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Enhancing Leachate Treatment with Electrocoagulation: A Computational Approach Using Response Surface Methodology

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ABSTRACT

Malaysia's growing population and industrialisation have increased solid waste accumulation in landfills, leading to a rise in leachate production. Leachate, a highly contaminated liquid from landfills, poses environmental risks and affects water quality. Conventional leachate treatments are costly and time-consuming due to the need for additional chemicals. Therefore, the Electrocoagulation process could be used as an alternative method. Electrocoagulation is an electrochemical method of treating water by eliminating impurities by applying an electric current. In the present study, the optimisation of contaminant removal was investigated using Response Surface Methodology. Three parameters were considered for optimisation: the current, concentration of leachate, and the electrodes' distance. The outcome of this study includes ANOVA analysis, mathematical modelling and 3D surface plot modelling. The optimum condition for contaminants removal was obtained at a current of 4 Amp, a concentration of leachate of 90.95%, and an electrode distance of 3 cm. The outcomes obtained under these conditions were about 47.85% and 76.32% removal of COD and turbidity, respectively. Both percentage COD and turbidity removal models achieved significant results, demonstrating that at least one of the independent variables has a significant impact on the dependent variable.

Keywords: Current intensity, electrocoagulation process, electrode distance, leachate treatment, process optimisation, Response Surface Methodology (RSM)

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INTRODUCTION

Leachate, a concerning outcome of landfill activity, poses environmental risks, impacting ecosystems and water quality. It is produced when water seeps through other materials or solid waste and collects pollutants that are either suspended or dissolved in the process (Detho et al., 2024). This process occurs when rainwater or other liquids come into contact with waste products within the landfill. This liquid can dissolve and remove a variety of contaminants and materials, such as organic matter, heavy metals, chemicals, and pathogens, as it moves through the waste (Hussein et al., 2021). Leachate will not be directly discharged to a municipal wastewater treatment plant since it is a complicated and extremely contaminated liquid (Rangga et al., 2024). Municipal wastewater treatment plants may not be suited to handle the pollutants in leachate because they are primarily intended to treat domestic and industrial sewage. Thus, leachate is often treated in on-site treatment systems or specialised leachate treatment facilities.

Current leachate treatment methods still have some drawbacks in terms of time and cost. Standard physico-chemical procedures are inadequate for treating leachate due to high operational costs and recalcitrant matter in the leachate (Bandala et al., 2021). Among the emerging methods, electrocoagulation (EC) has shown great potential as a sustainable alternative for effective leachate treatment. The electrocoagulation (EC) process is an electrochemical method for treating water using a direct electric current without adding chemicals, where tiny particles of the contaminants are removed from the water. EC treatment for wastewater operates through electrochemical reactions when an electric current is applied between electrodes. At the anode, metal ions such as Al^{3+} are released and form metal hydroxides that act as coagulants, destabilising and aggregating suspended particles into larger flocs(Salim et al., 2024). Water electrolysis produces hydrogen gas and hydroxyl ions at the cathode, further aiding coagulation by raising the pH value (Sharma et al., 2021). The process has demonstrated the ability to effectively remove contaminants such as fluoride, arsenic, heavy metals, dyes, and oils from residual, surface, and underground water (López-Guzmán et al., 2021). Despite the established potential of EC to remove pollutants from leachate, challenges remain in optimising the process for high efficiency. For more than two decades, researchers have investigated the use of EC for leachate treatment (Ding et al., 2021; Galvão et al., 2020; Rookesh et al., 2022); however, significant gaps persist in understanding optimal operating conditions, particularly in the context of diverse and complex leachate compositions (Guo et al., 2022).

Response Surface Methodology (RSM) offers a powerful statistical and mathematical tool for optimising research studies. It enables the analysis and description of interactions between factors (independent variables) and responses (dependent variables) (Tay et al., 2023). In the context of EC, RSM facilitates the identification of ideal conditions for contaminant removal while accounting for variable interactions. Previous studies, such as those by Sediqi et al. (2021) have utilised RSM to optimise EC processes, focusing on minimising energy and resource consumption while treating landfill leachate. Recent works, including Faheem et al. (2022) and Apaydin and Özkan (2020) examined factors such as initial COD, initial pH, applied current, and electrolysis time using central composite design (CCD), while others such as Ameli et al. (2024) and Gautam et al. (2022) optimised current density, electrolysis time, and inter-electrode distance. However, the influence of leachate concentration on the electrocoagulation treatment process has received limited attention in the existing literature.

