaceutical and personal care products, commercial organic matter, and microplastics (Chen et al., 2024).

3. Overview of landfill leachate treatment technologies

Landfill treatment technologies can be classified into three main categories, biological, physicochemical, and membrane-based technologies, each with distinct effectiveness and limitations depending on leachate's age and composition. There has been long term use of biological methods to reduce landfill leachate, especially in cases where the leachate has a high BOD/COD ratio exceeding 0.5, achieving a COD removal of up to 85% (da Silva et al., 2022). Aerobic treatment, including activated sludge systems (AS), and Sequencing Batch Reactors (SBRs) has been widely applied, while anaerobic systems such as Upflow Anaerobic Sludge Blanket (UASB) reactors offer a low-energy alternative through biogas recovery. The biological treatment approaches are effective in the removal of ammonia and organic compounds, however, when the BOD/COD ratios of leachate drop below 0.1 as it stabilizes over time, biological treatment methods become largely ineffective towards refractory organic compounds and ammoniacal nitrogen (Mojiri et al., 2021; Žgajnar Gotvajn & Pavko, 2015). This limitation makes biological treatment methods alone insufficient for stabilized landfill leachate treatment, requiring alternative technologies or combined approaches.

Several biological methods, including aerobic systems such as activated sludge (AS) and sequencing batch

reactors (SBRs), as well as anaerobic systems such as upflow anaerobic sludge blanket (UASB), have been employed for young landfill leachate with BOD/COD ratio exceeding 0.5, exhibiting a COD removal efficiencies between 70 and 85% (Wang et al., 2018; da Silva et al., 2022). As the leachate stabilizes and BOD/COD ratio drops below 0.1, biological treatment methods become very ineffective for refractory organics and ammoniacal nitrogen removal, requiring an alternative or combined treatment approaches (Mojiri et al., 2021).

Membrane technologies remain the most popular landfill leachate treatment systems due to their high performance in the removal of a wide range of contaminants, generating a high-quality effluent meeting stringent discharge standards (Aboudi et al., 2023; Jamrah et al., 2024). RO and NF systems have achieved COD, heavy metals, ammoniacal nitrogen removals exceeding 90%, placing them amongst the most efficient standalone treatment options (Wang et al., 2023). However, the high organic load and complex nature of leachate is the major cause of membrane fouling, increasing maintenance costs and reducing the permeate flux and the lifespan of the membrane, and raising the overall operating cost, which limits large-scale applications (Aboudi et al., 2023).

Physicochemical methods such as air stripping, chemical oxidation, coagulation/flocculation, and adsorption are increasingly gaining popularity in stabilized leachate treatment where biological methods are ineffective (Yu et al., 2022). Amongst these methods, coagulation and adsorption are the primary physicochemical methods reviewed in this paper and are discussed in detail in the following sections.

While each of the discussed landfill leachate technologies (biological, membrane, and physicochemical) show effectiveness under optimal conditions, no single technology provides a comprehensive solution for stabilized landfill leachate treatment. Biological treatment technologies are limited by low biodegradability of stabilized leachate, membrane technologies face severe fouling problems and high operational costs, and standalone physicochemical technologies often struggle to address the full spectrum of pollutants including ammoniacal nitrogen and dissolved organic matter. These limitations highlight the need for hybrid treatment systems that combine the strengths of multiple technologies, creating a synergistic effect, particularly the coagulation-adsorption hybrid process, which is the focus of this review.

4. Coagulation in landfill leachate treatment

The coagulation treatment technology is based on the addition of chemical compounds known as coagulants, which can react with suspended particles and contaminants in a solution via several physicochemical mechanisms. Some of the commonly used coagulants include inorganic salts such as FeCl_2 , FeSO_4 , AlCl_3 and FeCl_3 . Bio-flocculants such as PG α 21Ca have shown promising

COD removal efficiencies of 80–90% at a pH value of 4, outperforming conventional salt coagulants under optimal conditions (de Melo Franco Domingos et al., 2023). According to Li et al. (2010), coagulation/flocculation process was investigated for the treatment of landfill leachate with parameters being further optimized using response surface methodology. The results achieved in the best-case scenario were the removal of 70% of COD, 93% of suspended solids, 97% of turbidity and 74% of toxicity. These results proved that coagulation-flocculation technology is an effective technology for the pretreatment of landfill leachate.

The coagulation process generally involves three main steps: rapid mixing, slow mixing, and settling. Daud et al. (2023) demonstrated that under optimal parameters including rapid mixing at a speed of 100 rpm, slow mixing at 30 rpm for 30 minutes, and settling for 24 hours, a COD removal of 73.1% was achieved using alum as a coagulant.

Suitable selection of coagulants and their dosage play a crucial role in the efficiency of the coagulation process (Ahmed et al., 2020). In addition, other parameters such as pH and leachate temperature also play a significant role in achieving a proper treatment (Bai et al., 2023).

