Journal of Emerging Technologies and Industrial Applications
Vol. 4 No. 1 (2025) pp. 1-5
e-ISSN: 2948-507X
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Journal homepage: https://jetia.mbot.org.my/index.php/jetia/index

Thermal Evaporation as a Sustainable Solution for Landfill Leachate Treatment: Removal Efficiency Analysis

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Abstract: Landfill leachate poses significant environmental challenges due to its high pollutant content, requiring effective treatment to meet regulatory standards. In Malaysia, landfill leachate management often struggles to comply with the Environmental Quality Regulations 2009, prompting the need for alternative technologies. This study investigates the effectiveness of evaporation as a treatment method, focusing on the removal efficiencies of COD, BOD, turbidity, NH3-N, and colour at varying temperatures (120°C, 152°C, 154°C, and 156°C). Results showed COD removal exceeded 98%, achieving 99.6% at 156°C, demonstrating effective degradation of organic pollutants. NH3-N and BOD reductions were 86.7% and 64.6%, respectively, though both remained above discharge limits. Turbidity reductions were substantial, with final values meeting environmental standards. Colour removal was significant at lower temperatures, decreasing to 136 PCU at 120°C but declined at higher temperatures, likely due to the volatilization of chromophoric compounds. The pH consistently decreased with increasing temperature but remained above the upper regulatory limit of 9.0, necessitating post-treatment neutralization. These findings align with recent studies demonstrating the effectiveness of evaporation in reducing COD and turbidity while highlighting its limitations in addressing NH3-N, BOD, and pH compliance. Evaporation shows strong potential as a primary treatment method, particularly for reducing organic pollutants and turbidity, but requires integration with secondary processes for comprehensive leachate management. This study provides valuable insights into optimizing evaporation-based treatments and contributes to the advancement of sustainable leachate management strategies.

Received 10 February 2025; Accepted 20 May 2025; Available online 30 June 2025

Keywords: Landfill leachate, Evaporation, COD removal, NH3-N reduction, Thermal treatment, Sustainable wastewater management

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1. Introduction

In Malaysia, municipal solid waste (MSW) management is primarily conducted through landfilling, with 89% of waste entering landfills directly with minimal treatment. Only 1% of MSW receives proper treatment, and a significant portion of landfills consists of open dumping sites (50%), controlled tipping (30%), and sanitary landfills with or without leachate treatment facilities (10%) [1]. Organic waste constitutes the largest fraction of MSW at 45%, making landfills significant contributors to environmental challenges such as methane emissions and leachate contamination [1]. Leachate is a highly polluted liquid generated from the decomposition of organic waste and the percolation of rainwater through landfill layers, typically containing high levels of organic and inorganic pollutants, including heavy metals, ammonia, and other hazardous compounds. To mitigate these impacts, Malaysia has established regulatory standards for leachate discharge under the Environmental Quality Act 1974, which mandates stringent control of pollutants such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), and ammonia nitrogen (NH3-N) to ensure compliance with environmental limits [2].

Biological treatment methods have historically served as the primary mechanism for landfill leachate management [3],[4]. However, these approaches alone increasingly fail to meet evolving regulatory requirements, particularly in light of the growing complexity of contaminants in leachate [5]. Supplementary treatment technologies, such as chemical precipitation, membrane filtration, and advanced oxidation processes, have been investigated to address these limitations [6],[7] Despite their efficacy, these methods are often hindered by significant operational costs, maintenance complexity, and the generation of secondary waste streams, limiting their applicability in resource-constrained settings such as Malaysia [8],[9] This situation necessitates the pursuit of treatment solutions that are both cost-effective and operationally efficient.

Evaporation emerges as a viable alternative for landfill leachate treatment, leveraging its ability to concurrently remove multiple contaminants in a single operation. By elevating leachate to its boiling point, this process separates volatile components and produces a concentrated residual stream, thereby significantly reducing the leachate volume [10]. Furthermore, the condensate obtained through evaporation generally exhibits markedly reduced pollutant concentrations, facilitating its disposal or potential reuse [10],[11]. However, despite its promise, the application of evaporation in leachate treatment has received limited systematic exploration, particularly regarding the influence of operational parameters such as temperature on contaminant removal efficiencies. A critical gap in the literature pertains to the insufficient evaluation of evaporation as a standalone treatment method for landfill leachate. Existing studies often neglect to detail how varying operational conditions - notably temperature - impact the removal efficiency of key pollutants. Addressing these gaps is crucial to developing optimized, practical protocols for leachate treatment that balance efficacy and feasibility.