This study addresses existing gaps by investigating the optimisation of COD and turbidity removal, focusing on the specific interactions between initial leachate concentration, applied current and electrode distance. The research also develops a mathematical model to illustrate these interactions and identify optimal conditions that maximise efficiency. By doing so, this work advances the application of EC in leachate treatment, addressing limitations in previous studies and offering a framework for future innovations in the field.

MATERIALS AND METHODS

Sample Collection

Leachate was collected at Jeram Sanitary Landfill (3°11’20’’ N,101°21’50″ E), located in Selangor, Malaysia. Table 1 shows the characteristics of raw leachate generated at Jeram Sanitary Landfill obtained from a previous study (Kamaludin et al., 2021).

Table 1
Characteristics of raw leachate from Jeram Sanitary Landfill

Parameter	Sunny Day	Rainy Day
pH	7.35	7.35
COD (mg/L)	1168.96	598.54
DO (mg/L)	8.41	8.32

The landfill began operation in 2007, receiving 3400 tonnes of waste daily. The design lifespan for this landfill is 20 years. Jeram Sanitary Landfill receives many kinds of waste, including domestic, food, market, wood pallets, and green waste. At Jeram Sanitary Landfill, raw leachate will go to the anaerobic lagoon before proceeding to the next process. There are three biological process stages in the three different SBR lagoons. The leachate will be aerated for 22 hours, and the aerator will be off for 2 hours. The leachate will be transferred to the next SBR stage during the off period. Later, it will be transferred to the settling tank before proceeding with the physical process.

Electrocoagulation Process

The electrocoagulation process uses direct current to break down the contaminants existing in the leachate as either dissolved or suspended particles (Das et al., 2022). In the present study, aluminium (Al) electrodes were used for both anode and cathode. Electrodes were submerged in 1 L of leachate diluted with distilled water according to the desired concentration. The electrodes' dimensions were 6.0 cm x 15.0 cm x 0.1 cm, with a total surface area of 360 cm^2. The dimension of the 1 L glass beaker was 21.0 cm in height with an 8.5 cm inner diameter and 9.0 cm outer diameter. The electrodes produced Al ions, Al^{3+}, during the EC process, which ions were essential for forming aluminium hydroxide, Al (OH)3, to remove the leachate's impurities. Additionally, a previous study has shown that Al electrodes removed 70% more COD than Fe electrodes (Tahreen et al., 2020). When direct current (DC) is applied at the electrodes, electrochemical reactions assist the coagulant production in situ without any chemical additions. The reactions of both electrode surfaces follow Equations 1 and 2 (Das et al., 2022).

Electrochemical reactions at anode:

$$Al \rightarrow Al^{3+}(aq) + 3e^{-} \qquad [1]$$

Electrochemical reactions at the cathode:

$$3H_2 0 + 3e^{-} \rightarrow \frac{3}{2} H_2(g) + OH^{-} \qquad [2]$$

The chemical reactions at the electrodes acted as coagulation, as shown in Equation 3, and initiated the flocculation process. The flocs settled for 20 minutes. The treated sample was then separated from the flocs using a cloth strainer before laboratory testing.

Formulation of coagulant:

$$Al^{3+}(aq) + 3H_2 0 \rightarrow Al(OH)_3 + 3H^{+} \qquad [3]$$

Rubber bands with different diameters were used to measure the distance between a pair of electrodes. The rubber bands were tied to ensure they did not move when submerged in the leachate. The crocodile clips were clipped on the spring clips to avoid direct contact with the liquid, and the crocodile clips were connected to the DC power supply.

Parameter for Leachate Treatment

In this study, two parameters were selected, namely, COD and turbidity. These two parameters are important criteria in the discharge standard. They are regulated by the Environmental Quality Act 1974 and its subsequent amendments and regulations, particularly focusing on the Environmental Quality (Control of Pollution from Solid Waste Transfer Station and Landfill) Regulations 2009, as shown in Table 2.

COD and turbidity were chosen as dependent variables because they are key indicators of leachate contamination and are affected by EC. COD measures dissolved organic matter, while turbidity tracks suspended particles. Therefore, both of these parameters are good indicators for assessing the effectiveness of EC in treating leachate, as they represent both dissolved and suspended contaminants.