4.1. Factors influencing the coagulation efficiency of landfill leachate

The nature and dose of coagulants are amongst the crucial factors affecting the coagulation process performance. Narendra et al. (2024) demonstrated that gradually increasing FeCl_3 dose enhanced COD and color removal due to the enhanced charge neutralization and sweep floc formation while avoiding excessive destabilization of colloids, although excessive doses of FeCl_3 resulted in colloid destabilization and reduced efficiency, and after a dose of 8g/L no significant improvement was observed. Coagulation/flocculation have shown potential in landfill leachate treatment with an average removal efficiency exceeding 75% for COD, organic matter, turbidity, TSS, and heavy metals. Ammoniacal nitrogen in contrast remains largely unaffected (Sossou et al., 2024). Qiao et al. (2023) showed that the combination of inorganic coagulants with polymeric flocculants like polyacrylamide (PAM) enhanced the treatment performance compared to the use of coagulants alone by promoting larger floc formation through adsorption bridging, while finding the optimum dose prevents destabilization.

pH is another crucial factor affecting COD and colour removal efficiencies, with optimal performance exhibited at pH values of 4–6.5, this pH adjustment is required prior to coagulant addition during the rapid mixing step for an effective charge neutralization and floc formation (Narendra et al., 2024; Khoo et al., 2020). Figure 1 shows the change in the removal efficiency of both COD and colour from landfill leachate samples in this study by the change in coagulant dosage (a) and the leachate's pH (b).

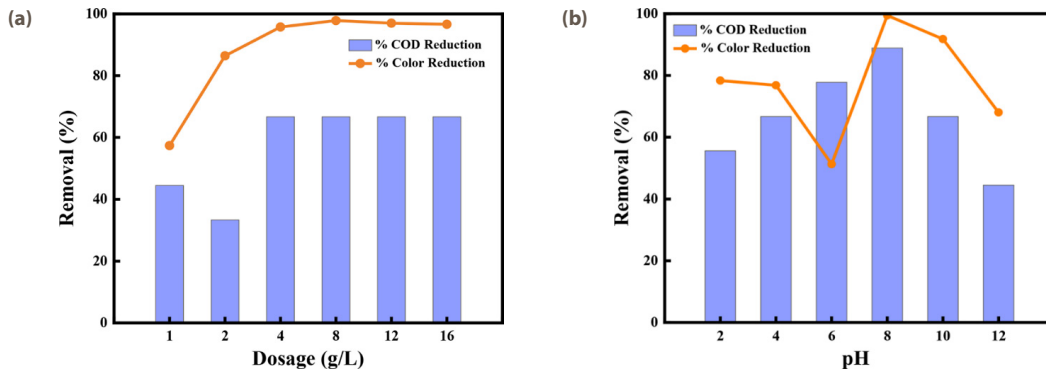


Figure 1. The impact of coagulant dosage (a) and leachate's pH (b) on the removal efficiencies of COD and colour

Despite its efficiency in eliminating suspended particles, turbidity, and high molecular weight organics, coagulation struggles with dissolved contaminants such as ammonia and heavy metals, achieving overall limited COD removal (Chen et al., 2024). Therefore, coagulation is more suitable as a pretreatment stage followed by other technologies such as adsorption and biological methods to achieve better removal efficiencies.

4.2. Adsorption in landfill leachate treatment

Adsorption is regarded as an efficient method for the removal of pollutants and contaminants from wastewater. One of the main characteristics that makes an adsorbent suitable for treatment process is high porosity, which results in larger surface area and thus better and faster removal of contaminants. In general, numerous materials can be employed as adsorbents. The adsorption technique works by adsorbing contaminants dissolved in water on the surface or interior of an adsorbent, resulting in solid-liquid separation of pollutants and water (He et al., 2023). Narendra et al. (2024) used MWCNTs as an adsorbent for the treatment of mature landfill leachate collected from a landfill site in Karnataka, India. The study achieved 65.66% COD removal through adsorption alone under optimal conditions of pH 2, a temperature of 55 degrees Celsius, and 60 minutes contact time.

The adsorption technique generally works following a principle; the pollutants within leachate adsorb to the surface or pores of a solid material (adsorbent) instead of staying dissolved in the liquid. This means that contaminants within landfill leachate such as colour, ammonia, nitrogen and heavy metals are retained on the surface of activated carbon, biochar, zeolites and some innovative adsorbents such as those based on industrial waste (Aftab et al., 2024).

Adsorption can be conducted through two principal approaches: batch adsorption for laboratory scale testing, and column adsorption for real life applications, where leachate is pumped through a packed column at a constant flow rate until adsorbent saturation when regeneration is required (Genethliou et al., 2023; Narendra et al., 2024).

