Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN
Copyright © 2025,

J. Mater. Environ. Sci., 2025, Volume 16, Issue 4, Page 661-680

http://www.jmaterenvironsci.com

Application of Response Surface Modelling for the Landfill Leachate Treatment by Electrocoagulation Method

Kodihalli Nagaraju Mutthuraj[1,], Baby Basil[1], Rajesh Chethan[1], Rajashekara Rakshitha[1], Panchaksharappa Gowda D. H.[2], Benamanahalli Motaiah Krishna[3], Basavarajappa Manoj Kumar[3], Nagaraju Pallavi *[,1]

[1]*Department of Environmental Science, School of Life Science, JSS Academy of Higher Education Research, Mysuru-570015, India.*
[2]*Department of Pharmacy Practice, JSS College of Pharmacy, JSS Academy of Higher Education Research, Mysuru-570015, India.*
[3]*Department of Environmental Engineering, SJCE, JSS Science & Technology University, Mysuru-570006, India.*
**Corresponding author: anupallavi@jssuni.edu.in*

Received *27 Sept 2024,*
Revised *31 Mar 2025,*
Accepted *03 Apr 2025*

***Citation**: Mutthuraj K. N., Basil B., Chethan R., Rakshitha R., Panchaksharappa Gowda D. H., Krishna B. M., Kumar B.M., Pallavi N. (2025) Application of Response Surface Modelling for the Landfill Leachate Treatment by Electrocoagulation Method, J. Mater. Environ. Sci., 16(4), 661-680*

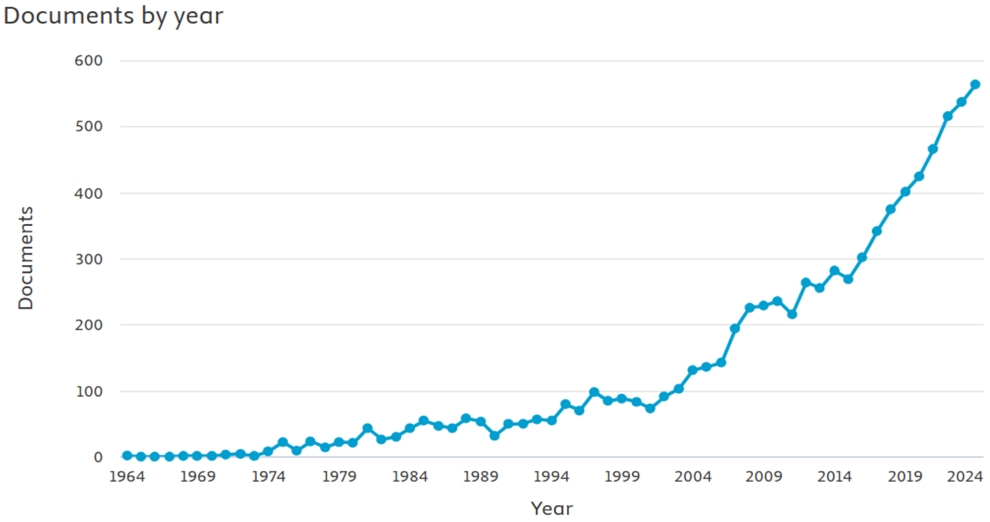
Abstract: The purpose of this research was to determine whether or not the electrocoagulation (EC) method with combined stainless-steel electrodes and aluminum electrodes was effective in removing color as well as BOD and COD from water samples that were gathered from the Mysuru Sanitary Landfill Site in the state Karnataka in India. The targeted types of parameters are total dissolved solids (TDS), chloride (Cl^-), chemical oxygen demand (COD), biological oxygen demand (BOD), pH, and turbidity. The stainless steel and aluminum were used in this method with fixed electrode distance(1cm), (3cm), (4cm) and fixed voltage(2v), (5v), (8 v) in 20 and 120minute take a sample for the analysis (20,120, mins). The influence of six variables, including applied voltage (I), inter-electrode distance (IED), and reaction time (RT), on the elimination of Turbidity, TDS, Cl, COD, and BOD was observed. Initial results showed the following optimum operating conditions: RT =120 min, pH = 5.24, T = 25 ◦C, IED = 1 cm The maximum removal efficiency of Turbidity, TDS, Cl^-, COD and BOD were stainless steel 93.23 percent, 56.73percent, 39.45percent, 51.40percent, and 61.97percent and Aluminium was 97.35 percent, 66.15 percent, 59.73 percent, 55.37 percent, and 53.32 percent respectively. This study concludes that the EC approach used to remove a parameter from Leachate water was effective.

Keywords: *Landfill leachate; Electrocoagulation; Response Surface Modelling; Design of Experiment; waste management*

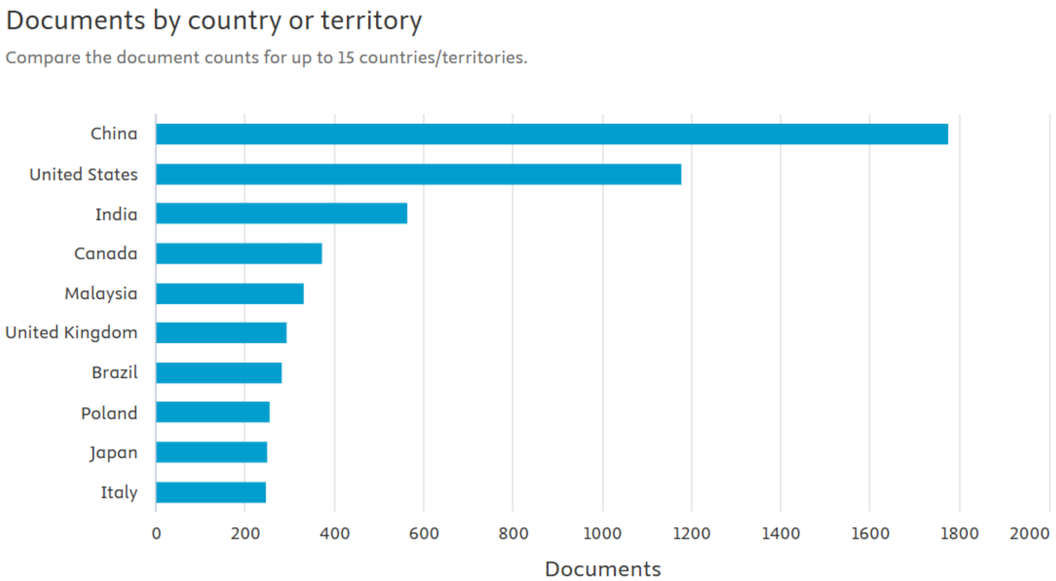
1. Introduction

The rise in population, increase in urban human settlement, and growth in the number of industries in recent years pose a significant challenge for managing solid waste for authorities (Zailani *et al.*, 2018). Therefore, solid waste dumping yards become a common sight in urban areas and metropolitan cities (Guo *et al.*, 2022). This is one of the easiest methods for the disposal of solid waste in landfill sites (Sadeghi *et al.*, 2018. Tezcan *et al.*, 2018). After filling up the place with solid waste there comes a problem of disposal of "Landfill Leachate" (Galvão *et al.*, 2020) which refers to a liquid that has been passed from various layers of solid waste deposited on that site and this results in the formation of heavily concentrated solution (Faheem *et al.*, (2019). Generally, landfill leachate contains a high concentration of organic and some inorganic substances, and this concentration also depends on the nature of the waste that has been dumped and its age. (Naje *et al.*, 2019). After the generation of leachate, it might percolate into the soil and pollute the groundwater system (Ilhan *et al.*, 2018) and if the leachate gets into water bodies it will pose a serious threat to the flora fauna of that aquatic ecosystem (Dia *et al.*, 2018). So, letting the leachate can adversely affect our environment hence it's important to treat the leachate before letting it into the environment (Tezcan *et al.*, 2018) (Dia *et al.*, 2018). In many regions of the globe, the overexploitation of freshwater resources poses a danger to the safety of the food supply as well as the general wellness of humans (Contreras *et al.*, 2009), So, releasing untreated leachate water can also be included in this which will result in another major problem with the current problems we are facing.

The bibliometric analysis has become a more suitable tool for visualizing the evolution of scientific production across different fields (Aichouch *et al.*, 2025; Lrhoul *et al.*, 2023; N'diyae *et al.*, 2022). The examination of literature indicated that more than 8000 Scopus-indexed documents were published on "landfill leachate water" from 1964 to 2024, as shown in **Scheme 1**. We observe that an increase of more than 500 articles per year is evident over the last few years. Industrialized countries are more preoccupied with treating wastewater to ensure high-quality water and maintain health (**Scheme 2**).