Table 2
Parameters and limits for leachate discharge in Malaysia

Parameter	**Limit**
Chemical Oxygen Demand (COD)	≤ 20 mg/L
Turbidity	5 NTU
pH	6.0–9.0

Pollutant Removal Analysis

The sludge generated after the EC process was removed from the treated sample using a cloth strainer before conducting the Chemical oxygen demand (COD) and Turbidity testing. The COD was measured by the HACH method-reactor Digestion Method (Method 8000) digestion in the 0–1500 mg/L range, and the turbidity was determined using a Hach 2100Q portable turbidity meter.

Based on the obtained result, the removal percentage of the pollutant was calculated using the expression in Equation 4 as follows:

$$Removal\ (\%) = \frac{C_i - C_f}{C_i} \quad [4]$$

Where Ci and Cf are the COD and turbidity concentration at the treatment's beginning and end, respectively.

Response Surface Methodology (RSM)

Response surface methodology is one of the methods used in the Design of Experiments (DOE) software that helps optimise the electrocoagulation process. Three parameters or factors were used as input in this study, which included the concentration of leachate, applied current, and the electrodes' distance. Initial leachate concentration is critical as it represents the amount of organic matter that needs to be oxidised. It directly influences adjustments to other operational factors, such as current intensity, to achieve effective removal. Electrode distance, on the other hand, affects the strength of the electric field. A shorter distance creates a stronger electric field, improving the rate of electrolysis. However, if the distance is too short, it can result in excessive current density, leading to increased power consumption, overheating, or electrode degradation (Hanif et al., 2022). Additionally, applied current impacts energy consumption, which is critical in optimising the process for efficiency and cost-effectiveness (Faheem et al., 2022). Table 3 shows the range values of DC, concentration of leachate, and electrode distance that were input in the software.

The applied current ranged from 1.5A to 4.0A, considering the high contamination level of the leachate and referring to the optimum conditions suggested by Galvão et al. (2020).

Table 3
Range values for parameters

Parameter	Current, Amp	Concentration of Leachate, %	Electrodes' Distance, cm
Range Value	1.5–4.0	50–100	0.8–3.0

The electrodes' distance between the anode and the cathode was set between 0.8 cm and 3.0 cm (Ameli et al., 2024). A shorter distance between the anode and the cathode can result in a higher electric field intensity. 0.8 cm is considered practical for rapid treatment and efficient contaminants removal, while 3.0 cm is the maximum value to reduce electrode wear (Guo et al., 2022). Therefore, based on these ranges, 13 different values with varying combinations of each factor and level were carried out, as shown in Table 4.

Table 4
Parameters generated by RSM

Std	Run	Factor 1	Factor 2	Factor 3
		A: Current (Amp)	B: Concentration (%)	C: Electrodes' Distance (cm)
1	5	4	100	0.80
2	10	4	50	3
3	9	1.50	100	3
4	3	1.50	50	0.80
5	4	0.98	75	1.90
6	11	4.52	75	1.90
7	13	2.75	39.65	1.90
8	12	2.75	110.36	1.90
9	6	2.75	75	0.34
10	2	2.75	75	3.46
11	8	2.75	75	1.90
12	1	2.75	75	1.90
13	7	2.75	75	1.90

The model's goodness of fit was assessed using the coefficient of determination (R^2), where a value close to 1 indicates strong agreement between experimental and predicted outcomes. The significant factors and interactions influencing COD and turbidity removal percentages were identified through analysis of variance (ANOVA). Statistical significance was determined by examining *p*-values. Factors with *p*-values less than 0.05 (indicating a probability higher than 95%) were considered significant for the removal process. Subsequently, three-dimensional plots along with contour plots were generated to visualise the effects of these significant factors on both parameters. The optimal ranges for each factor to achieve effective COD and turbidity removal were determined using desirability functions. The quadratic mathematical model was employed to predict the optimal conditions for the treatment process.

Three trial experiments were conducted based on the optimised conditions suggested by the Response Surface Methodology (RSM) to verify their accuracy. Data in triplicates were expressed as mean ± standard deviation. The experimental results were verified by comparing them to the predicted outcomes from the RSM model. A less than 10% deviation between the predicted and experimental results was considered acceptable, confirming the model's validity.