The objective of this study is to assess the efficacy of evaporation for landfill leachate treatment, with a focus on the role of temperature in removing COD, BOD, turbidity, ammonia nitrogen, and colour content. By systematically evaluating the performance of evaporation across a range of temperatures, this research aims to identify optimal operational conditions for maximizing pollutant removal. The findings are anticipated to enhance the understanding of evaporation as a sustainable treatment technology and to provide actionable guidelines for its implementation in landfill management systems. Additionally, this study seeks to contribute to the broader discourse on waste management by addressing both technical and environmental considerations.

2. Methodology

The experiment was conducted to evaluate the efficacy of evaporation for landfill leachate treatment at varying temperatures. Leachate samples were collected from Seelong Sanitary Landfill, Johor, Malaysia, and stored at 4°C to minimize biological activity prior to experimentation. A 200 mL aliquot of the leachate was subjected to initial water quality analysis to establish baseline parameters, including COD, BOD, turbidity, colour, pH, and NH_3-N content.

As shown in Fig. 1, the experimental setup consisted of a round-bottomed flask heated by a controlled heating mantle, connected to a Liebig condenser and a collection beaker to capture the condensate. The leachate was heated to predefined temperatures of 120°C, 152°C, 154°C, and 156°C. Vaporized leachate was condensed into a liquid form using the Liebig condenser, and the condensate was collected after the complete evaporation of the sample. Subsequently, the condensate was analysed using standard methods for wastewater examination to determine the final concentrations of COD, BOD, turbidity, colour, pH, and NH_3-N. Removal efficiencies were calculated using the formula:

$$Removal\ Efficiency\ (\%) = \frac{Initial\ Value - Final\ Value}{Initial\ Value} \times 100$$

Comparisons were made across the four temperature conditions to determine the optimal temperature for pollutant removal. All experiments were performed under controlled laboratory conditions to minimize external influences on evaporation. The study aimed to identify the optimal temperature range for maximum pollutant removal while evaluating the limitations of evaporation as a standalone leachate treatment method. This data provides valuable insights into the applicability and efficiency of evaporation in landfill leachate management.

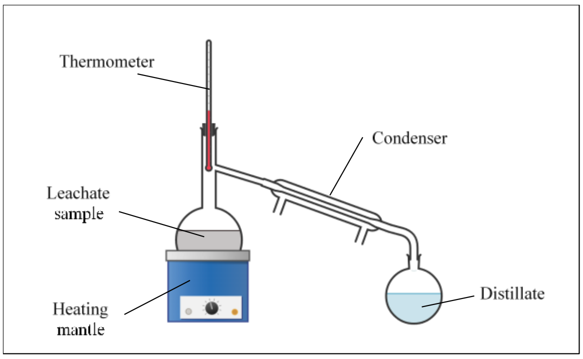

Fig. 1 - Experimental setup for the evaporation process of leachate

3. Results and Discussions

Table 1 demonstrates the significant reductions in key leachate pollutants achieved through evaporation at varying temperatures, particularly in COD and turbidity removal, while highlighting persistent challenges in NH3-N, BOD, and pH compliance. COD levels decreased dramatically from 9230 mg/L to 36.7 mg/L at 156°C, surpassing the regulatory limit of 400 mg/L. This aligns with findings by previous study, who achieved 99.99% COD removal using a hybrid evaporation and reverse osmosis system, emphasizing the robustness of thermal methods for organic pollutant degradation [12]. NH3-N reductions from 1370 mg/L to 182 mg/L at 156°C fell significantly short of the regulatory limit of 5 mg/L, demonstrating evaporation's limited effectiveness for ammonia removal. This is consistent with previous study, who highlighted the necessity of secondary treatments like biochar-seeded struvite precipitation, which achieved NH3-N removal efficiencies of up to 85.4%, to meet discharge standards [13].

BOD reductions were moderate, dropping from 184.8 mg/L to 65.5 mg/L at 156°C, but remained above the regulatory limit of 20 mg/L. This aligns with previous study, who emphasized the importance of integrating evaporation with biological or chemical treatments to improve BOD removal [14]. Colour reductions were most pronounced at lower temperatures, declining from 11533 PCU to 136 PCU at 120°C, aligning with trends reported by previous study. However, colour slightly increased at higher temperatures, likely due to the volatilization of organic compounds [15]. Turbidity consistently declined across all temperatures, reaching as low as 12.4 NTU at 120°C, though not directly regulated. The pH decreased from 11.62 to 9.11 at 156°C, remaining slightly above the upper regulatory limit of 9.0. Previous study highlighted the need for post-evaporation neutralization to address residual alkalinity, ensuring compliance with discharge standards [14]. Overall, while evaporation effectively reduces COD and turbidity to meet regulatory standards, its limitations in addressing NH3-N, BOD, and pH compliance underscore the need for complementary treatments. Combining evaporation with advanced methods such as biological processes or reverse osmosis enhances overall leachate management and ensures compliance with environmental regulations.