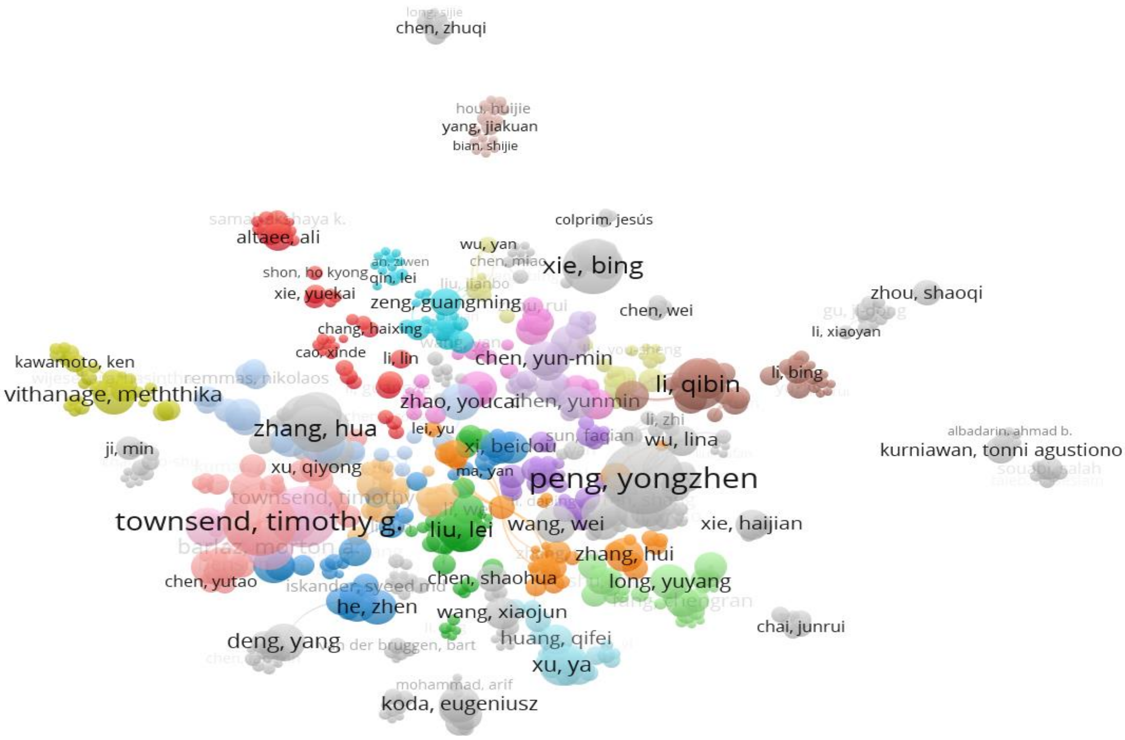


Scheme 1. Evolution of the papers from 1964 to 2024



Scheme 2. Repartition of Countries interested in "landfill leachate water"

The author's productivity and analysis of keywords, such as “landfill leachate water,” can be prepared using VOSviewer through a network map of organizational and co-authorship analysis, employing a clustering technique, and MS-Excel for graphical and statistical analysis. **Scheme 3** contains a thousand authors shown as circular nodes. Nodes are larger when they occur more frequently. Clusters of nodes with similar color schemes represent associations between them. Data obtained show that the most published are: Aziz H.D., Malaysia, (Id=7005960760) publishing 61 papers followed by Townsend T.G. (US) (Id=7005921623) reaching 46 papers and Christensen, T.H. (Danmark) (Id=7202547231), 45 papers etc…



Scheme 3. Network visualization map of author-author clusters

There are various techniques for treating domestic wastewater. Still, those methods aren’t enough to treat landfill leachate (Akartasse *et al.*, 2022a; 2022b; Elazzouzi *et al.*, 2016), because it contains most heavy metals and hazardous chemicals and also includes microplastic and these are highly difficult to treat (Merzouk *et al.*, 2010). Recent years of research show that electrocoagulation is been successfully treated in many types of waste waters majorly: -Metal processing wastewater, semiconductor production wastewater, textile dyeing wastewater, tannery wastewater, olive mill wastewater, urban wastewater, and also in organic removal from poultry wastewater (Bouknana *et al.*, 2021; Bhagawan *et al.*, 2018; Ding *et al.*, 2018; Shankar *et al.*, 2018). Hence Electrocoagulation can be used for treatment due to its lesser cost, easy installation, and maintenance (Li *et al.*, 2011). So, it can become one of the better treatment methods for Leachate treatment (Hawari *et al.*, 2020). Many insoluble hydroxide ions of heavy metals can be oxidized. It also helps in reducing the BOD and COD levels of leachate and it is an important factor considered in water treatment (Hawari *et al.*, 2020).

The chemistry of the aqueous medium, particularly its conductivity, has a huge impact on the EC process (Sardari *et al.*, 2018). The mechanism of EC's ion generation may be illustrated using the examples of iron and aluminium which were both utilized as catalysts (Verma *et al.*, 2013). In this investigation, the anode and cathode have used the term "electrolytic system" which refers to a system that uses electricity (Sediqi *et al.*, 2021). Iron causes the formation of iron hydroxide. When it comes

to iron or steel, two processes for the manufacturing of aluminium anodes and metal hydroxide have been considered (Galvão *et al.*, 2020) (Dura *et al.*, 2019). Given its capacity to eliminate organic debris and persistent contaminants from landfill leachate (GilPavas *et al.*, 2018); electrocoagulation (EC) is a promising treatment method. EC is a method that may remove suspended and dissolved particles from wastewaters and has a wide range of uses (Sharma *et al.*, 2021) Electrolysis is used in the process to create destabilizing agents that lead to charge neutralization, forming metallic cations and having the same effect as the addition of coagulants (Bharath *et al.*, 2020).
The primary objective of this research is to investigate the treatment of landfill leachate water using the electrocoagulation method. And for designing the size and thickness of the electrode. For a better study of the treatment efficacy of aluminium and stainless-steel electrodes for the treatment of leachate water. The RSM method is used to determine the factors affecting the EC method and to compare the efficiency of aluminium and stainless steel.

2. Methodology

Experimental Setup

In the present study EC process for the treatment of leachate water was set up at the bench scale in the lab. The experimental reactor had a width of 9 cm, a length of 14cm, and a height of 15cm with a capacity of 1.7 L. Stainless steel and aluminium electrodes of same size and mallet-like shape, which involves a bottom square (5x5 cm), a long arm (9cm), and a holder (5cm length and 1 cm width) were used. The experiment had fixed time (20 minutes and 120 minutes), voltage (2V,6V, and 8V), and electrode distance (1cm,3cm, and 4cm) designed used RSM.

Fig:1. (a) Experimental setup of EC in lab scale with 2 electrodes of Stainless steel
(b) Experimental setup of EC on lab scale with 2 electrodes of Aluminium

2.2 Material Used In The Experiment

The materials used in the experiment are shown in Figure 2. (a)Glass Reactor The experimental reactor had a width of 9 cm, length of 14cm, and height of 15cm. The capacity volume of the reactor is 2 L. The treatment water volume for each run was 1.7 L the reactor was made up of plexiglass of 5mm thickness. (b) Electrode Holder, the electrode holder was placed on the reactor to hold the electrode for the experiment running it was marked 1cm, 3cm, and 4cm. (c) Wire for DC connection (d) Stainless Steel electrode. (e) The aluminium electrode (f) DC power supply 0–40 V; 0–6 A.

2.3 Collection Of Landfill Leachate Sample

The Landfill leachate water sample was sampled from the Mysuru Sanitary Landfill site which is located in Vidayranyapuram, in Mysuru city, Karnataka, India which is at a distance of 8km from the city center (Figure 3). The location of Mysore city in GPS is at 12.30°N 76.65°E with a mean altitude of 770 meters (Bharath M., 2020).

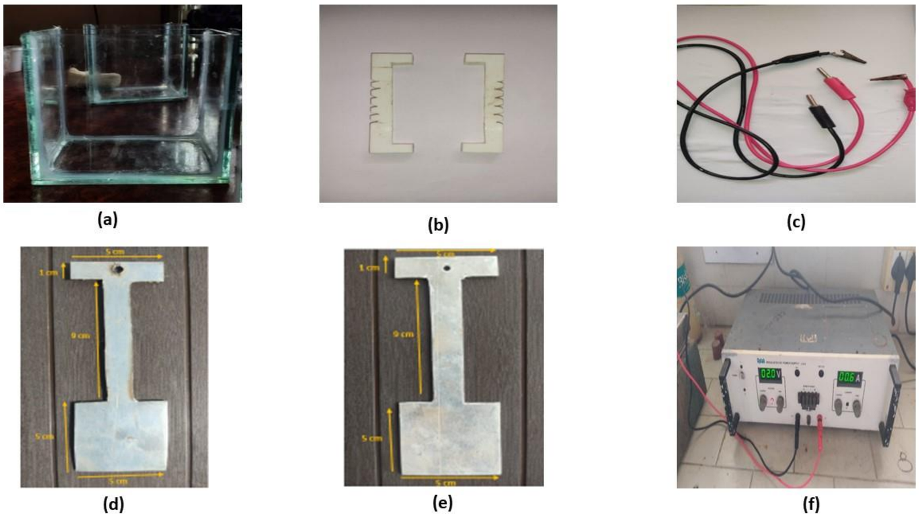


Fig 2. (a) Glass reactor, (b) Electrode holder, (c) Wire for DC connection, (d) Stainless steel Electrode (e) Aluminium Electrode, (f) DC Power supply

Fig 3 Map of Mysuru sanitary landfill site, Mysuru, Karnataka, India

2.4. Design Of Experiment (DoE)

Response surface methodology (RSM) is a widely used modeling method in experimental designing, and for evaluating several factors and obtaining optimum value. Here histological methods of RSM were used to determine the important factor in treating the seawater using electrocoagulation. In this study, Design Expert software and the JMP software are used to illustrate the results. JMP PRO 15 software was used to design the graphs. Analysis of variance (ANOVA) is a statistical approach, to determine the significant difference that lies between the independent factor and dependent factors. p-values of the analysis which is less than 0.5 signifies the operating factors that substantially affect the treatment process.

3. Results and Discussion

3.1 Stainless Steel Electrode

The stainless-steel electrode acted as both anode and cathode in the electrocoagulation experiment. In the DoE process the voltage(V), time (min), and distance (cm) were considered the independent factors as shown in Table 1. The responses as the percentage removal efficiency of chloride (Cl^-), total dissolved solids (TDS), turbidity, COD, and BOD are the dependent factors according to our design.