RESULTS AND DISCUSSIONS

ANOVA Analysis

The analysis of variance (ANOVA) statistics for the percentage of COD and turbidity removal are shown in Tables 5 and 6, respectively. The associated *p*-value for each model was below 0.05, suggesting that the corresponding model terms are significant. The terms

Table 5
ANOVA for a fitted quadratic polynomial model for COD removal

Parameter	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2535.46	9	281.72	148.53	0.0008	significant
A	870.70	1	870.70	459.07	0.0002	
B	56.82	1	56.82	29.96	0.0120	
C	1.73	1	1.73	0.9120	0.4100	
AB	62.61	1	62.61	33.01	0.0105	
AC	231.5	1	231.50	122.05	0.0016	
BC	78.03	1	78.03	41.14	0.0077	
A^2	11.61	1	11.61	6.12	0.0897	
B^2	19.33	1	19.33	10.19	0.0496	
C^2	320.86	1	320.86	169.17	0.0010	
Residual	5.69	3	1.90			
Lack of Fit	0.7836	1	0.7836	0.3194	0.6289	not significant
Pure Error	4.91	2	2.45			
Cor Total	2541.15	12				

A, B, AB, AC, BC, B^2, and C^2 are significantly illustrated by $p < 0.05$ for COD removal. Meanwhile, terms A, B, AB, BC, and C^2 are significant for turbidity removal. The insignificant term represented by *p*-values above 0.05 was removed from further analysis. Reducing the number of insignificant terms can improve the model's performance.

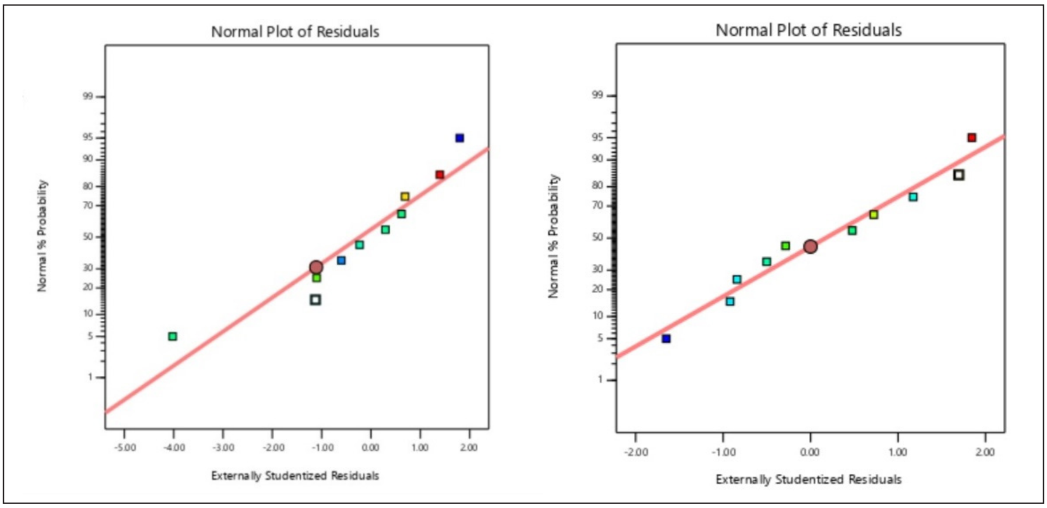
Table 6
ANOVA for a fitted quadratic polynomial model for turbidity removal

Parameter	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	862.74	7	123.25	10.80	0.0093	significant
A	129.93	1	129.93	11.38	0.0198	
B	181.26	1	181.26	15.88	0.0105	
C	4.03	1	4.03	0.3533	0.5781	
AB	121.03	1	121.03	10.60	0.0225	
AC	20.57	1	20.57	1.80	0.2372	
BC	240.21	1	240.21	21.05	0.0059	
C^2	203.55	1	203.55	17.83	0.0083	
Residual	57.07	5	11.41			
Lack of Fit	51.19	3	17.06	5.80	0.1505	not significant
Pure Error	5.88	2	2.94			
Cor Total	919.81	12				

The R^2 were 0.99 and 0.93 for the COD and turbidity models, highlighting the high correlation between experimental and predicted values. Additional evaluation to validate the suitability of the proposed models was conducted using additional diagnostic tools within RSM, including a normal plot of residuals illustrated in Figure 1. The linear relationship between students' residuals and the normal probability plot indicated a strong correlation between predicted and observed data.