Non-conventional adsorbents derived from a wide range of agricultural residues and industrial waste materials have been investigated as lower-cost alternatives to traditional activated carbon and can be chemically modified to enhance performance (Khoo et al., 2020). The adsorption method is effective when combined with other methods such as coagulation or biological treatment technologies.

4.3. Factors affecting adsorption efficiency

The efficiency of adsorption in the removal of contaminants can be affected by various factors. These factors include the pH of the solution, the adsorbent dose, contact time and agitation speed (which influence external mass transfer and the diffusion of contaminants toward the adsorbent surface), temperature, and the initial concentration of the pollutant and competing ions. The pH of the landfill leachate is considered one of the most important parameters affecting its treatment efficiency. For the adsorption process, optimal efficiencies are achieved in acidic to neutral pH (3–7), as acidic pH works better for organic pollutants and heavy metal adsorption. High pH (>8) achieves worse efficiencies due to OH⁻ competition. Adjusting pH to values between 4 and 6 often doubles the removal efficiencies of COD and colour. According to a study published by Narendra et al. (2024), COD removal efficiencies of 44.44% were achieved under pH values of 2 and 4, and maximum colour reduction of 95.10% and the highest COD removal were achieved at a pH value of 2.

The dose of the adsorbent is another crucial factor that affects the efficiency of the removal of contaminants, the higher the dose of the adsorbent, the greater the surface area and thus the faster uptake of the pollutant. The optimum range is typically 2–10 g/L, dosages exceeding this range do not improve the efficacy of pollutants removal but instead increase sludge production and require a higher operational cost. As an example, a study conducted by Narendra et al. (2024) in which an adsorbent (multi-walled carbon nanotubes (MWCNTs)) dosage of 4g/L achieved the optimal COD removal efficiency, and the doses of 5 and 6 g/L reported COD removal efficiencies with negligible differences.

Contact time and agitation are important parameter, contact time determines whether the adsorption has reached equilibrium state, initial rapid uptake occurs within the first 30–60 minutes (surface area), followed by slow diffusion into the pores. Most leachate studies found that 60–120 minutes was sufficient for 80–90% of maximum removal, together with a decrease in removal efficiency above 180 minutes. Gentle agitation (100–150 rpm) improves mass transfer, but excessive mixing may detach the adsorbent (Genethliou et al., 2023).

Temperature can also generally enhance adsorption kinetics although it may reduce capacity for some certain leachate contaminants. Removal rises by 10–30% between 20 °C and 50 °C due to quicker diffusion; however, below 60 °C, endothermic desorption might occur, lowering efficiency. For practical reasons, leachate investigations frequently employ ambient temperatures (20–30 °C) (Narendra et al., 2024).

Higher initial COD or metal concentrations increase removal efficiency due to the increase of driving force but decrease adsorption capacity per gram of adsorbent. Competing ions (high Cl^- , SO_4^{2-} , NH_4^+ in leachate) and humic compounds can clog sites and reduce efficiency by 20–50% compared to synthetic solutions. Coagulation pre-treatment is frequently utilized to reduce this effect (Luo et al., 2020).

The adsorption method has many advantages including the low cost and most importantly its effectiveness in pollutants removal (Hidayu & Muda, 2016).

5. Hybrid coagulation-adsorption processes

As described in the section overviewing landfill leachate treatment methods, most of these technologies have drawbacks, some in many cases can be solved and overcome through the combination of two or more treatment processes into hybrid processes. Combined treatment processes have developed as a highly efficient method of managing the variable and complicated nature of landfill leachate, which is often ineffectively treated with single stage approaches. Recent studies have demonstrated that a combination of biological, chemical and physical treatment methods maximizes the complementary nature of the methods, leading to increased removal efficiency and effluent quality. Membrane bioreactor (MBR) combinations with nanofiltration (NF), and adsorption-based systems, have demonstrated COD removal efficiencies of nearly or more than 90%, and substantial enhancements in leachate biodegradability, as measured by higher BOD5/COD ratios (Jamrah et al., 2024).

Moreover, combined processes, also known as hybrid systems, effectively bypass the constraints of single process treatments, as they cover a wider range of contaminants, including refractory organics, ammonia, and heavy metals, and enable the more convenient adherence to stringent environmental discharge standards. The emerging body of literature proves the crucial importance of combined processes in the creation of sustainable landfill

leachate management and highlights the need to further develop and streamline these integrated treatment systems (Jamrah et al., 2024).