3.1.1. Response surface modeling for Turbidity removal

To optimize the turbidity removal efficiency as the response factor Response Surface Methodology (RSM) analysis was accomplished according to our design of 11 trials of three independent factors i.e Voltage as X1, Distance as X2, and Time as X3 are the coded values as given in the Table 1. Figure 4 below depicts the leachate water percentage removal of turbidity of actual Vs predicted value. This is used to evaluate whether the applied model is significant or insignificant for turbidity removal. R^2 value of 0.94 signifies that the model is significant.

Table 1. The removal efficiency of Total Dissolved solids (TDS), turbidity, chloride (Cl^-), BOD and COD by stainless steel electrode

Sl No	Voltage (V)	Distance (cm)	Time (min)	pH	Turbidity (NTU)	Chloride (mg/l)	COD (mg/l)	BOD (mg/l)	TDS (mg/l)
1	2	1	20	8.32	13.23	3.94	2.18	1.56	3.65
2	2	1	120	8.86	24.26	19.61	15.33	12.68	13.49
3	2	4	20	8.19	5.88	1.15	0.39	1.45	2.10
4	2	4	120	8.29	14.70	5.67	4.00	4.37	10.09
5	8	1	20	8.91	46.32	9.85	12.40	12.77	19.92
6	8	1	120	9.74	93.23	56.73	39.45	51.40	61.97
7	8	4	20	8.53	29.41	5.24	2.73	2.18	5.70
8	8	4	120	8.78	50	9.46	19.53	18.61	11.61
9	5	3	20	8.51	36.02	8.30	6.64	6.87	8.84
10	5	3	70	8.97	66.91	39.07	14.64	9.12	18.84
11	5	3	120	9.22	83.82	12.61	25.00	26.32	28.80

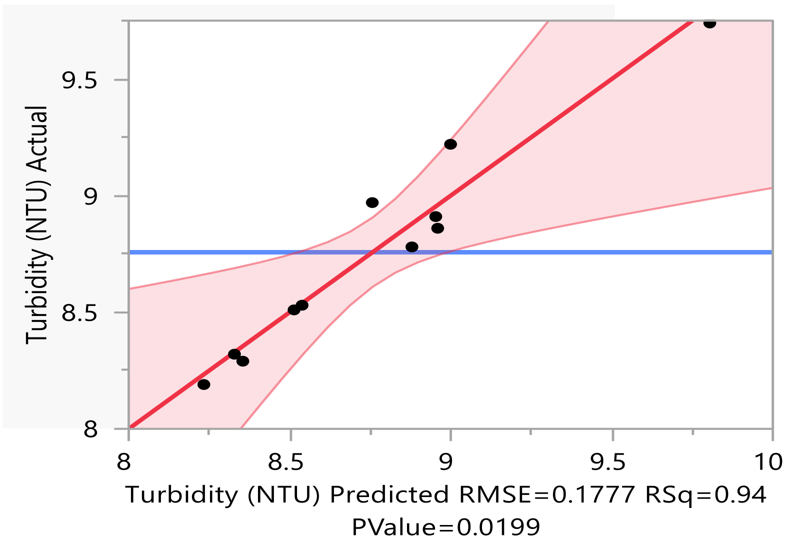


Fig 4. Graph representing the plot of actual Vs predicted turbidity removal.

The ANOVA findings confirmed clearly that the experimental and the predicted values of turbidity removal efficiency of leachate water were the same. Table 2 explains the significance of the model with the percentage removal of turbidity. A lesser p-value can be concluded that the model is significant and the independent factors are also important in the turbidity removal. The ANOVA findings revealed the model was statistically significant and can be used to optimize and forecast the electrocoagulation process for removing turbidity from leachate.

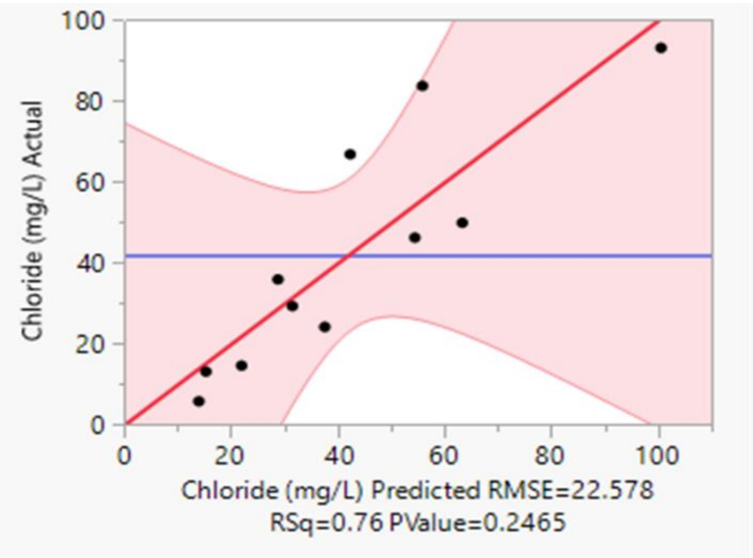
Table 2: Analysis of Variance (ANOVA) for Turbidity

Factors	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	0.71195294	22.5543	0.0090*
Distance (m) (1,4)	1	1	0.41581176	13.1727	0.0222*
Time (min) (20,120)	1	1	0.58971905	18.6820	0.0124*
Voltage (V) * Distance (m)	1	1	0.05120000	1.6220	0.2718
Voltage (V) * Time (min)	1	1	0.02420000	0.7666	0.4307
Distance (m) * Time (min)	1	1	0.13005000	4.1199	0.1122

3.1.2. Response surface modeling for chloride removal

To optimize the chloride removal efficiency as the response factor Response Surface Methodology (RSM) as explained above was used as given in the Table 1. The actual percentage removal of chloride vs predicted value is plotted as shown in figure 5 below. This information proves that the applied model is not so significant for chloride removal with 0.76 as the R^2 value.

The ANOVA findings confirmed clearly that the experimental and the predicted values of chloride removal efficiency of leachate water were not so close. The model significance can be determined from the results of the analysis of variance (ANOVA) shown in Table 3. From the table, it can be depicted that the independent factors are not important and that the model accurately reflects the data volatility. The $R^2 = 0.76$, which is the correlational coefficient value suggests that independent factors accounted for 76% of the variation in chloride removal efficiency. Overall, the analysis of variance results showed that the model was statistically insignificant and was unable to predict or optimize the percentage of chloride removal from leachate water by the electrocoagulation method



.

Fig 5. Graph representing the plot between predicted and actual chloride removal.

Table 3. Result of Analysis of Variance of Chloride

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	3468.2390	6.8033	0.0595
Distance (m) (1,4)	1	1	516.2434	1.0127	0.3712
Time (min) (20,120)	1	1	1443.5760	2.8317	0.1677
Voltage (V) * Distance (m)	1	1	233.6041	0.4582	0.5356
Voltage (V) * Time (min)	1	1	283.8153	0.5567	0.4970
Distance (m) * Time (min)	1	1	101.7451	0.1996	0.6782

3.1.3. Response surface modeling for COD removal

To optimize the COD removal efficiency as the response factor Response Surface Methodology (RSM) as given in the above explanations. And depicted in Table 1. A plot of actual COD removal vs predicted COD removal is depicted in Figure 6, to evaluate the significance of the model in terms of COD removal. The R^2 value of 0.72 and 0.3125 P-value signifies that the model was not significant.

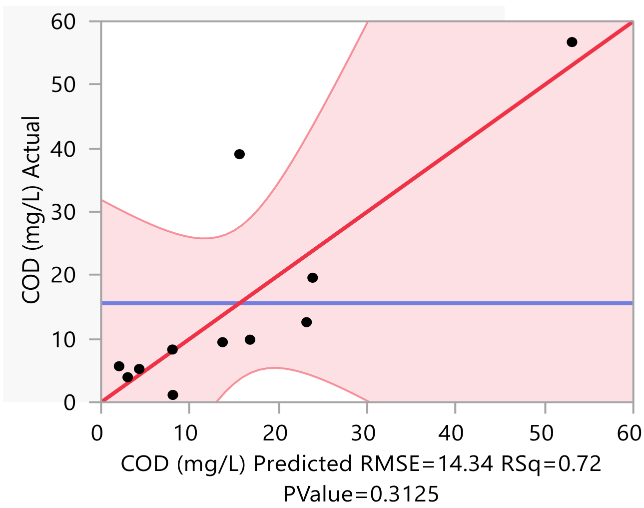


Fig 6. Graph representing the plot between predicted and actual COD removal.

Table 4: Result of Analysis of Variance of COD

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	419.26959	2.0389	0.2265
Distance (m) (1,4)	1	1	421.02724	2.0474	0.2257
Time (min) (20,120)	1	1	592.31108	2.8804	0.1649
Voltage (V) * Distance (m)	1	1	154.44031	0.7510	0.4350
Voltage (V) * Time (min)	1	1	119.42851	0.5808	0.4885
Distance (m) * Time (min)	1	1	361.93951	1.7601	0.2553

The results of the ANOVA showed that there was a large gap between experimental data and anticipated COD removal of leachate water. The model accurately depicts the variations in the data, and the provided parameters are not important. R^2 = 0.72, the correlation coefficient of the model indicates that the independent factors were only 72%. Overall, the analysis of variance results showed that the model was statistically insignificant and was unable to predict or optimize the removal of COD from leachate water by electrocoagulation.

3.1.4. Response surface modeling for BOD removal

To optimize the BOD removal efficiency as the response factor Response Surface Methodology (RSM) analysis as given in the Table 1. Figure 7 depicts the actual vs predicted value of BOD removal. There is a good relation between actual and predicted values with 0.98 as the R^2 value which shows that the model was significant in terms of BOD removal.

