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Landfill Leachate Treatment Using Electrocoagulation

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Abstract: Landfill leachate, particularly stabilized leachate, presents significant environmental challenges due to its high pollutant load, including COD, BOD, ammoniacal nitrogen (NH_3-N), total suspended solids (TSS), color, and turbidity. Conventional biological and chemical treatments struggle to address the recalcitrant nature of stabilized leachate. This study evaluates a continuous flow electrocoagulation (EC) system as an alternative treatment method, focusing on the influence of current density on pollutant removal efficiencies. Experiments were conducted using a custom-designed EC reactor equipped with iron and aluminum electrodes, with current densities ranging from 10 to 40 mA/cm². Key operational parameters, including flow rate and hydraulic retention time, were optimized to simulate real-world landfill leachate conditions. Results revealed a direct correlation between current density and pollutant removal efficiency. At the highest current density of 40 mA/cm², the system achieved significant reductions in TSS (72.14%), color (33.85%), and turbidity (25.40%). However, lower removal rates were observed for COD (18.12%) and NH_3-N (19.27%), indicating the limitations of EC in addressing recalcitrant organic compounds and ammonia. The enhanced removal at higher current densities is attributed to increased coagulant generation and improved flotation and sedimentation processes. These findings demonstrate the potential of EC as an effective primary treatment for stabilized landfill leachate, particularly for reducing suspended solids, color, and turbidity. However, the moderate removal efficiencies for COD and NH_3-N suggest that hybrid approaches, integrating EC with complementary processes such as advanced oxidation or adsorption, are necessary for comprehensive pollutant removal.

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1. Introduction

Landfills remain the predominant method for municipal solid waste disposal worldwide, with approximately 37% of global waste managed through landfilling [1]. In Malaysia, landfills are the primary disposal method, handling about 80% of the nation's solid waste [2]. However, a major concern with landfills is the production of leachate - a hazardous liquid that forms when water percolates through waste, dissolving contaminants. This leachate, characterized by high levels of chemical oxygen demand (COD), biological oxygen demand (BOD), ammonia-nitrogen, and heavy metals, presents significant environmental risks [3],[4]. If unmanaged, leachate can pollute surface and groundwater, adversely affecting ecosystems, agriculture, and human health. Contamination of potable water sources has been linked to public health concerns, including the spread of diseases and toxic substance accumulation in the food chain [5].

Conventional leachate treatment methods, such as biological, chemical, and physical approaches, have limited success, particularly for stabilized leachate. Biological processes, such as activated sludge, struggle to degrade the non-biodegradable fraction of stabilized leachate, which develops after a landfill matures [6]. Stabilized leachate has low biodegradability, high ammonia, and refractory organic compounds that resist degradation [7]. Chemical coagulation methods, while effective, require significant chemicals, leading to increased costs, secondary pollutants, and large volumes of sludge [8],[9]. Physical methods, such as membrane filtration and adsorption, are cost-prohibitive for large-scale applications and prone to fouling [10],[11]. These limitations underscore the need for cost-effective, sustainable leachate treatment alternatives. Electrocoagulation (EC) has emerged as a promising option due to its ability to generate coagulants in situ without chemical additives [12]–[14]. EC combines electrochemistry, coagulation, and flotation, offering reduced chemical usage, simpler sludge management, and broad-spectrum contaminant removal.

Despite the advantages of EC, its application in landfill leachate treatment has been limited, particularly under continuous flow conditions. While much existing research has emphasized batch systems, which do not simulate continuous landfill inflow, this study specifically investigates the influence of current density on pollutant removal in a continuous flow EC setup, focusing on key contaminants such as COD, BOD, NH_3-N, and TSS. This narrow focus on current density aims to optimize one of the most critical parameters affecting EC efficiency for stabilized landfill leachate, where refractory organic compounds and ammonia are prominent. By assessing removal efficiencies at various current densities, this study seeks to generate insights that can guide practical EC application and further advancements in landfill leachate management.