The statistical model was then used to generate the quadratic model regression. In terms of their coded factors, the final regression model is expressed by the following second-order polynomial in Equations 5 and 6, respectively. It represents the relationship between input variables and a response variable using quadratic terms.

$$\begin{aligned} COD\ Removal, \% \\ = +21.37 + 14.75A - 3.77B - 0.6576C - 5.60AB \\ + 10.76AC + 6.25BC + 1.31A^2 - 1.69B^2 + 6.87C^2 \end{aligned} \quad [5]$$



(a) (b)

Figure 1. Normal plot of residuals for (a) COD removal and (b) Turbidity removal

$$Turbidity\ Removal, \% \\ = +60.29 + 5.70A + 6.73B - 1.00C - 7.78AB \\ + 3.21AC + 10.96BC + 5.36C^2 \quad [6]$$

The mathematical model generated in RSM offers significant benefits for optimising the removal of COD and turbidity from leachate. It helps identify the best combination of process variables to maximise the efficiency of COD and turbidity removal. Additionally, it allows for accurate prediction of the removal efficiency under various conditions, reducing the need for extensive experimentation. Furthermore, the model provides a quantitative basis for decision-making, enabling the selection of the most effective parameters to enhance the removal process from leachate.

3D-plot Surface Modelling

COD Removal

The interaction effect of leachate concentration and current on COD removal is shown in Figure 2. It became evident from the figure that the current had a more pronounced effect on COD removal compared to the concentration of leachate. The percentage of COD removal increased proportionately with higher Amp, with the maximum removal of 45% achieved at 4.5 Amp. Conversely, there were no notable changes in COD removal percentage throughout the different ranges of leachate concentration. According to Shahedi et al. (2020), a high current level stimulates increased COD removal by accelerating the formation rate of coagulants, thereby enhancing contaminant removal efficiency.

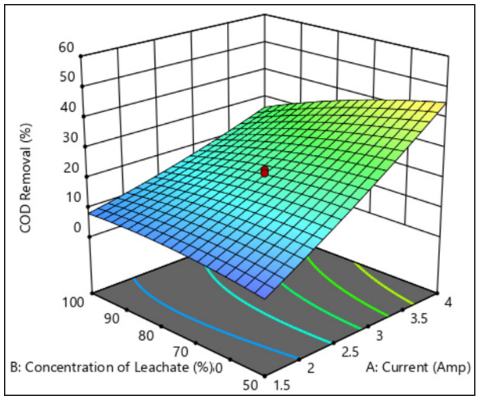


Figure 2. 3D response surface plot of the interaction effect of current and concentration of leachate on COD removal

COD removal during the EC process primarily occurs through coagulation and subsequent flocculation mechanisms facilitated by the *in situ* formation of coagulants. When a direct current is applied, the anodic dissolution of aluminium electrodes generates Al^{3+} ions, which hydrolyse to form aluminium hydroxide, Al $(OH)_3$. These hydroxides serve as effective coagulants, adsorbing organic contaminants responsible for the COD load (Gasmi et al., 2022). Therefore, increased current strengthens the electric field, accelerating the dissolution of aluminium and the formation of hydroxides as illustrated in Figure 2.

The surface plot in Figure 3 illustrates the response of COD removal efficiency based on the interaction between the current and the distance between the electrodes. As the current increases from 0.8 to 3.5 Amp, the COD removal efficiency tends to rise, suggesting that higher currents enhance the COD removal process by providing more electrical energy. Conversely, as the distance between the electrodes decreases from 2.45 cm to 1.35 cm, the COD removal efficiency also increases significantly, indicating that a smaller electrode distance favours more effective interaction and, thus, higher COD removal efficiency.

The plot demonstrates a non-linear interaction between current and electrode distance, with the highest COD removal efficiencies achieved at higher currents and shorter electrode distances. The red dot on the plot represents the optimal point, indicating the specific combination of current and electrode distance that maximises efficiency. Based on the surface plot, it can be concluded that while both factors significantly influence COD removal efficiency, electrode distance appears to be the more significant factor. This differs from the findings from Nasrullah et al. (2022), who reported that electrode distance had less effect on treatment at high current intensities, likely due to the higher current range (15–20 A) used in their study. Nevertheless, compared to the change along the current axis, the steep increase in COD removal efficiency with decreasing electrode distance suggests that optimising electrode spacing is crucial for achieving higher COD removal rates in the present study.