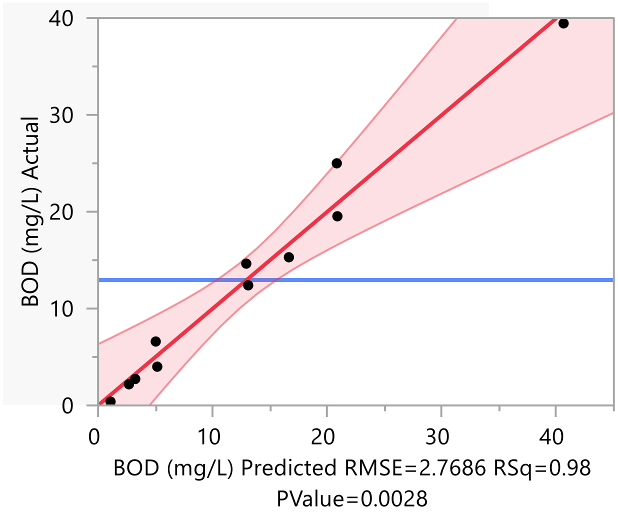


Fig 7. Graph representing the plot between predicted and actual BOD removal.

Table 5. Result of Analysis of Variance BOD

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	373.76626	48.7614	0.0022*
Distance (m) (1,4)	1	1	174.88094	22.8149	0.0088*
Time (min) (20,120)	1	1	508.52518	66.3421	0.0012*
Voltage (V) * Distance (m)	1	1	34.03125	4.4397	0.1028
Voltage (V) * Time (min)	1	1	91.93680	11.9941	0.0257*
Distance (m)*Time (min)	1	1	48.80720	6.3674	0.0651

The findings of the analysis of variance (ANOVA) displayed in Table 5 support the model's relevance. The model's low p-value, which shows that it accurately captures data variations and that the given parameters are significant, leads to the conclusion of significance. The correlation coefficient i.e. R^2 = 0.98, indicates that 98% of the changes in BOD removal efficiency were dependent on independent factors. Overall, the analysis of variance findings showed that the model was statistically significant and could be used to predict and optimize the percentage of BOD removed from leachate treatment utilizing electrocoagulation.

3.1.5. Response surface modeling for TDS removal

To optimize the TDS removal efficiency, the Response Surface Methodology (RSM) analysis was utilized as given in Table 1. The predicted TDS removal vs actual TDS removal is plotted in Figure 8. with an R^2 value of 0.97. The outcomes of the analysis of variance (ANOVA) reported in Table 7 serve as confirmation of the model's importance. The lesser p-value for all three independent factors and for the interaction of Voltage and time demonstrate that the model properly reflects the data fluctuations and that the specified parameters are significant. The correlation coefficient of 0.97, indicates that independent factors were responsible for 97% of the changes in TDS removal efficiency. The model was statistically significant overall, and the analysis of variance results showed that it could be used to forecast and optimize the percent removal of TDS from leachate water.

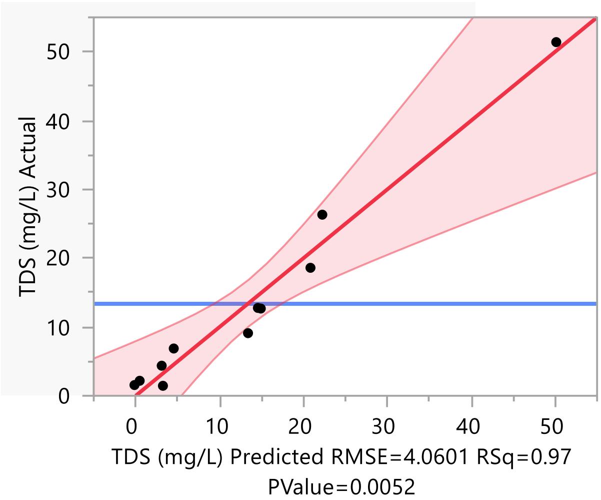


Fig 8. Graph representing the plot between predicted and actual TDS removal

Table 6. Result of Analysis of Variance TDS

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	637.85236	38.6951	0.0034*
Distance (m) (1,4)	1	1	218.21289	13.2378	0.0220*
Time (min) (20,120)	1	1	628.21421	38.1104	0.0035*
Voltage (V) * Distance (m)	1	1	152.86261	9.2734	0.0382*
Voltage (V) * Time (min)	1	1	210.22751	12.7534	0.0234*
Distance (m) * Time (min)	1	1	115.59601	7.0126	0.0571

3.1.6. Effect Summary of SS electrode

The reference blue line indicates the two-equivalent -log10(0.01) value. A parameter is considered significant if its Log-Worth value is greater than two. The running duration has the biggest impact on leachate treatment, with a log worth of 2.908 and a p-value of 0.00124, respectively. This analysis leads us to the conclusion that the time distance voltage affects the leachate water treatment.

Source	Log Worth		P Value
Time (min) (20,120)	2.908		0.00124
Voltage (V) (2,8)	2.655		0.00221
Distance (m) (1,4)	2.056		0.00880
Voltage (V) * Time (min)	1.632		0.02335
Voltage (V) * Distance (m)	1.418		0.03821
Distance (m) * Time (min)	1.243		0.05709

Fig 9: Effect summary disclosing the Log Worth and P-value

3.2. Aluminium electrode

The Aluminium electrode was used in the electrocoagulation experiment as both anode and cathode. The Landfill leachate water sample was treated by electrocoagulation method with independent factors such as voltage, time, and distance as given in Table 7. The removal efficiency of turbidity, total dissolved solids (TDS), chloride salt (Cl), COD, and BOD were.

Table 7. The removal efficiency of turbidity, chloride (Cl^-), Total Dissolved solids (TDS), BOD, and COD by aluminium electrode

Sl No	Voltage (V)	Distance (cm)	Time (min)	pH	Turbidity (NTU)	Chloride (mg/L)	COD (mg/L)	BOD (mg/L)	TDS (mg/L)	Sludge weight (g)
1	2	1	20	8.23	16.17	3.97	15.82	9.25	6.05	12.8
2	2	1	120	8.67	44.11	19.61	32.91	34.45	16.26	
3	2	4	20	8.18	10.29	1.00	4.101	2.737	3.029	2.56
4	2	4	120	8.49	20.58	5.76	12.50	6.532	11.91	
5	8	1	20	8.36	42.64	9.854	25.29	22.88	13.12	48.76
6	8	1	120	9.17	97.35	59.73	55.37	53.32	66.15	
7	8	4	20	8.3	13.23	5.24	3.320	10.52	8.769	14.63
8	8	4	120	8.75	44.11	9.460	15.03	19.63	27.83	
9	5	3	20	8.29	32.35	8.308	7.76	8.81	14.57	19.78
10	5	3	70	8.56	57.35	23.85	24.80	16.25	20.76	
11	5	3	120	8.83	75.00	39.90	31.83	27.62	29.86	

3.2.1. Response surface modeling for turbidity removal

To optimize turbidity removal efficiency, Response Surface Methodology (RSM) analysis was used (Table 8). The relationship between the projected and actual turbidity removal is plotted as shown in Figure 10 below 0.98819 of the R^2 value signifies that the model is effective and significant in predicting the turbidity of leachate water. The findings of the analysis of variance (ANOVA) displayed in Table 9 support the model's relevance.

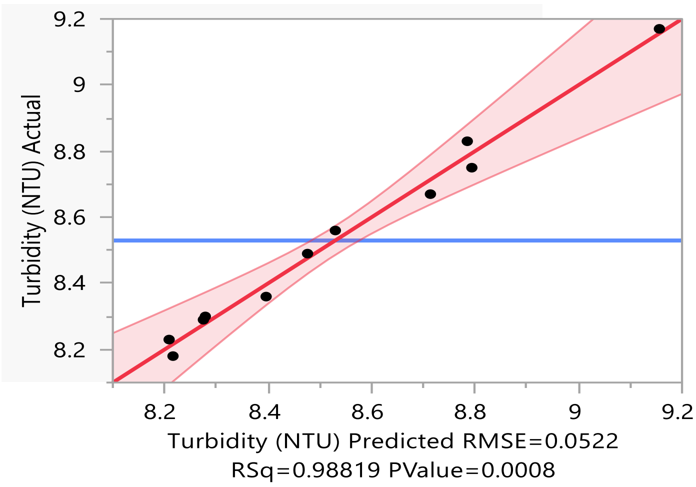


Fig 10. Graph representing the plot between predicted and actual Turbidity removal

The ANOVA's high F-ratio and low p-value show that the independent components are significant and that the model accurately captures data fluctuations. The model's correlation coefficient, R^2 = 0.98819, indicates that 98.819% of the variations in turbidity removal effectiveness were caused by independent causes. The model was statistically significant overall and could be used to forecast and optimize the percent removal of turbidity of leachate water, according to the analysis of variance data.

Table 8. Result of Analysis of Variance for Turbidity

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	0.1353243	49.7173	0.0021*
Distance (m) (1,4)	1	1	0.0493243	18.1214	0.0131*
Time (min) (20,120)	1	1	0.5596250	205.603	0.0001*
Voltage (V) * Distance (m)	1	1	0.0078125	2.8703	0.1655
Voltage (V) * Time (min)	1	1	0.0325125	11.9449	0.0259*
Distance (m) * Time (min)	1	1	0.0300125	11.0264	0.0294*

3.2.2. Response surface modeling for Chloride removal

To optimize the chloride removal efficiency as the response factor Response Surface Methodology (RSM) analysis was utilized as given in the Table 9. The relationship between the actual and anticipated chloride removal is displayed, as shown in Figure 11 below, to determine if the applied model is significant or inconsequential for the removal of chloride. The R^2 value for removing chloride from leachate water is 0.89.