Table 1 - Initial and final concentrations of leachate parameters at different evaporation temperatures

Temperature (°C)	COD (mg/L)	BOD (mg/L)	Turbidity (NTU)	NH3-N (mg/L)	Colour (PCU)	pH
Initial	9230	184.8	125.6	1370	11533	11.62
120	163	122.4	12.4	612	136	10.98
152	127	108.4	18.1	293	218	9.31
154	66	90.4	15.6	238	1270	9.27
156	36.7	65.5	18.3	182	1010	9.11
Standards*	400	20	-	5	-	6.0 – 9.0

Table 2 and Fig. 2–6 collectively present the removal efficiencies of COD, BOD, turbidity, NH3-N, and colour at different evaporation temperatures, providing insights into the process's performance. COD removal efficiencies were consistently high, exceeding 98% across all temperatures and reaching 99.6% at 156°C (Figure 2), reflecting the efficient thermal degradation of organic pollutants. This aligns with Bandala et al. [6], who reported similar COD removal trends in thermal treatment studies. NH3-N removal followed a positive trend, increasing from 55.3% at 120°C to 86.7% at 156°C (Figure 5), indicating that ammonia volatilization is enhanced at higher temperatures, as supported by findings from Zhao et al. [16]. BOD removal was moderate, starting at 33.8% at 120°C and increasing to 64.6% at 156°C (Figure 3). Despite these improvements, the results suggest the persistence of biodegradable organics, a limitation also observed in studies by Di Palma et al. [17], who recommended coupling thermal methods with biological treatments to address BOD effectively. Turbidity reductions were substantial, reaching a peak efficiency of 90.2% at 120°C but declining slightly at higher temperatures, as shown in Figure 4. This may be attributed to the resuspension of fine particulates at elevated temperatures, consistent with observations by Ye et al. [18].

Table 2 - Removal efficiencies (%) of leachate parameters at different evaporation temperatures

Parameter	120°C	152°C	154°C	156°C
COD	98.2	98.6	99.3	99.6
BOD	33.8	41.4	51.1	64.6
Turbidity	90.2	85.6	87.6	85.4
NH3-N	55.3	78.6	82.6	86.7
Colour	98.8	98.1	89.0	91.2

Colour removal displayed variability, starting at 98.8% at 120°C but decreasing to 91.2% at 156°C (Figure 6). The reduced efficiency at higher temperatures could result from the thermal breakdown of chromophoric compounds into smaller, more stable molecules, a phenomenon noted by Ahsan et al. [19]. Overall, while evaporation effectively removed COD, turbidity, and colour to near-compliance levels, NH3-N and BOD reductions remained insufficient to meet regulatory standards without additional treatment. These findings emphasize the potential of evaporation as a primary treatment step for leachate, particularly for COD and turbidity, but highlight the necessity of integrated treatment systems to address ammonia and biodegradable organics fully. The trends observed in this study corroborate recent advancements in thermal leachate treatment, positioning evaporation as a critical component of sustainable landfill leachate management strategies.