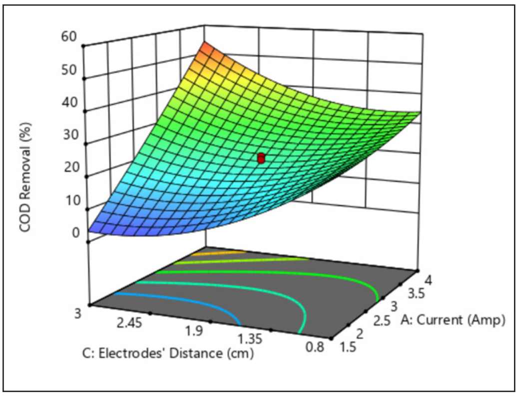


Figure 3. 3D response surface plot of the interaction effect of current and electrodes' distance on COD removal

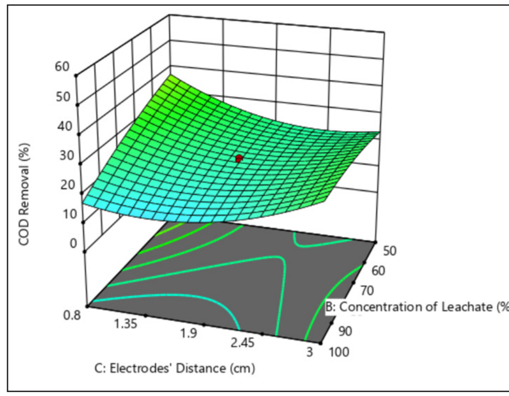


Figure 4. 3D response surface plot of the interaction effect of leachate's concentration and electrodes' distance on COD removal

Figure 4 shows the response of COD removal efficiency based on the interaction between leachate concentration and the distance between the electrodes. From the findings, when the distance between the electrodes decreases from 3 cm to 0.8 cm, the COD removal efficiency gradually increases, suggesting that a smaller electrode distance enhances COD removal efficiency. At a fixed current at 2.75 Amp and 75% leachate, the 0.34 cm electrode distance produced 35% COD removal compared to the 1.9 cm distance that achieved only 19.87%. This trend is consistent with a previous study by Rookesh et al. (2022) that reported 44.1% and 40.6% COD removal with 0.66 cm and 1.5 cm electrode distance, respectively.

According to Ameli et al. (2024), a narrower inter-electrode distance will form more gas bubbles, which increases the possibility of collisions between coagulants and pollutants. Furthermore, shorter electrode distances intensify the electric field, promoting more uniform coagulant dispersion and faster aggregation of suspended particles, as depicted in Figure 4. Nonetheless, overly close electrode spacing can lead to electrode passivation or gas bubble shielding, reducing process efficiency. Thus, as per the present study, RSM is crucial for optimising electrode spacing to achieve efficient COD removal.

The COD removal percentage varies with the concentration, from 50% to 100%, with higher leachate concentrations generally showing a slight decrease in efficiency. Under 3 Amp current, 100% concentration achieved 10.03% COD removal and increased considerably to 56.1% using 50% leachate. The concentration of leachate directly determines the pollutant load in the solution. Higher concentrations typically mean a greater variety and number of contaminants, which can saturate or overwhelm the treatment system, reducing efficiency. From the results, it can be concluded that leachate concentration is the more significant factor in this interaction. Compared to the more gradual response to changes in electrode distance, the more pronounced change in COD removal efficiency with varying leachate concentrations suggests that optimising leachate concentration is crucial for achieving higher COD removal rates. While electrode distance influences the operational efficiency of the EC process, leachate concentration fundamentally dictates system performance in terms of COD removal. The chemical interactions between coagulants and organic contaminants primarily drive COD reduction, highlighting leachate concentration as the more critical parameter.

Turbidity Removal

Figure 5 illustrates the interaction between current and leachate concentration on turbidity removal percentage. The plot indicates that turbidity removal efficiency increases with higher current levels up to a certain optimal point, after which the effect may remain unchanged or decrease.