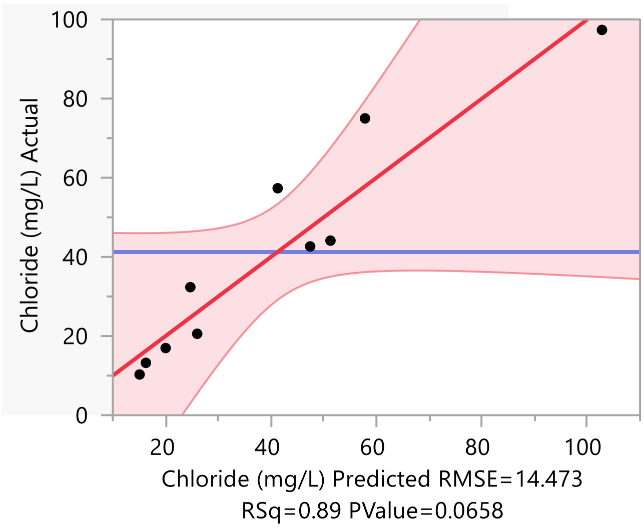


Fig 11. Graph representing the plot between predicted and actual Chloride removal

Table 9. Result of Analysis of Variance for Chloride

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	1651.7506	7.8850	0.0484*
Distance (m) (1,4)	1	1	1170.5956	5.5881	0.0773
Time (min) (20,120)	1	1	2307.2437	11.0142	0.0294*
Voltage (V) * Distance (m)	1	1	343.7442	1.6409	0.2694
Voltage (V) * Time (min)	1	1	289.9232	1.3840	0.3046
Distance (m) * Time (min)	1	1	206.8578	0.9875	0.3766

The findings of the analysis of variance (ANOVA) displayed in Table 9 support the model's relevance. The higher F-value and a low p-value in the ANOVA show that the model well captures data variations and that the given parameters are significant. Since this model's correlation coefficient is $R^2 = 0.89$, 89% of the variations in chloride reduction were likely caused by independent factors. The model was statistically significant overall, and the analysis of variance results showed that it could be used to forecast and optimize the percent removal of chloride from leachate water.

3.2.3. Response surface modeling for COD removal

To optimize the COD removal efficiency as the response factor Response Surface Methodology (RSM) analysis was used as given in the Table 10. Figure 12 below shows the relationship between the actual COD removal and the anticipated COD removal, which is to determine if the applied model is significant or inconsequential for the COD reduction. The R^2 value for removing COD from leachate water is 0.87.

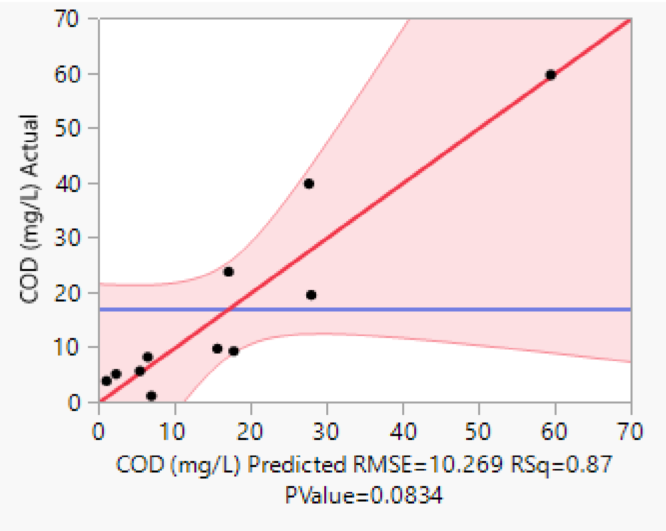


Fig 12. Graph representing the plot between predicted and actual COD removal.

Table 10. Result of Analysis of Variance for COD

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	470.4684	4.4611	0.1022
Distance (m) (1,4)	1	1	451.3969	4.2803	0.1074
Time (min) (20,120)	1	1	1103.8574	10.4671	0.0318*
Voltage (V) * Distance (m)	1	1	183.8403	1.7432	0.2572
Voltage (V) * Time (min)	1	1	143.3971	1.3597	0.3084
Distance (m) * Time (min)	1	1	403.7061	3.8281	0.1220

The findings of the analysis of variance (ANOVA) displayed in Table 10 support the model's relevance. Low p-value for time in the ANOVA shows that the model well captures data variations, and that time is a very important factor when compared to the other two factors. Since this model's correlation coefficient is $R^2 = 0.89$, independent factors account for 89% of the changes.

3.2.4. Response surface modeling for BOD removal

To optimize the BOD removal efficiency as the response factor Response Surface Methodology (RSM) analysis as given in the Table 11. The relationship between the actual and expected BOD elimination is plotted, as shown in Figure 13 below, to determine if the model being employed is significant or insignificant for the BOD reduction. The R^2 value for the leachate water's BOD decrease was 0.98 which shows that the model is very significant.

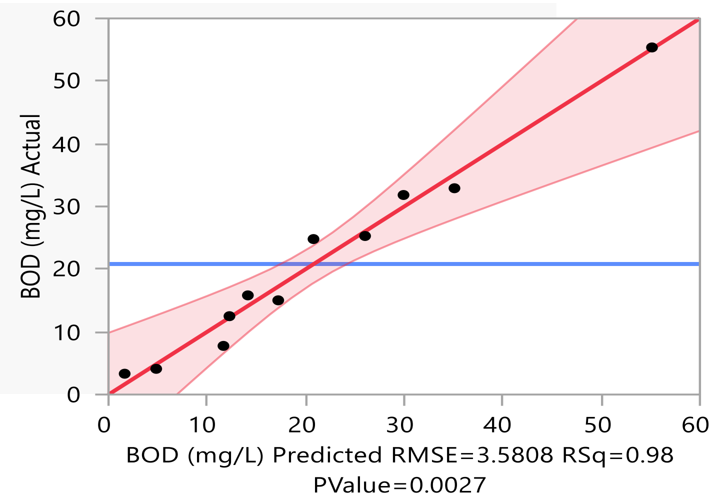


Fig 13: - Graph representing the plot between predicted and actual BOD removal

Table 11: Result of Analysis of Variance of BOD

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	199.94125	15.5937	0.0168*
Distance (m) (1,4)	1	1	888.32247	69.2813	0.0011*
Time (min) (20,120)	1	1	775.82336	60.5074	0.0015*
Voltage (V)*Distance (m)	1	1	113.85405	8.8796	0.0407*
Voltage (V)*Time (min)	1	1	33.21125	2.5902	0.1828
Distance (m)*Time (min)	1	1	91.53045	7.1386	0.0557

The analysis of variance (ANOVA) findings presented in Table 11 support the model's importance. With the ANOVA, the high F-ratio and low p-value show that the model well captures the data variations and that the set parameters are significant. Since this model's correlation coefficient R^2 = 0.98, 98% of the variations in BOD reduction were likely caused by independent factors. Overall, the analysis of variance results showed that the model was statistically significant and that it could be used to predict and optimize the percentage of BOD removal from leachate water.

3.2.5. Response surface modeling for TDS removal

To optimize the TDS removal efficiency as the response factor Response Surface Methodology (RSM) analysis as given in the Table 12. Figure 14 below shows the relationship between the actual TDS removal and the anticipated TDS removal, which is utilized to determine if the applied model is significant or inconsequential for the TDS reduction. The R^2 value for the leachate water's turbidity removal was 0.99283, which demonstrates the model's importance. The findings of the analysis of variance (ANOVA) displayed in Table 12 support the model's relevance. The model effectively reflects the fluctuations in the data, by high F-ratio, and the low p-value. The TDS removal efficiency changes were caused by independent factors 99.283% of the time, according to the correlation coefficient for this model, R^2= 0.99283. The findings of the analysis of variance indicated that the model could be used to predict and optimize the percent removal of TDS from leachate water, and it was statistically significant.

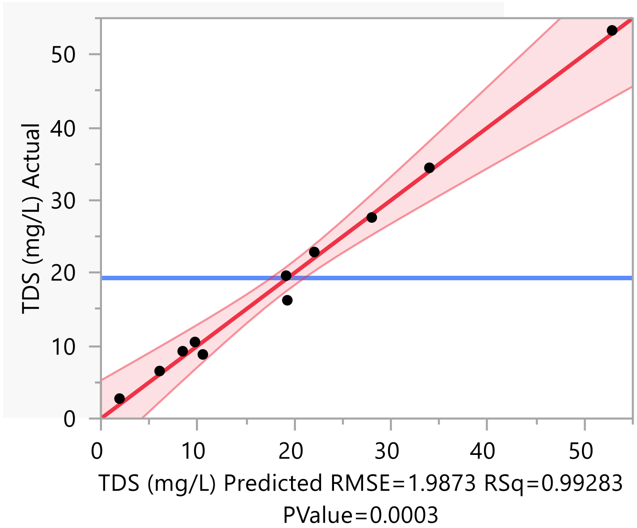


Fig 14. Graph representing the plot between predicted and actual TDS removal

Table 12. Result of Analysis of Variance of TDS

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Voltage (V) (2,8)	1	1	372.70603	94.3702	0.0006*
Distance (m) (1,4)	1	1	707.98596	179.2640	0.0002*
Time (min) (20,120)	1	1	820.58184	207.7736	0.0001*
Voltage (V) * Distance (m)	1	1	16.87805	4.2736	0.1076
Voltage (V) * Time (min)	1	1	13.93920	3.5294	0.1335
Distance (m) * Time (min)	1	1	228.33845	57.8159	0.0016*

3.2.6. Effect Summary of Al electrode

Source	Longworth		PValue
Time (min) (20,120)	3.871		0.00013
Distance (m) (1,4)	3.745		0.00018
Voltage (V) (2,8)	3.202		0.00063
Distance (m) * Time (min)	2.794		0.00161
Voltage (V) * Time (min)	1.587		0.02591
Voltage (V) * Distance (m)	1.390		0.04074

The running duration has the biggest impact on leachate treatment, with a p-value of 0.00013. This analysis leads us to the conclusion that time, distance, and voltage all affect how leachate water is treated. Because of the model's importance, the prediction profiler can be used to anticipate the response for specific parameter values.