Numerous studies have shown that the combination of different processes increases the removal efficiency of different contaminants from landfill leachate compared to single technique operations. Different combinations work with different landfill leachates with different characteristics such as age and composition as discussed in detail in the previous sections. Amongst all these combination processes, the hybrid process of coagulation-adsorption process as a physical + chemical combination treatment process shows the most promising results, making a cost-effective and efficient landfill leachate treatment method. In a study by Jaradat et al. (2021), $\text{Fe}(\text{SO}_4)_3$ coagulant was used on a landfill leachate with an initial COD of 2500 mg/L achieved 65% COD removal. The coagulation was followed with an adsorption using eggshell waste, which removed an additional 25–30% of COD under optimal conditions (coagulant dose and pH). High heavy metals removal percentages were also achieved during this study under coagulant optimal dose of 3.0 g/L and a pH of 5.8.

Recent studies indicate that adsorption and coagulation in combination enhance the overall treatment efficiency by enhancing the removal efficiencies of COD, ammoniacal nitrogen, heavy metals and colour. A pilot-scale hybrid system with adsorption as a pre-treatment step and electrocoagulation and biological treatment showed removal efficiencies of 95.5% of ammonium nitrogen, 98.8% of colour, and 85.7% of dissolved COD, which indicated the synergistic effect of adsorption and coagulation-based processes (Genethliou et al., 2023). The use of zeolite as an adsorbent in the adsorption step led to a significant increase in the removal of ammonium, which proves the effectiveness of natural adsorbents in combination systems.

This combination processes methodology has been further advanced by innovative modified coagulants and adsorbents. A modified coagulant, polyaluminum chloride sulfate (PACS), was also shown to be highly effective in removing suspended solids and colour in membrane bioreactor effluent of landfill leachate, with 79.3% COD and 91.3% colour removal during coagulation, which was further enhanced to 98.9% COD removal after sequential electrooxidation (Bayat et al., 2023). This underscores the benefits of using tailored coagulants in combination with adsorption and oxidation processes to achieve stringent discharge standards.

Natural polymers like chitosan and bio-flocculants as well as modified bio-adsorbents have been explored to enhance the coagulation and adsorption performance and reduce chemical sludge production and environmental impact (Chen et al., 2024; Maharjan & Ghimire, 2023). These new materials enhance floc formation and adsorption capacity particularly of refractory organics and heavy metals.

The combination of coagulation-adsorption process is therefore a flexible and cost-effective method of treating landfill leachate especially when combined with advanced oxidation or biological stages. It effectively overcomes

the limitations of standalone coagulation or adsorption, including inadequate removal of dissolved low-molecular-weight organics and ammonia nitrogen, without raising secondary pollution issues (Chen et al., 2024; Cherni et al., 2022).

Narendra et al. (2024) demonstrated that using FeCl_3 as a coagulant followed by MWCNT as an adsorbent achieved a COD removal of 77.78% and colour removal of 99.65% through coagulation alone, which was further enhanced to a COD removal of 88.89% and 100% colour removal after the adsorption process, demonstrating a synergistic effect of the hybrid process. Similar study by Xiong et al. (2021) reported removal efficiencies up to 99% and 95% for humic and protein-like substances respectively, resulting in high colour removal performance through combined coagulation-adsorption approach.

The Coagulation-adsorption hybrid process offers significant cost advantages over membrane technologies, avoiding the high maintenance cost while keeping comparable leachate treatment performance. The use of natural or waste-derived adsorbents such as eggshell waste, fly ash, and zeolites further reduces operational costs, supporting circular economy principles (Gandhimathi et al., 2013; Jaradat et al., 2021).

One of the main challenges facing coagulation-adsorption systems is generated sludge management during the coagulation process. This chemical sludge contains concentrated pollutants, which requires proper disposal or treatment. The use of natural coagulants such as chitosan and $\text{PG}\alpha 21\text{Ca}$ has been proven to generate less sludge with reduced volume and toxicity, making sludge management more sustainable (Chen et al., 2024; Maharjan & Ghimire, 2023).

The reviewed literature demonstrated that FeCl_3 coupled with activated carbon or MWCNTs consistently achieved the highest overall COD and colour removal efficiencies, while natural adsorbents such as zeolites and natural clays proved most effective for ammoniacal nitrogen removal. The pH range achieving the optimal results for coagulation was 4–6.5 and 2–7 for adsorption process, these pH ranges should be carefully controlled to maximize the synergistic effect of the hybrid system. Future research should focus on long-term performance evaluation, sludge minimization strategies, as well as large-scale implementation of these systems.

6. Conclusions

This paper overviewed different landfill leachate treatment methods, with a focus on coagulation and adsorption processes, as well as the hybrid coagulation-adsorption treatment process. This review highlights the fact that standalone biological, membrane, or even physicochemical treatment methods each suffer from their own specific limitations and weaknesses when applied individually, especially with old (stabilized) landfill leachate. Biological treatment methods are restricted by the leachate's low bio-

degradability, while membrane systems suffer from severe fouling and clogging resulting in high operational costs.