When the leachate concentration is maintained at 75%, the lowest current at 0.98 Amp produced 51.33% turbidity removal, increasing to 73.77% at 1.5 Amp. However, it was reduced to 67.45% removal efficiency when the current increased further to 4.52 Amp. Conversely, higher leachate concentrations tend to decrease turbidity removal efficiency, indicating an inverse relationship. The turbidity removal decreased from 62.31% to 55.81% when the concentration increased from 50% to 100% with a 4 Amp current supply. Lower leachate concentrations can improve mass transfer conditions, as the driving force for pollutant migration toward the electrodes is less hindered. This leads to improved contact between the pollutants and the active electrode surface. Notably, the current is the more significant factor affecting turbidity removal, as its increase leads to a substantial improvement in removal efficiency compared to the more detrimental effect of increased leachate concentration.

Figure 6 illustrates how the distance between electrodes and the leachate concentration interact to remove the turbidity.

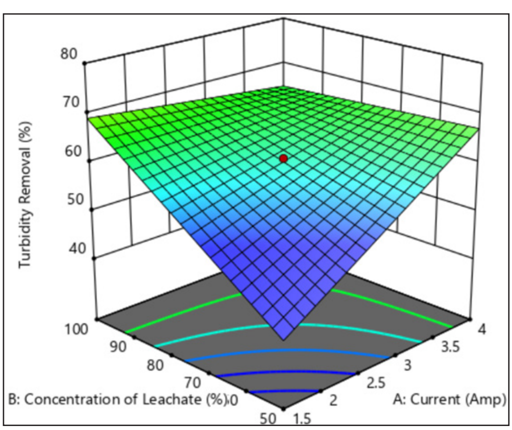


Figure 5. 3D response surface plot of the interaction effect of current and concentration of leachate on turbidity removal

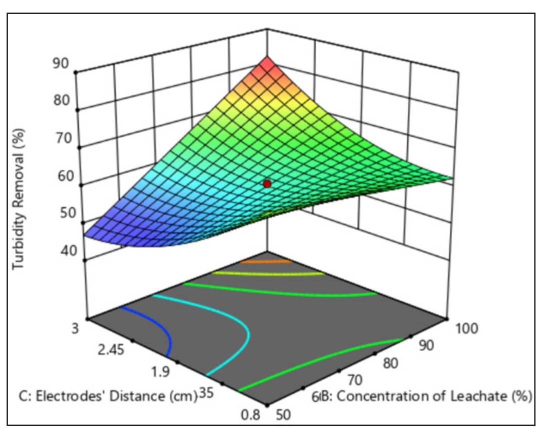


Figure 6. 3D response surface plot of the interaction effect of concentration of leachate and electrodes' distance on turbidity removal

The interaction shows that the turbidity removal was determined to be more influenced by the electrodes' distance than the concentration of leachate. 73.94% turbidity but reduced to 62.31% at 3 cm. The result is supported by a study by Gautam et al. (2022) that reported 37.9% COD removal at a 3.0 cm electrode distance, while 43.3% was achieved at a 1.5 cm electrode distance. Turbidity is primarily caused by suspended solids rather than dissolved contaminants. Therefore, the concentration of leachate, which primarily reflects dissolved pollutants, has a lesser impact on turbidity removal. While dilution lowers the overall load of dissolved pollutants, it has minimal effect on the suspended solids, causing turbidity. This makes electrode distance a more critical factor for turbidity removal efficiency.

Optimum Conditions for COD and Turbidity Removal from Leachate Using EC Process

The optimisation process was conducted to determine the optimum COD and turbidity removal using Design of Expert 13 software. During the optimisation step, the operational conditions (current, leachate concentration, and electrode distance) were set "within the range." In contrast, the responses (COD and turbidity removal percentages) were set to "maximum" to achieve the highest performance. The optimum working conditions and their respective removal efficiencies were identified and are presented in Table 7.

Table 7
Optimum condition for COD and turbidity removal

Result	Current, Amp	Leachate, %	Electrodes' Distance, cm	Removal %	
				COD	Turbidity
Model prediction	4	90.95	3	51.73 ± 4.39	79.88 ± 6.91
Verification				47.85 ± 3.2	76.32 ± 5.11

Under the optimal conditions of the EC process (current: 4 Amp; leachate concentration: 90.95%; and electrode distance: 3 cm), COD removal efficiency reached 51.73%, while turbidity removal achieved 79.88%. These outcomes were identified as the best performance using a desirability function value of 1.0, indicating a perfect compromise between the multiple response variables. The high desirability score highlights the robustness of the optimisation methodology in predicting conditions that maximise treatment efficiency.