3.3 Independent experimental variables' impact on Electrocoagulation using stainless-steel electrode

JMP was used to create a three-dimensional response surface plot to comprehend how the independent experimental variable affected the results of electrocoagulation. The below figures 16, 17, and 18 display the 3D response surface plots of voltage, distance and time.

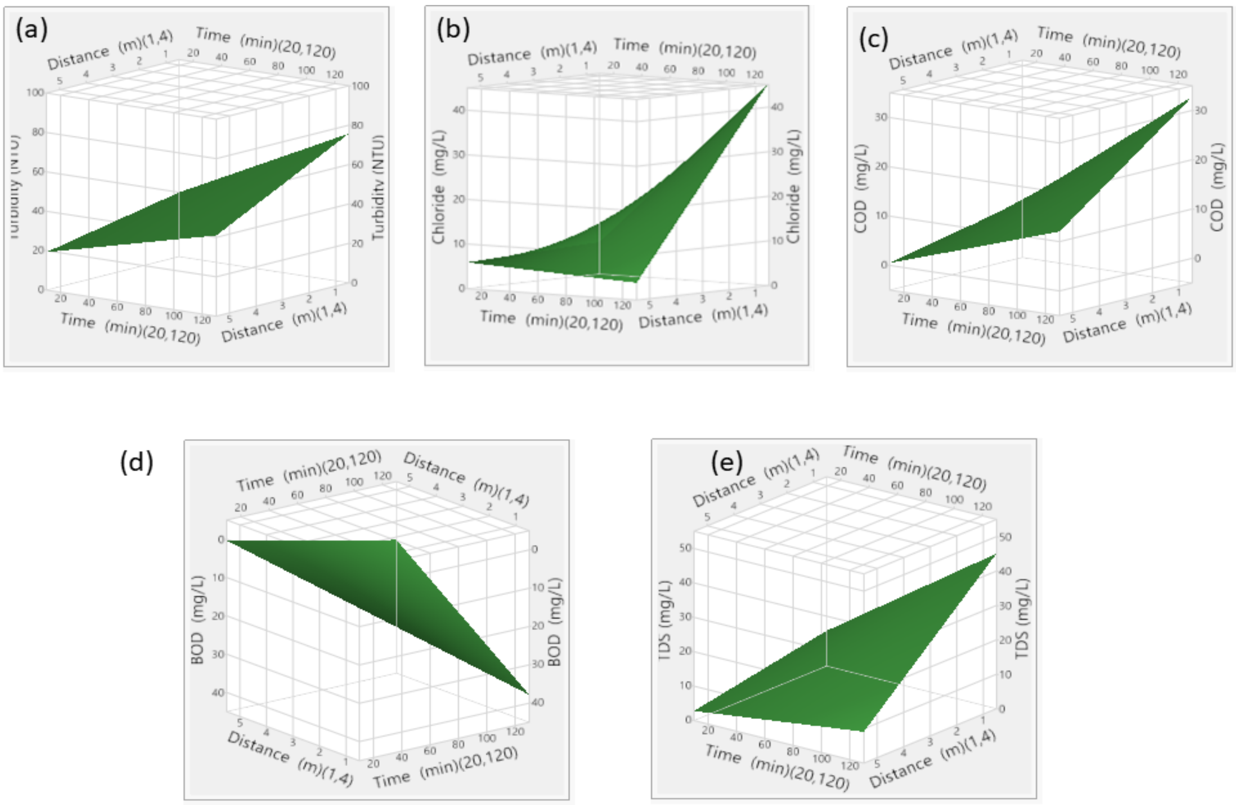


Fig.16 Image displaying the impact of experimental variables on the electrocoagulation of (Distance vs. time) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS).

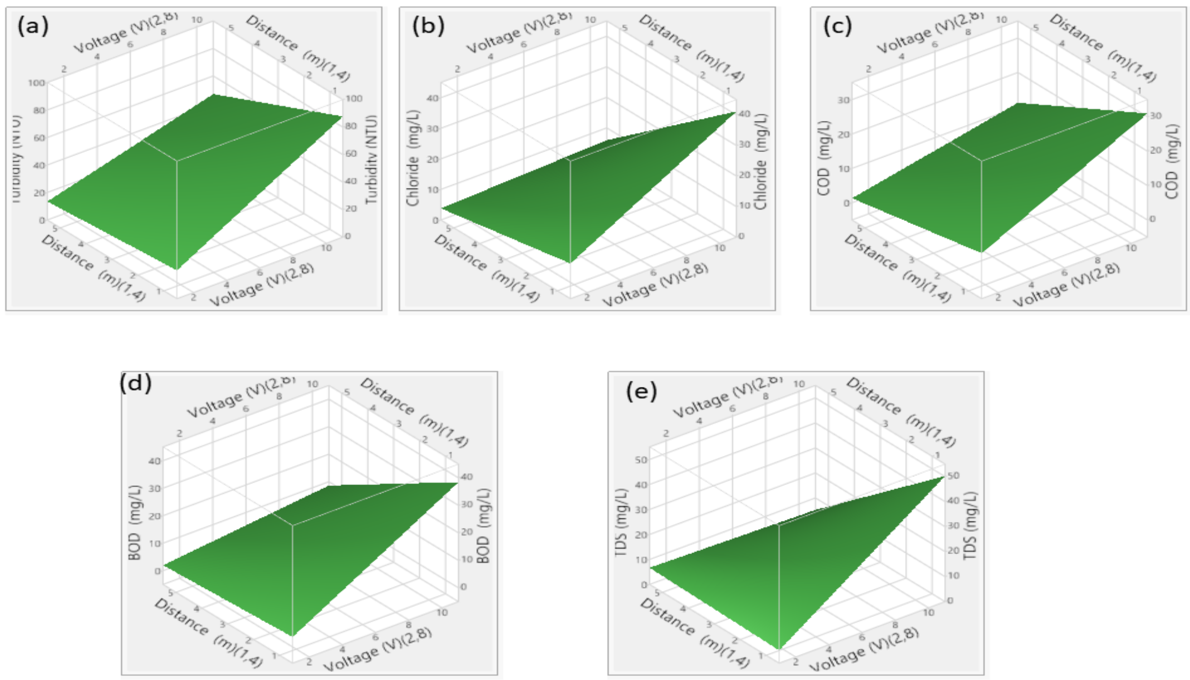


Fig.17 Image displaying the impact of experimental variables on the electrocoagulation of (Voltage Vs Time) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS)

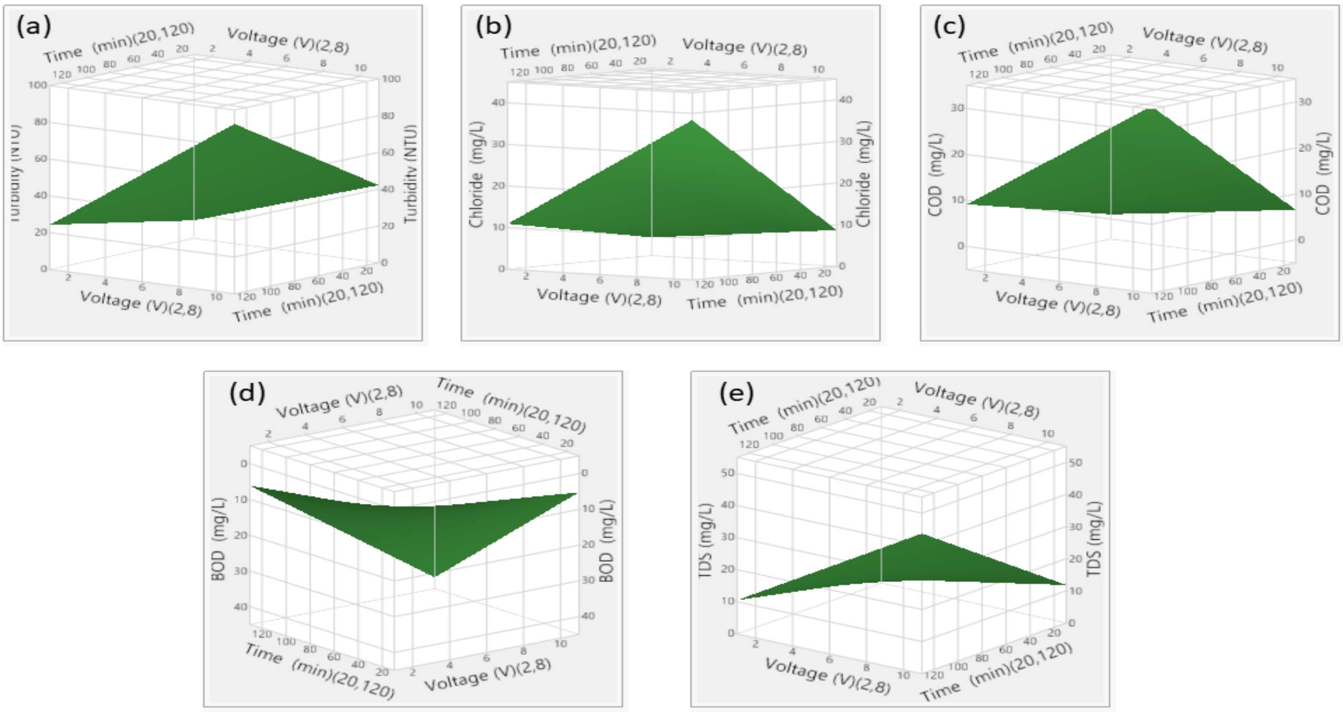


Fig.18 Image displaying the impact of experimental variables on the electrocoagulation of (Voltage Vs distance) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS).