Coagulation/flocculation removes up to 70% COD, 93% suspended particles, 97% turbidity, and 74% toxicity, making it an excellent pretreatment approach; however, it struggles with dissolved pollutants such as ammoniacal nitrogen. Adsorption efficiently complements coagulation by targeting dissolved organic matter, ammoniacal nitrogen, and heavy metals, with effectiveness highly influenced by operational factors such as pH, adsorbent dose, and contact time.

The combination of coagulation as a leachate treatment stage followed by subsequent adsorption processes consistently shows a synergistic effect, resulting in much higher overall removal efficiencies for organic matter, nitrogen species, color, and heavy metals compared to either of the processes when used on their own. Among the examined combinations, FeCl_3 combined with activated carbon or MWCNTs exhibited the best results for COD and color removal. Zeolite-based adsorbents proved most efficient for ammoniacal nitrogen removal. The combination of two methods, coagulation and adsorption, allows achieving COD removal efficiencies of more than 80% and ammonium nitrogen removal efficiencies of more than 90% from landfill leachate.

The reviewed research shows that hybrid coagulation-adsorption systems offer a versatile, cost-effective, and long-term treatment solution for landfill leachate, especially when natural or waste-derived materials are used. These systems have a high potential for meeting the environmental standards for wastewater discharge. However, sludge management remains a significant issue requiring further attention for large-scale implementation. Future research should concentrate on improving operating conditions such as pH control, coagulant and adsorbent dosage, and process sequencing, as well as long-term performance, sludge management, and life-cycle evaluations to enable large-scale implementation.

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References

- Abdel-Shafy, H. I., Ibrahim, A. M., Al-Sulaiman, A. M., & Oka-sha, R. A. (2024). Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain*