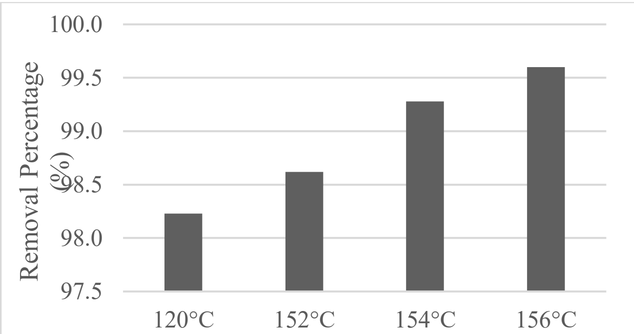

Fig. 2 - Removal percentage of COD at different temperature

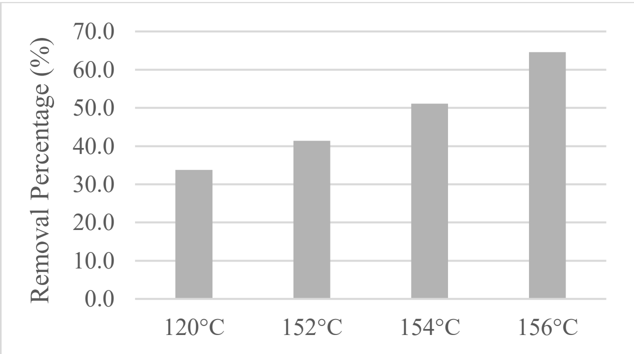

Fig. 3 - Removal percentage of BOD at different temperature

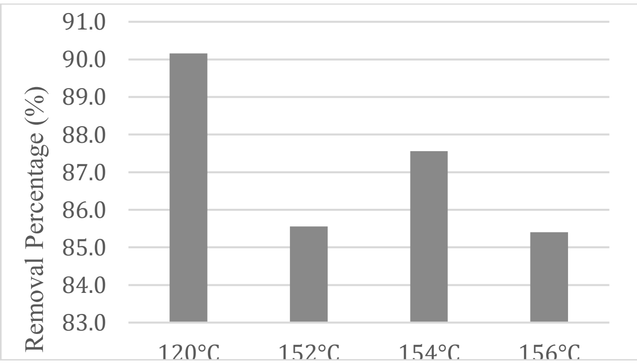

Fig. 4 - Removal percentage of turbidity at different temperature

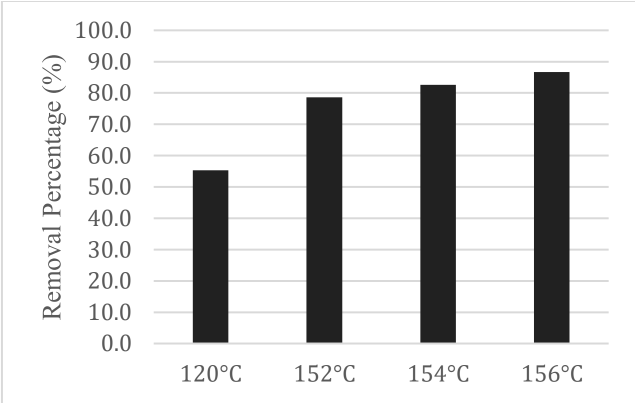

Fig. 5 - Removal percentage of ammoniacal nitrogen at different temperature

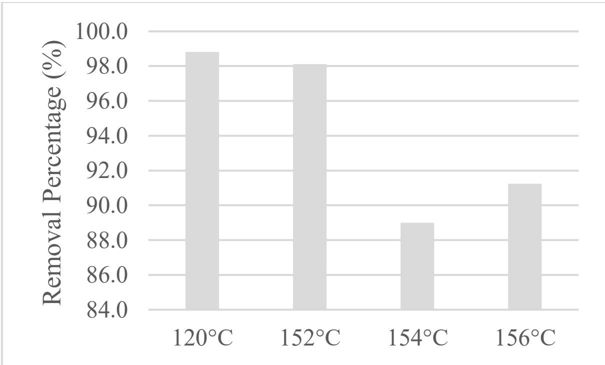

Fig. 6 - Removal percentage of colour at different temperature

4. Conclusion

This study evaluated the effectiveness of evaporation as a primary treatment method for landfill leachate, demonstrating its capability to significantly reduce key pollutants. COD removal exceeded 99% at the highest temperature of 156°C, highlighting the efficiency of thermal degradation in addressing organic pollutants. Turbidity and colour reductions were also substantial, with final values meeting or approaching regulatory standards. However, BOD and NH3-N, despite notable reductions of 64.6% and 86.7%, respectively, remained above permissible discharge limits, indicating the limitations of evaporation in fully addressing biodegradable organics and ammonia nitrogen. Additionally, while pH consistently decreased with temperature, it remained slightly above the upper regulatory threshold, emphasizing the need for post-treatment neutralization to meet compliance requirements. These findings align with recent advancements in thermal treatment technologies and underscore evaporation's potential as a robust solution for landfill leachate management. The process is particularly effective as a primary treatment step for reducing COD, turbidity, and colour. However, to achieve full regulatory compliance, integration with secondary processes such as biological treatments or chemical neutralization is necessary to address residual pollutants. This study provides valuable insights into

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optimizing evaporation-based treatments and reinforces its role in advancing sustainable leachate management strategies. Future research should focus on improving energy efficiency, scaling the technology for practical applications, and developing integrated treatment systems to enhance overall performance and economic feasibility.

Acknowledgement

This work was supported by the Universiti Teknologi Malaysia (UTM) Fundamental Research Grant (Grant No. Q.J130000.3846.22H85).

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