Recent studies have underscored the effectiveness of electrocoagulation (EC) in the treatment of stabilized landfill leachate under continuous flow conditions. Amusa *et al.* [15] explored a continuous-flow EC system focused on optimizing inlet flow rate and current density, demonstrating that specific parameter adjustments significantly enhance pollutant removal efficiency. Similarly, Mehralian *et al.* [16] developed a continuous-flow EC reactor aimed at improving energy efficiency and optimizing electrode configuration and hydraulic retention time, both of which are critical for effective pollutant reduction in aged landfill leachate. In another study, Lu *et al.* [17] tested a two-step electrochemical process integrating electrooxidation and EC as a tertiary treatment, achieving notable reductions in colour and organic content from bio-treated leachate. These findings collectively indicate the importance of detailed evaluations of EC process parameters to improve pollutant removal from complex wastewater streams.

This study aims to address these gaps by evaluating the effectiveness of a continuous flow electrocoagulation system for treating stabilized landfill leachate. Specifically, this research will assess the influence of current densities on the removal efficiency of key pollutants, including COD, BOD, ammonia-nitrogen, and total suspended solids (TSS). Additionally, the study will explore other operational parameters, such as electrode type, flow rate, and pH, to understand their impact on the EC process. The objectives are to evaluate pollutant removal, explore the feasibility of a continuous flow EC reactor, and identify improvements for scaling up this technology to provide a sustainable solution for landfill leachate management.

2. Methodology

The methodology for this study involved designing and operating a continuous flow EC system to treat stabilized landfill leachate. The experimental setup consisted of an electrocoagulation reactor equipped with iron and aluminum electrodes arranged in a monopolar parallel configuration. The reactor was operated under continuous flow conditions to simulate real-world landfill leachate treatment scenarios.

Leachate Sampling and Preparation: Leachate samples were collected from Seelong Sanitary Landfill, Johor, Malaysia. Samples were stored at 4°C to minimize biological activity prior to experimentation. Before treatment, the leachate was characterized to determine initial concentrations of COD, BOD, NH_3N, TSS, colour and turbidity.

Reactor Design and Configuration: The EC reactor was designed with a working volume of 10 liters, with electrodes placed at an inter-electrode distance of 1 cm. The reactor was equipped with a DC power supply to provide a controllable current density ranging from 10 to 40 mA/cm². The influent flow rate was adjusted to achieve different hydraulic retention time (HRT) of 60 minutes.

Operational Procedure: For each experiment, 10 litres of leachate were introduced into the reaction tank and subjected to batch treatment for 30 minutes, without any mixing mechanism in the chamber. Following this phase, continuous operation commenced by pumping the leachate from the feed tank to the reactor via a peristaltic pump at a controlled flow rate of 400 ml/min. The treated leachate overflowed into a settling tank where solid-liquid separation occurred through flotation and sedimentation. The experiment concluded after collecting 300 ml of treated leachate from the effluent, which was subsequently analysed for composition. Between experiments, electrodes were cleaned with dilute hydrochloric acid to ensure removal of any residual impurities.

Operational Parameters: The study investigated the effect of current density as the key operational parameter, with values of 10, 20, 30, and 40 mA/cm². The current density was adjusted to determine its impact on pollutant removal efficiency.

Data Collection and Analysis: During the experiments, samples of treated leachate were collected to measure the concentrations of COD, BOD, NH_3N, TSS, colour, and turbidity. The removal efficiency for each pollutant was calculated based on the difference between influent and effluent concentrations.

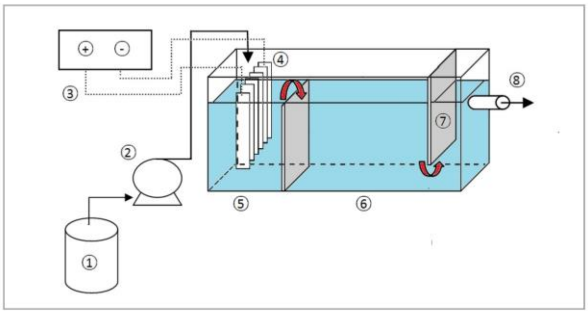

Fig. 1 - Schematic diagram for continuous EC reactor set-up

Table 1 - Components of EC Reactor

No.	Component
1	Feed tank
2	Peristaltic pump
3	Adjustable DC power supply
4	Carbonised iron electrodes
5	Reaction tank
6	Sludge settling tank
7	Baffle
8	Effluent