- Shams Engineering Journal, 15(1), Article 102293.
<https://doi.org/10.1016/j.asej.2023.102293>
- Aboudi, K., Rajpal, A., Tyagi, V. K., & Tawfik, A. (2023). Aerobic treatment of landfill leachate. In *Landfill leachate management*. IWA Publishing. https://doi.org/10.2166/9781789063318_0015
- Aftab, B., Ok, Y. S., Cho, J., & Hur, J. (2019). Targeted removal of organic foulants in landfill leachate in forward osmosis system integrated with biochar/activated carbon treatment. *Water Research*, 160, 217–227.
<https://doi.org/10.1016/j.watres.2019.05.076>
- Aftab, B., Yin, G., Maqbool, T., Hur, J., & Wang, J. (2024). Enhanced landfill leachate treatment performance by adsorption-assisted membrane distillation. *Water Research*, 250, Article 121036.
<https://doi.org/10.1016/j.watres.2023.121036>
- Ahmed, Z., Yusoff, M. S., & Mokhtar, K. N. H. (2020). Application of natural coagulants for sustainable treatment of semi-aerobic landfill leachate. *AIP Conference Proceedings*, 2267, Article 020024. <https://doi.org/10.1063/5.0017406>
- Bai, F., Tian, H., Wang, C., & Ma, J. (2023). Treatment of nanofiltration concentrate of landfill leachate using advanced oxidation processes incorporated with bioaugmentation. *Environmental Pollution*, 318, Article 120827.
<https://doi.org/10.1016/j.envpol.2022.120827>
- Bayat, M. E., Bilgin, O. N., Varank, G., Yazici Guvenc, S., & Can-Güven, E. (2023). Efficient treatment of landfill leachate membrane bioreactor effluent through sequential coagulation–flocculation and electrooxidation. *Environmental Science: Water Research & Technology*, 9(9), 2253–2262.
<https://doi.org/10.1039/D3EW00290J>
- Baettker, E. C., Kozak, C., Knapik, H. G., & Aisse, M. M. (2020). Applicability of conventional and non-conventional parameters for municipal landfill leachate characterization. *Chemosphere*, 251, Article 126414.
<https://doi.org/10.1016/j.chemosphere.2020.126414>
- Chen, H., Xu, H., Zhong, C., Liu, M., Yang, L., He, J., Sun, Y., Zhao, C., & Wang, D. (2024). Treatment of landfill leachate by coagulation: A review. *Science of The Total Environment*, 912, Article 169294. <https://doi.org/10.1016/j.scitotenv.2023.169294>
- Cherni, Y., Elleuch, L., Kasmi, M., Sghaier-Hammami, B., Chourabi, K., Chatti, A., Trabelsi, I., & Kallel, A. (2022). Detoxification of leachate by coagulation treatment prior to fermentation and possible reuse in irrigation. *CLEAN – Soil, Air, Water*, 50(6), Article 2000395. <https://doi.org/10.1002/clen.202000395>
- Daud, N. M., Abdullah, S. R. S., Hasan, H. A., Othman, A. R., & Nur, I. I. (2023). Coagulation-flocculation treatment for batik effluent as a baseline study for the upcoming application of green coagulants/flocculants towards sustainable batik industry. *Heliyon*, 9(6), Article e17284.
<https://doi.org/10.1016/j.heliyon.2023.e17284>
- da Silva, V. E. P. S. G., Rollemberg, de S., e Santos, S. G. da, Silva, T. F. C. V., Vilar, V. J. P., & dos Santos, A. B. (2022). Landfill leachate biological treatment: Perspective for the aerobic granular sludge technology. *Environmental Science and Pollution Research*, 29, 45150–45170.
<https://doi.org/10.1007/s11356-022-20451-3>
- de Melo Franco Domingos, J., de Alencar Neves, T., de Sousa Maia, D. L., Carvalho Siqueira, R., Araújo Marques, M. V., Alves, O. L., Guimarães, J. R., Antunes Nolasco, M., & Rosa, A. H. (2023). Effect of the association of coagulation/flocculation, hydrodynamic cavitation, ozonation and activated carbon in landfill leachate treatment system. *Scientific Reports*, 13, Article 9502. <https://doi.org/10.1038/s41598-023-36662-8>
- El-Saadony, M. T., Saad, A. M., El-Wafai, N. A., Abou-Aly, H. E., Salem, H. M., Soliman, S. M., Abd El-Mageed, T. A., Elrys, A. S., Selim, S., Abd El-Hack, M. E., Kappachery, S., El-Tarabily, K. A., & AbuQamar, S. F. (2023). Hazardous wastes and management strategies of landfill leachates: A comprehensive review. *Environmental Technology & Innovation*, 31, Article 103150.
<https://doi.org/10.1016/j.eti.2023.103150>
- Gandhimathi, R., Durai, N. J., Nidheesh, P. V., Ramesh, S. T., & Kanmani, S. (2013). Use of combined coagulation-adsorption process as pretreatment of landfill leachate. *Iranian Journal of Environmental Health Science & Engineering*, 10, Article 24.
<https://doi.org/10.1186/1735-2746-10-24>
- Gautam, P., Kumar, S., & Lokhandwala, S. (2019). Advanced oxidation processes for treatment of leachate from hazardous waste landfill: A critical review. *Journal of Cleaner Production*, 237, Article 117639. <https://doi.org/10.1016/j.jclepro.2019.117639>
- Genethliou, C., Tatoulis, T., Charalampous, N., Dailianis, S., Tekerkopoulou, A. G., & Vayenas, D. V. (2023). Treatment of raw sanitary landfill leachate using a hybrid pilot-scale system comprising adsorption, electrocoagulation and biological process. *Journal of Environmental Management*, 330, Article 117129.
<https://doi.org/10.1016/j.jenvman.2022.117129>
- He, H., Zhang, C., Yang, X., Huang, B., Zhe, J., Lai, C., Liao, Z., & Pan, X. (2023). The efficient treatment of mature landfill leachate using tower bipolar electrode flocculation-oxidation combined with electrochemical biofilm reactors. *Water Research*, 230, Article 119544.
<https://doi.org/10.1016/j.watres.2022.119544>
- Hidayu, A. R., & Muda, N. (2016). Preparation and characterization of impregnated activated carbon from palm kernel shell and coconut shell for CO₂ capture. *Procedia Engineering*, 148, 106–113. <https://doi.org/10.1016/j.proeng.2016.06.463>
- Jagaba, A. H., Kutty, S. R. M., Lawal, I. M., Abubakar, S., Hassan, I., Zubairu, I., Umaru, I., Abdurrahman, A. S., Adam, A. A., Ghalib, A. A. S., Almahbashi, N. M. Y., Al-dhawi, B. N. S., & Noor, A. (2021). Sequencing batch reactor technology for landfill leachate treatment: A state-of-the-art review. *Journal of Environmental Management*, 282, Article 111946.
<https://doi.org/10.1016/j.jenvman.2021.111946>
- Jamrah, A., AL-Zghoul, T. M., & Al-Qodah, Z. (2024). An extensive analysis of combined processes for landfill leachate treatment. *Water*, 16(12), Article 1640. <https://doi.org/10.3390/w16121640>
- Jaradat, A. Q., Telfah, D. B., & Ismail, R. (2021). Heavy metals removal from landfill leachate by coagulation/flocculation process combined with continuous adsorption using eggshell waste materials. *Water Science and Technology*, 84(12), 3817–3832. <https://doi.org/10.2166/wst.2021.493>
- Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a Waste 2.0: A global snapshot of solid waste management to 2050*. World Bank Group.
<https://doi.org/10.1596/978-1-4648-1329-0>
- Khoo, K. S., Tan, X., Show, P. L., Pal, P., Juan, J. C., Ling, T. C., Ho, S. H., & Nguyen, T. H. P. (2020). Treatment for landfill leachate via physicochemical approaches: An overview. *Chemical and Biochemical Engineering Quarterly*, 34(1), 1–24.
<https://doi.org/10.15255/CABEQ.2019.1703>
- Li, S., Yang, Y., Zheng, H., Zheng, Y., Jing, T., Ma, J., Nan, J., Leong, Y. K., & Chang, J. S. (2022). Advanced oxidation process based on hydroxyl and sulfate radicals to degrade refractory organic pollutants in landfill leachate. *Chemosphere*, 297, Article 134214. <https://doi.org/10.1016/j.chemosphere.2022.134214>
- Li, W., Hua, T., Zhou, Q., Zhang, S., & Li, F. (2010). Treatment of stabilized landfill leachate by the combined process of coagulation/flocculation and powder activated carbon adsorption. *Desalination*, 264(1–2), 56–62.
<https://doi.org/10.1016/j.desal.2010.07.004>