A validation experiment was conducted under the same conditions to verify these results. The validation experiment recorded 47.48% COD removal and 76.32% turbidity removal. The percentage differences between the predicted and experimental results were calculated to be 8.11% and 4.66% for COD and turbidity, respectively. These discrepancies are relatively minor and fall within an acceptable range of below 10%, affirming the reliability and accuracy of the model used for process optimisation. The narrow gap between the predicted and experimental results underscores the reliability of the statistical model and optimisation approach. The observed variations might arise from operational factors such as electrode wear, slight current density fluctuations, or the leachate matrix's inherent heterogeneity. These findings emphasise the importance of thorough experimental design and statistical validation in ensuring the reproducibility and scalability of EC processes.

The COD removal efficiency under optimal conditions reflects the EC process's ability to oxidise and coagulate organic matter in the leachate. However, the moderate efficiency (51.73%) suggests that a portion of the organic load comprises recalcitrant compounds resistant to degradation (Lebron et al., 2021). These chemical substances, such as compounds, include certain pesticides, synthetic polymers, or complex organic molecules like polycyclic aromatic hydrocarbons (PAHs) that are resistant to degradation or breakdown by natural biological, chemical, or physical processes (Bandala et al., 2021). This aligns with the known limitations of EC, particularly for treating complex organic matrices such as leachate, where a combination of advanced oxidation processes or biological treatment might be necessary for complete COD removal (Sharma et al., 2021). On the other hand, the turbidity removal efficiency of 79.88% indicates the effective destabilisation and aggregation of colloidal particles in the leachate through coagulation mechanisms (Hanif et al., 2022). The higher turbidity removal compared to COD removal suggests that the EC process preferentially targets high-molecular-weight particulate and colloidal impurities over dissolved organic matter (Ogedey & Oguz, 2024).

Overall, the results demonstrate the potential of EC as a viable treatment technology for leachate, particularly in reducing turbidity and partially mitigating COD. However, further process enhancement, such as optimising electrode material, introducing hybrid treatment systems, or employing sequential treatments, could be investigated to achieve higher removal efficiencies and broader pollutant coverage. In addition, future scope could include investigating the treatment of specific pollutants found in leachate, such as heavy metals, focusing on lead, mercury, cadmium, and chromium. Removal of organic pollutants such as volatile organic compounds and pesticides, biochemical oxygen demand (BOD), and specific hydrocarbons such as petroleum hydrocarbons could be explored using EC. Based on the result of the present study, understanding how EC addresses these diverse contaminants will help refine the process for different leachate compositions.

Additionally, scaling up EC to industrial applications will require overcoming challenges such as ensuring consistent treatment efficiency, minimising energy consumption, managing electrode degradation, and maintaining long-term system stability (Hanif et al., 2022) managing electrode degradation, and maintaining long-term system stability (Das et al., 2022). Exploring alternative electrode materials, such as titanium, platinum (Sadaf et al., 2024), or carbon-based electrodes (Guo et al., 2022) may offer improved performance and durability compared to traditional materials like iron or aluminium. Finally, conducting detailed economic and environmental impact assessments will provide insights into the long-term feasibility and sustainability of EC as a treatment solution for leachate at larger scales (Gasmi et al., 2022).

CONCLUSION

This study offers a novel contribution to leachate treatment by focusing on optimising leachate concentration in the EC process. Previous studies have primarily concentrated on factors such as applied current and electrode distance, often overlooking the significant influence of leachate concentration on treatment efficiency. The optimum conditions for the input factors were identified: current at 4 Amperes, leachate concentration at 90.95%, and electrode distance at 3 cm. Under these conditions, the actual results achieved were 47.85% COD removal and 76.32% turbidity removal. The R^2 values were 0.99 for COD and 0.93 for turbidity, indicating a high correlation between the experimental and predicted values. The results demonstrate that higher leachate concentrations generally reduced COD removal efficiency, as expected, due to the increased complexity and contamination load. This insight is particularly valuable for scaling up the EC process in real-world applications, where leachate concentration can vary significantly.

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