3. Results and Discussions

Table 2 shows the characteristic of Seelong Sanitary Landfill leachate. As shown in the table, the leachate demonstrates exceptionally high values for multiple contaminants, including pH (11.32), colour (11,511 PCU), turbidity (122.38 NTU), NH_3N (1,370 mg/L), TSS (276.67 mg/L), BOD_5 (160.28 mg/L), and COD (7,927 mg/L), all of which far exceed acceptable limits under Malaysian regulations. These values indicate that the leachate is highly stabilized and contains substantial levels of non-biodegradable pollutants, as evidenced by the low BOD_5/COD ratio of 0.18. This ratio points to a high concentration of refractory organic matter that is resistant to biological breakdown, suggesting that conventional biological treatment methods would struggle to achieve significant pollutant reduction. The high pH, in particular, indicates alkaline conditions, which often result from the degradation of nitrogenous and organic compounds over time, further complicating biological treatments.

This characterization emphasizes the challenge posed by stabilized leachate, which often requires advanced treatment solutions capable of breaking down complex organics and reducing ammonia content to prevent environmental contamination. Recent studies consistently highlight these challenges, with findings from Wijekoon et al. [3] and Ma et al. [4] documenting similar issues with recalcitrant compounds in aged leachate, thus underscoring the need for advanced or hybrid approaches like EC that offer broader pollutant removal capabilities beyond biological methods.

Table 2 - The characteristics of Seelong Sanitary Landfill leachate

Parameters	Unit	Average	Standards*
pH	-	11.32	6.0 - 9.0
Colour	PCU	11,511	-
Turbidity	NTU	122.38	-
Ammoniacal Nitrogen (NH_3-N)	mg/l	1370	5
Total Suspended Solids (TSS)	mg/l	276.67	50
Biological Oxygen Demand (BOD_5)	mg/l	160.28	20
Chemical Oxygen Demand (COD)	mg/l	7927	400
BOD_5 / COD Ratio	-	0.18	-

*Environmental Quality (Pollution Control from Solid Waste Transfer Stations and Landfills) Regulations 2009 – P.U. (A) 433/2009

Table 3 presents the pollutant removal efficiencies achieved at various current densities (10, 20, 30, and 40 mA/cm²), demonstrating a direct correlation between current density and removal rates for parameters such as colour, turbidity, NH_3-N, TSS, BOD, and COD. At the highest current density of 40 mA/cm², removal efficiencies reached 33.85% for colour, 25.40% for turbidity, 19.27% for NH_3-N, 72.14% for TSS, 29.87% for BOD, and 18.12% for COD. This improvement in pollutant removal with increased current density can be attributed to the enhanced generation of coagulant species, such as $Fe(OH)_3$, from the electrodes. The production of these species, combined with electrolysis-derived gas bubbles, facilitates pollutant destabilization, aggregation, and subsequent sedimentation. Notably, TSS removal is particularly efficient at higher current densities, likely due to effective coagulation and flotation processes that capture and remove suspended solids.

However, the lower removal rates for COD and NH_3-N indicate that these parameters are less responsive to EC alone, as both represent complex and recalcitrant pollutants. Ammoniacal nitrogen, for instance, often requires additional oxidation or adsorption steps, which are not inherently provided by the EC process. COD, reflecting organic content, includes both biodegradable and non-biodegradable fractions, with the latter often consisting of humic substances and other persistent compounds. The relatively moderate removal of COD and NH_3-N even at 40 mA/cm² suggests that while EC is effective for colour, turbidity, and TSS reduction, it may not fully address the removal of more challenging contaminants without further optimization or supplementary treatments. Similar findings have been observed in the previous work [18]–[21] where current density was found to be a key factor in EC efficiency, though additional processes were often necessary to handle complex leachate compositions effectively.