- Lindamulla, L., Nanayakkara, N., Othman, M., Jinadasa, S., Herath, G., & Jegatheesan, V. (2022). Municipal solid waste landfill leachate characteristics and their treatment options in tropical countries. *Current Pollution Reports*, 8, 273–287. <https://doi.org/10.1007/s40726-022-00222-x>
- Luo, H., Zeng, Y., Cheng, Y., He, D., & Pan, X. (2020). Recent advances in municipal landfill leachate: A review focusing on its characteristics, treatment, and toxicity assessment. *Science of The Total Environment*, 703, Article 135468. <https://doi.org/10.1016/j.scitotenv.2019.135468>
- Maharjan, A., & Ghimire, A. (2023). A review on coagulation/Flocculation for the treatment of landfill leachate. In *Proceedings of 14th IOE Graduate Conference*. IOE. <https://conference.ioe.edu.np/publications/ioegc14/IOEGC-14-217-PS3-019-352.pdf>
- Mohammad-pajooh, E., Weichgrebe, D., & Cuff, G. (2017). Municipal landfill leachate characteristics and feasibility of retrofitting existing treatment systems with deammonification – A full scale survey. *Journal of Environmental Management*, 187, 354–364. <https://doi.org/10.1016/j.jenvman.2016.10.061>
- Mojiri, A., Zhou, J. L., Ratnaweera, H., Ohashi, A., Ozaki, N., Kindaichi, T., & Asakura, H. (2021). Treatment of landfill leachate with different techniques: An overview. *Water Reuse*, 17(1), 66–96. <https://doi.org/10.2166/wrd.2020.079>
- Narendra, K. R., Shetty, S. J., Prashant, S., Gurumurthy, S. C., & Biliangadi, N. B. (2024). Landfill leachate treatment by incorporating MWCNTs assisted adsorption and coagulation process. *Emergent Materials*, 8, 1659–1669. <https://doi.org/10.1007/s42247-024-00858-z>
- Qiao, Y., Jin, R., Gao, J., Wang, K., Jiang, Y., Xiong, J., Jia, M. Y., He, Z., & Liu, J. (2023). Process of landfill leachate pretreatment using coagulation and hydrodynamic cavitation oxidation. *RSC Advances*, 13(46), 32175–32184. <https://doi.org/10.1039/D3RA04259F>
- Sackey, L. N. A., Koči, V., & van Gestel, C. A. M. (2020). Ecotoxicological effects on *Lemna minor* and *Daphnia magna* of leachates from differently aged landfills of Ghana. *Science of The Total Environment*, 698(12), Article 134295. <https://doi.org/10.1016/j.scitotenv.2019.134295>
- Sossou, K., Bala Prasad, S., Agbotsou, K. E., Saidou Souley, H., & Mudigandla, R. (2024). Characteristics of landfill leachate and leachate treatment by biological and advanced coagulation process: Feasibility and effectiveness – An overview. *Waste Management Bulletin*, 2(2), 181–198. <https://doi.org/10.1016/j.wmb.2024.04.009>
- Swar, S. S., Boonnorat, J., & Ghimire, A. (2023). Algae-based treatment of a landfill leachate pretreated by coagulation-flocculation. *Journal of Environmental Management*, 342, Article 118223. <https://doi.org/10.1016/j.jenvman.2023.118223>
- Wang, L., Li, Y., Pu, L., Yang, M., Lu, H., Gu, X., & Wang, X. (2023). Copolyimide membranes fabricated by nonsolvent-induced phase separation for helium extraction from natural gas. *Separation and Purification Technology*, 313, Article 123455. <https://doi.org/10.1016/j.seppur.2023.123455>
- Wang, K., Li, L., Tan, F., & Wu, D. (2018). Treatment of landfill leachate using activated sludge technology: A review. *Archaea*, 2018(1), Article 1039453. <https://doi.org/10.1155/2018/1039453>
- Xiong, J., Zhang, C., Yang, X., Zhou, T., & Yang, S. (2021). Combining chemical coagulation with activated coke adsorption to remove organic matters and retain nitrogen compounds in mature landfill leachate. *Environmental Technology*, 42(22), 3487–3495. <https://doi.org/10.1080/09593330.2020.1732475>
- Xu, X., Liu, X., Oh, M., Park, J., & Chen, Y. F. (2019). Adsorption properties of heavy metal ions in landfill leachate by Na-bentonite. *Materialpruefung/Materials Testing*, 61(1), 81–87. <https://doi.org/10.3139/120.111284>
- Ye, W., Hong, M., Huang, X., Chen, T., Gu, A., Lin, X., Li, X., Chen, X., Seo, D. H., Zhao, S., Chen, X., van der Bruggen, B., Xie, M., & Lin, J. (2023). Towards effective recovery of humate as green fertilizer from landfill leachate concentrate by electro-neutral nanofiltration membrane. *Science of The Total Environment*, 896, Article 165335. <https://doi.org/10.1016/j.scitotenv.2023.165335>
- Yu, D., Pei, Y., Ji, Z., He, X., & Yao, Z. (2022). A review on the landfill leachate treatment technologies and application prospects of three-dimensional electrode technology. *Chemosphere*, 291, Article 132895. <https://doi.org/10.1016/j.chemosphere.2021.132895>
- Yuan, Z., He, C., Shi, Q., Xu, C., Li, Z., Wang, C., Zhao, H., & Ni, J. (2017). Molecular insights into the transformation of dissolved organic matter in landfill leachate concentrate during biodegradation and coagulation processes using ESI FT-ICR MS. *Environmental Science and Technology*, 51(14), 8110–8118. <https://doi.org/10.1021/acs.est.7b02194>
- Žgajnar Gotvajn, A., & Pavko, A. (2015). Perspectives on biological treatment of sanitary landfill leachate. In *Wastewater treatment engineering*. IntechOpen. <https://doi.org/10.5772/60924>