3.4 Independent experimental variables Impact electrocoagulation using aluminium electrode.

JMP was used to create a three-dimensional response surface plot to comprehend how the independent experimental variable affected the results of electrocoagulation by distance, voltage, and time. The below figures 19, 20, and 21 display the 3D response surface plots of voltage, distance and time.

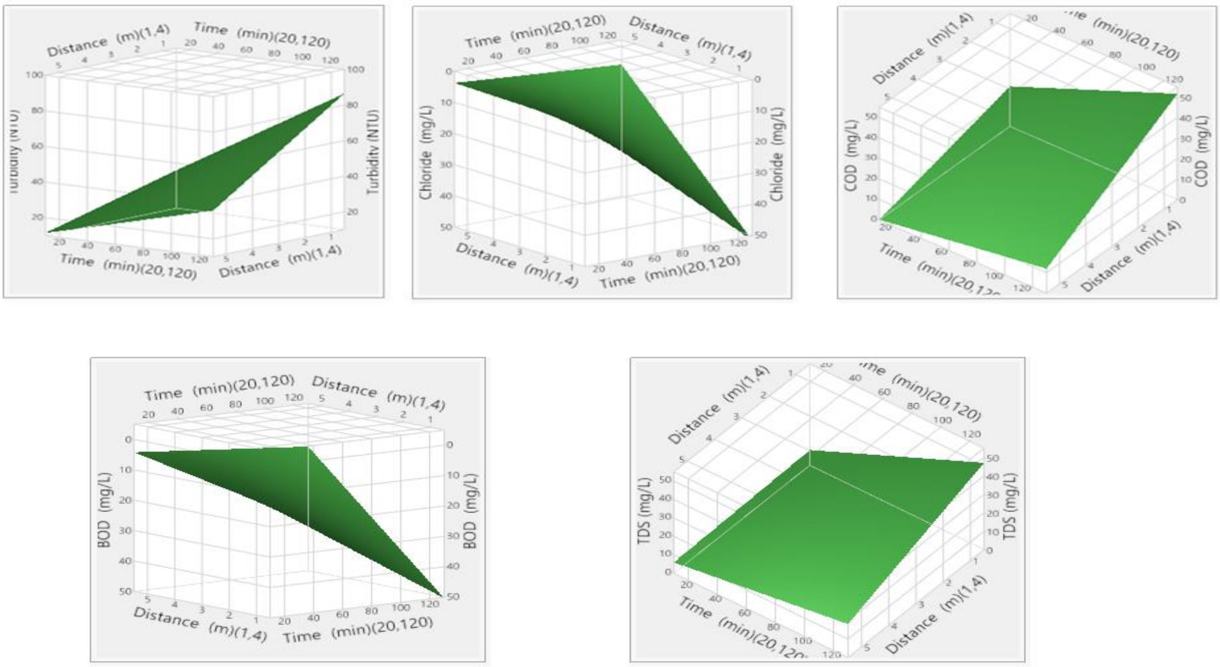


Fig.19 Image displaying the impact of experimental variables on the electrocoagulation of (Voltage vs. distance) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS).

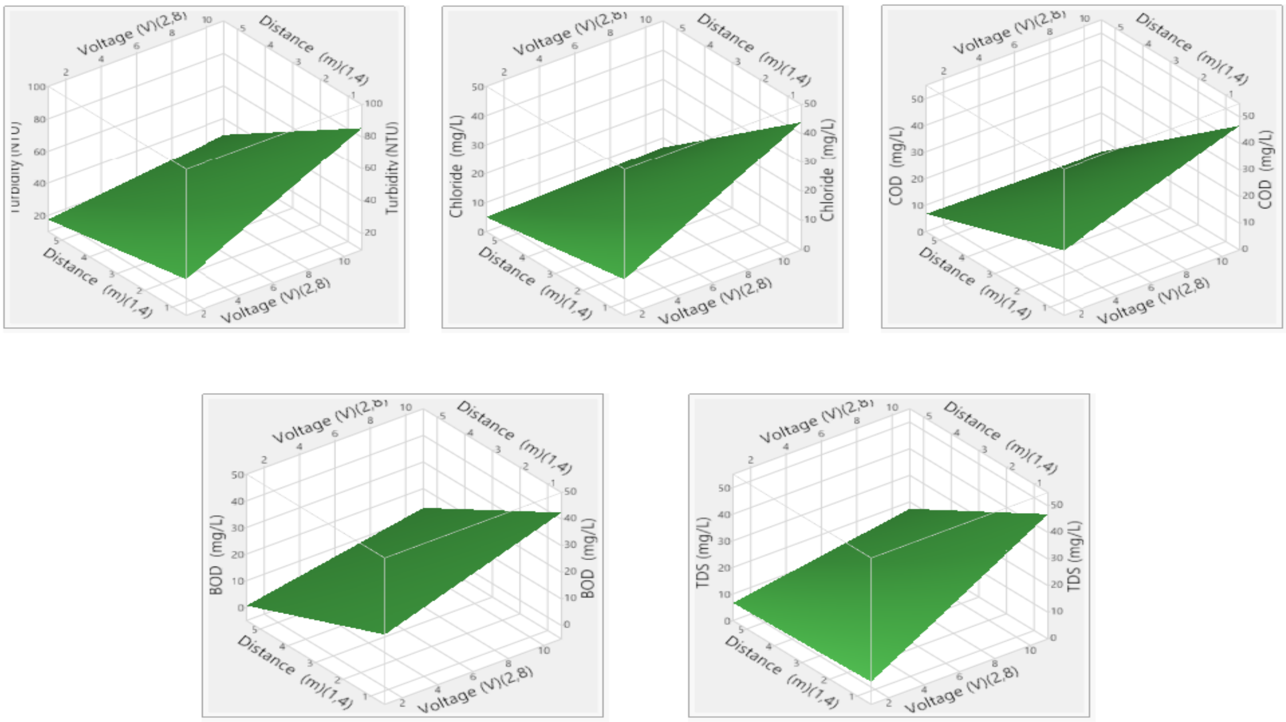


Fig.20 Image displaying the impact of experimental variables on the electrocoagulation of (Distance vs. time) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS).

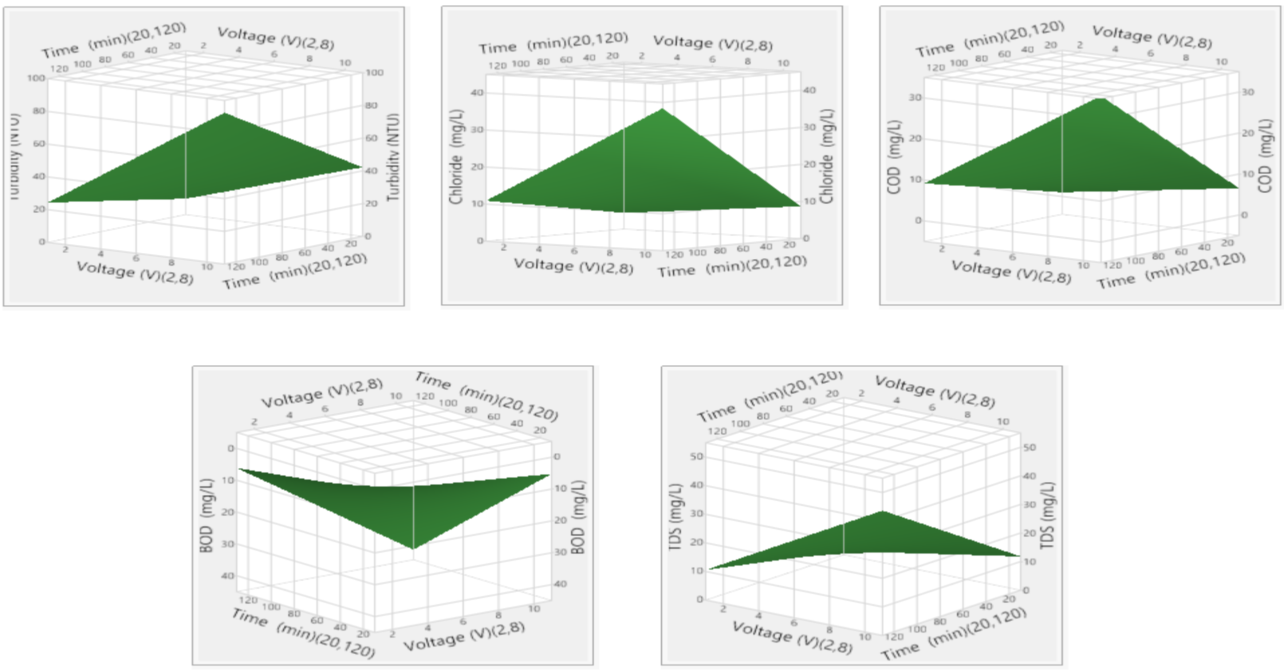


Fig.21 Image displaying the impact of experimental variables on the electrocoagulation of (Voltage Vs Time) as response surface plots, a. Turbidity. b. chloride (Cl−). c. chemical oxygen demand (COD). d. biological oxygen demand (BOD). e. Total dissolved solids (TDS).