Table 3 - The removal of pollutant in leachate at different current density

Parameters	Unit	Initial Conc.	10 mA/cm²		20 mA/cm²		30 mA/cm²		40 mA/cm²	
			Final Conc.	Removal (%)	Final Conc.	Removal (%)	Final Conc.	Removal (%)	Final Conc.	Removal (%)
Colour	PCU	11,511	8291	27.97	7960	30.85	7755	32.63	7614	33.85
Turbidity	NTU	122.38	98.4	19.59	97.76	20.12	94.26	22.98	91.3	25.40
NH_3-N	mg/l	1370	1212	11.53	1175	14.23	1125	17.88	1106	19.27
TSS	mg/l	276.67	95.5	65.48	88.9	67.87	81.34	70.60	77.09	72.14
BOD_5	mg/l	160.28	136.3	14.96	130.62	18.51	120.3	24.94	112.4	29.87
COD	mg/l	7927	7041	11.18	6957	12.24	6715	15.29	6491	18.12

Figure 2 visually depicts the incremental increase in pollutant removal efficiency across different current densities, further illustrating the positive impact of higher current densities, especially for colour and TSS removal. As current density rises from 10 to 40 mA/cm², there is a clear improvement in removal efficiency for each parameter, with colour and TSS achieving the highest reductions. The increase in removal rates can be explained by the augmented formation of coagulant species and gas bubbles at higher currents, which enhance the aggregation of suspended particles and flotation of pollutants. In particular, the colour and turbidity reductions suggest that EC effectively destabilizes colloidal and dissolved organic compounds responsible for colour, facilitating their aggregation and removal.

Nevertheless, the modest removal percentages for COD and NH_3-N, despite higher current densities, highlight a limitation of EC in addressing certain stable pollutants. These results suggest that while EC is highly effective for treating turbidity, colour, and particulate matter, it may require process augmentation or integration with other treatment methods to target ammonia and persistent organic compounds. This observation is consistent with other studies that have noted EC's effectiveness in removing suspended and colloidal matter but have identified the need for complementary processes when dealing with stabilized leachate. For instance, previous study reported that while EC could achieve substantial removal for certain pollutants, the addition of processes like adsorption or advanced oxidation may be required for comprehensive treatment [22]–[26] Thus, while the current findings validate the use of EC as an effective primary treatment for Seelong landfill leachate, further refinement in operational parameters or hybrid approaches could enhance the removal of refractory pollutants.

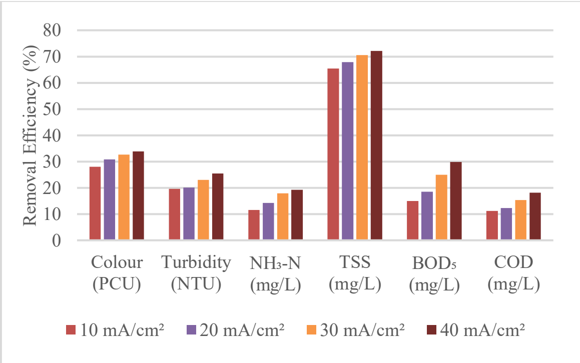

Fig. 2 - The removal of pollutant in leachate at different current density

4. Conclusion

This study demonstrates the potential of a continuous flow electrocoagulation (EC) system for treating stabilized landfill leachate, achieving notable reductions in turbidity, color, and total suspended solids (TSS) while highlighting the challenges in addressing recalcitrant pollutants such as COD and ammoniacal nitrogen. The findings indicate that current density is a critical parameter influencing pollutant removal efficiency, with higher densities enhancing coagulation and flotation processes. However, the moderate removal rates for COD and NH_3-N suggest the need for complementary treatments, such as advanced oxidation or adsorption, to achieve comprehensive pollutant reduction. These results underscore the viability of EC as a primary treatment method for landfill leachate while advocating for hybrid approaches to optimize its performance in managing complex wastewater streams effectively.

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