SAVARTYŲ FILTRATO VALYMAS TAIKANT HIBRIDINĮ KOAGULIACIJOS IR ADSORBCIJOS PROCESĄ: APŽVALGA

Santrauka. Savartynų filtrato valymas yra reikšminga ir sudėtinga aplinkosaugos problema. Savartynų filtratui būdinga kompleksinė ir kintanti cheminė sudėtis; jame gali būti sunkiųjų metalų, sunkiai biologiškai skaidomų organinių teršalų, amonio azoto, ksenobiotinių bei kitų aplinkai pavojingų junginių. Dėl mažo biologinio skaidumo ir didelės atsparių organinių junginių koncentracijos įprastiniai valymo metodai, įskaitant biologinius ir membraninius procesus, dažnai neužtikrina pakankamo stabilizuoto, ypač seno, savartynų filtrato išvalymo efektyvumo. Vienas perspektyvių sprendimų yra kelių technologinių procesų derinimas, kai koaguliacija ir flokuliacija taikomos kaip pirminio valymo etapas, o po jų vykdoma adsorbicija. Toks procesų derinys gali sudaryti sąlygas efektyviai šalinti skirtingų savybių teršalus, kartu mažinant bendrąsias valymo sąnaudas, ypač tais atvejais, kai adsorbicijai naudojamasi natūralios, nebrangios arba šalutinės kilmės medžiagos. Šiame straipsnyje sistemiskai analizuojamos savartynų filtrato fizikinės ir cheminės savybės, tradiciniai bei pažangūs jo valymo metodai ir pagrindiniai technologiniai parametrai, lemiantys procesų efektyvumą. Pagrindinis dėmesys skiriamas hibridiniam koaguliacijos ir adsorbicijos procesui, kurio veiksmingumas pastaraisiais metais vis dažniau nagrinėjamas moksliniuose tyrimuose. Literatūros duomenys rodo, kad dėl koaguliacijos ir adsorbicijos procesų sinerginio poveikio galima pasiekti didesnę kaip 80 % cheminio deguonies suvartojimo (ChDS) sumažėjimą ir daugiau kaip 90 % amonio azoto pašalinimo efektyvumą. Tokie rezultatai daugeliu atvejų reikšmingai viršija atskirai taikomų koaguliacijos arba adsorbicijos procesų efektyvumą. Straipsnyje kritiškai vertinamos dažniausiai naudojamų koagulantų ir adsorbentų savybės bei jų taikymo efektyvumas, analizuojama svarbiausių eksploatacinių parametrų įtaka hibridinio proceso veiksmingumui, taip pat identifikuojami esminiai technologiniai ribotumai ir perspektyviausios tolesnių tyrimų kryptys.

Reikšminiai žodžiai: savartynų filtratas, filtrato valymas, koaguliacija, adsorbicija, koagulantai, organiniai teršalai, amonio azotas.