Conclusion

Water treatment is critical to guaranteeing access to safe domestic usage water. The current research assessed the suitability of the EC technique for removing Turbidity (TDS, CL, COD, and BOD) from saline water utilizing aluminium electrodes and stainless-steel electrodes. Furthermore, the effects of current density (I), electrode distance (D), and time (T) on salt removal were examined. The ideal circumstances were as follows: Under the combined electrical connection of aluminium electrodes, RT = 120 min, IED = 1 cm, and 10 voltage EC were demonstrated to be particularly effective for turbidity removal from landfill leachate water. Using ideal EC process conditions, the removal percentages for Turbidity, TDS, Cl, COD, and BOD were 97.35 percent, 66.15 percent, 59.73 percent, 55.37 percent, and 53.32 percent respectively. The removal % is lower in this experiment because the electrode thickness was 1mm and the surface area was less; however, as the thickness and surface area of the electrode increased, so did the removal percentage. The current study's results demonstrate the technical viability of electrocoagulation as a dependable technology for removing turbidity, COD, BOD.

Acknowledgement: Authors acknowledges the JSS Academy of Higher Education and Research, Mysuru, for Providing financial assistance and for the laboratory facility.

Disclosure statement: Conflict of Interest: The authors declare that there are no conflicts of interest. Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

Aichouch I., Kachbou Y., Bouklah M., Merimi C. (2025) Bibliometric analysis using VOSviewer: Analysis of Steel Corrosion using EIS, *J. Mater. Environ. Sci.* 16 (3), 411-421

Akartasse N., Azzaoui K., Mejdoubi E., Elansari L. L., *et al*. (2022), Chitosan-Hydroxyapatite Bio-Based Composite in film form: synthesis and application in Wastewater, *Polymers*, 14(20), 4265, https://doi.org/10.3390/polym14204265

Akartasse N., Azzaoui K., Mejdoubi E., *et al*. (2022), Environmental-Friendly Adsorbent Composite Based on Hydroxyapatite/Hydroxypropyl Methyl-Cellulose for Removal of Cationic Dyes from an Aqueous Solution, *Polymers*, 14(11), 2147; https://doi.org/10.3390/polym14112147

Bhagawan D., Poodari S, Chaitanya N, Ravi S, Rani YM, Himabindu V. (2018) Industrial solid waste landfill leachate treatment using electrocoagulation and biological methods. *Desalin Water Treat*, 137–42, https://doi.org/10.5004/dwt.2017.20335

Bharath M., Krishna BM, Manoj Kumar B, (2020). Degradation and biodegradability improvement of the landfill leachate using electrocoagulation with iron and aluminium electrodes: A comparative study, *Water Pract Technol*, 15(2), 540–9. https://doi.org/10.2166/wpt.2020.04

Bouknana D., Serghini Caid H., Hammouti B., Rmili R., Hamdani I. (2021), Diagnostic study of the olive oil industry in the Eastern region of Morocco, *Materials Today: Proceedings*, 45(8), 7782-7788; https://doi.org/10.1016/j.matpr.2021.03.563

Contreras J., Villarroel M, Navia R, Teutli M, (2009), Treating landfill leachate by electrocoagulation, *Waste Manag Res*, 27(5), 534–41. https://doi.org/10.1016/j.jhazmat.2007.10.035

Dia O., Drogui P., Buelna G, Dubé R, (2018) Hybrid process, electrocoagulation-biofiltration for landfill leachate treatment, *Waste Manag*, 75, 391–9. https://doi.org/10.1016/j.wasman.2018.02.016

Ding J., Wei L, Huang H, Zhao Q, Hou W, Kabutey FT, (2018) Tertiary treatment of landfill leachate by an integrated Electro-Oxidation/Electro-Coagulation/Electro-Reduction process: Performance and mechanism, *J. Hazard Mater*, 351, 90–7, https://doi.org/10.1016/j.jhazmat.2018.02.038

Dura A., Breslin C.B. (2019) Electrocoagulation using stainless steel anodes : Simultaneous removal of phosphates, Orange II and zinc ions, *J Hazard Mater*, 374, 152–8. https://doi.org/10.1016/j.jhazmat.2019.04.032

Elazzouzi M., Haboubi K., Elyoubi M.S. (2016), Electrocoagulation-flocculation as a low-cost process for pollutants removal from urban wastewater, *Chem Eng Res Des*, 117, 614-626, http://dx.doi.org/10.1016/j.cherd.2016.11.011

Faheem K., Khan SU, Washeem M, Khan SU, Greenlee LF, Lawler DF (2019) Energy efficient removal of COD from landfill leachate wastewater using electrocoagulation: parametric optimization using RSM. *Int J Environ Sci Technol*, 19(5), 3625–36 https://doi.org/10.1016/j.desal.2017.11.030

Guo Z., Zhang Y, Jia H, Guo J, Meng X, Wang J. (2022) Electrochemical methods for landfill leachate treatment: A review on electrocoagulation and electrooxidation. *Sci Total Environ*, 806, 150-529.

https://doi.org/10.1016/j.scitotenv.2021.150529
Galvão N., de Souza JB, *et al*. (2020) Landfill leachate treatment by electrocoagulation: Effects of current density and electrolysis time. *J Environ Chem Eng*, 8(5), 1–8. doi:10.1016/j.jece.2020.104368
GilPavas E., Dobrosz-Gómez I., Gómez-García M.Á. (2018) Optimization of sequential chemical coagulation - electro-oxidation process for the treatment of an industrial textile wastewater, *J Water Process Eng*, 22, 73–9, https://doi.org/10.1016/j.jwpe.2018.01.005
Hawari A.H., Alkhatib A.M., Hafiz MA, Das P. (2020). A novel electrocoagulation electrode configuration for the removal of total organic carbon from primary treated municipal wastewater, *Environ Sci Pollut Res*, 27(19), 23888–98. 10.1007/s11356-020-08678-4
Ilhan F, Kurt U, Apaydin O, Gonullu MT (2018) Treatment of leachate by electrocoagulation using aluminium and iron electrodes, *J Hazard Mater*,154(1–3), 381–9. https://doi.org/10.1016/j.jhazmat.2007.10.035
Li X, Song J, Guo J, Wang Z, Feng Q, (2011) The Performance of Electrocoagulation Process in Removing Organic and Nitrogenous Compounds from Landfill Leachate in a Three-Compartment, *Reactor Environ Sci*, 10, 1159–64, https://doi.org/10.12911/22998993/145290
Lrhoul H., Turki H., Hammouti B., Benammar O. (2023), Internationalization of the Moroccan Journal of Chemistry: A bibliometric study, Heliyon, 9(5), e15857, https://doi.org/10.1016/j.heliyon.2023.e15857
Merzouk B., Madani K., Sekki A. (2010) Using electrocoagulation – electro fl otation technology to treat synthetic solution and textile wastewater, *two case studies*, 250(2), 573–7. http://dx.doi.org/10.1016/j.desal.2009.09.026
Muhammad Niza N., Yusoff M.S., Mohd Zainuri M.A.A., *et al.* (2020). Performance of batch electrocoagulation with vibration-induced electrode plates for landfill leachate treatment, *J Water Process Eng*, 36, https://doi.org/10.1016/j.jwpe.2020.101282
Naje A.S., Ajeel MA, Ali IM, Al-Zubaidi HAM, Alaba PA (2019) Raw landfill leachate treatment using an electrocoagulation process with a novel rotating electrode reactor. *Water Sci Technol*, 80(3), 458–65. https://doi.org/10.2166/wst.2019.289
N'diaye A.D., Hammouti B., Nandiyanto A. B. D., Al Husaeni D. F. (2022), A review of biomaterial as an adsorbent: From the bibliometric literature review, the definition of dyes and adsorbent, the adsorption phenomena and isotherm models, factors affecting the adsorption process, to the use of Typha species waste as a low-cost adsorbent, *Communications in Science and Technology*, 7 No.1, 140-153
Shankar R., Singh L, Mondal P, Chand S. (2018) Removal of COD, TOC, and color from pulp and paper industry wastewater through electrocoagulation, *Desalin Water Treat*, 52(40–42), 7711–22. https://doi.org/10.1080/19443994.2013.831782
Sardari K., Fyfe P, Lincicome D., Wickramasinghe S.R. (2018). Aluminium electrocoagulation followed by forward osmosis for treating hydraulic fracturing produced waters g ra p h i c a l ab s t r a c t, *desalination*, 428, 172–81. https://doi.org/10.1016/j.desal.2017.11.030
Sadeghi M., Fadaei A, Tadrisi M, Bay A, Naghizadeh A (2018). Performance evaluation of a biological landfill leachate treatment plant and effluent treatment by electrocoagulation. *Desalin Water Treat*, 115, 82–7. https://doi.org/10.5004/dwt.2018.22263
Sediqi S., Bazargan A., Mirbagheri S.A. (2021) Consuming the least amount of energy and resources in landfill leachate electrocoagulation, *Environ Technol Innov*, 22, 101454. doi:10.1016/j.eti.2021.101454
Sharma L., Prabhakar S, Tiwari V, Dhar A, Halder A, (2021) Optimization of EC parameters using Fe and Al electrodes for hydrogen production and wastewater treatment, *Environ Adv*, 3, 100029. https://doi.org/10.1016/j.envadv.2020.100029
Tezcan Un U., Filik Iscen C, Oduncu E, Akcal Comoglu B, Ilhan S (2018) Treatment of landfill leachate using integrated continuous electrocoagulation and the anaerobic treatment technique. *Environ Prog Sustain Energy*, 37(5),1668–76. https://doi.org/10.1002/ep.12850
Verma S.K., Khandegar V, Saroha AK, (2013) Removal of Chromium from Electroplating Industry Effluent Using Electrocoagulation., 17(2), 146–52. 10.1061/(ASCE)HZ.2153-5515.0000170
Zailani L.W.M., Zin N.S.M. (2018) Application of Electrocoagulation in Various Wastewater and Leachate Treatment-A Review, *IOP Conf Ser Earth Environ Sci*, 140(1), 012-052. https://iopscience.iop.org/article/10.1088/1755-1315/140/1/01205

(2025) ; http://www.jmaterenvironsci.com