



Electrocoagulation treatment of oily wastewater using perforated electrodes: Process optimization via response surface methodology

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Oily wastewater poses a significant environmental concern due to its high chemical oxygen demand (COD) and complex composition, which limits the effectiveness of conventional treatment methods. In the present study, an electrocoagulation (EC) process employing perforated electrodes was investigated for the effective removal of COD from oily wastewater. A direct current (DC) power supply was used to operate the EC reactor, and process optimization was performed using response surface methodology (RSM) based on a Box-Behnken Design (BBD). The influence of three key operational parameters, namely, initial pH, current density, and electrolysis time, on COD removal efficiency was systematically evaluated. The results revealed that electrolysis time was the most influential parameter, followed by current density and pH. At the central levels of pH and current density, a treatment duration of 25 min resulted in approximately 72% COD removal. The optimized operating conditions were identified as pH 5.42, current density of 5 mA/cm², and electrolysis time of 25 min, under which a maximum COD removal efficiency of 91.81% was achieved with a specific energy consumption of 1.835 kWh/m³. The findings demonstrate the effectiveness of the electrocoagulation process and highlight its potential application as a decentralized treatment option for complex oily wastewater.

Keywords: Box-Behnken design, Chemical oxygen demand, Decentralized wastewater treatment, Electrocoagulation, Oily wastewater, Response surface methodology

Introduction

Oily wastewater reduces the water quality and makes it unsuitable for use, if discharged into the environment without any treatment. The oil content tends to float on the surface of water bodies, which results in blocking the natural sunlight, oxidation etc., affecting the quality of water, aquatic life¹. This imparts hindrance to natural functioning of the ecosystem. The contaminated water is introduced into the surface water and groundwater, through the hydrological cycle of the water, thus induces risk to natural ecosystem and human health^{2,3}. The biodegradability of oil is limited in water as well as in soil, thus posing a significant risk to the environment⁴.

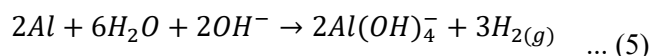
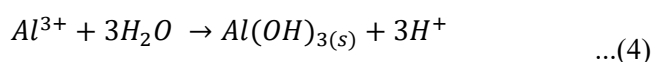
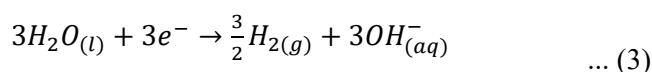
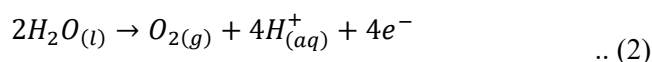
The oil content in wastewater is present in various forms such as grease, kerosene, diesel, gasoline, cooking oil etc⁵. Major sources of oily wastewater include oil refineries, petrochemical industries, food processing plants, textile industries, automobile workshops, restaurants and domestic kitchens⁶. Engine oil spills and greasing while servicing are also

common practices in automobile workshops. These lubricants get mixed into the water during cleaning operations and mix with the effluent wastewater from an automobile workshop^{7,8}. The waste or used engine oil is not recycled fully and is thrown away or discarded unscientifically⁹.

Removing oil from wastewater is one of the most challenging tasks for treatment facilities¹⁰. In wastewater, oil is mostly present in emulsified form, these emulsions are prepared from mechanical agitation or stabilizers, making the whole treatment process difficult¹¹. Most of the treatment plants installed are based on conventional treatment processes such as physical, chemical and biological, working on the principle of sedimentation, precipitation and biodegradation respectively. These treatment processes require longer treatment span, large amenities, and are low in efficiency for oil removal¹². The working efficiency of traditional methods remains unsatisfactory and needs advanced treatment approaches⁵.

Advanced treatment processes such as electro-oxidation (EO), electro-coagulation (EC), hybrid processes etc. have shown significant removal efficiency for oily wastewater and emerging contaminants^{3,13}. Advanced oxidation processes (AOPs) use hydroxyl radicals generated in situ to treat wastewater, such as ozone oxidation, Fenton-oxidation etc. have performed well^{14,15}. Hybrid processes such as electrochemical advanced oxidation combine EC with oxidation, resulting in simultaneous production of coagulants and oxidants^{16,17}. However, these methods require large capital investment to control and operate various parameters¹⁸.

EC has emerged as a promising, fast and efficient technology in treating oily wastewater^{19,20}. EC is a method that uses electric current to remove impurities. An EC setup consists of two electrodes, namely anode and cathode, powered by a DC source. During EC process, the most important chemical reaction involves the dissolution of metal ions (Al^{3+} , Fe^{3+} , etc.) at anode⁴ and production of hydrogen gas, formation of hydroxyl ions at cathode⁵. The metal ions produced at anode destabilize the colloid particles by neutralizing charges and form metal hydroxides such as $Al(OH)_3$, $Fe(OH)_3$ etc. by reacting with hydroxyl ions^{11,21}. The reaction Eqs (1-5) reveal the mechanism behind the formation of flocs by aluminum²⁰.



These in-situ prepared coagulants species possess high surface area and high affinity for contaminants present in water²². The combined act of adsorption, chemical precipitation and sorption by coagulant species tend to increase the specific gravity of contaminants through flocculation, leading to the separation of the contaminants from the water²³. Owing to this, EC process has become efficient technology for the decentralized wastewater treatment units.

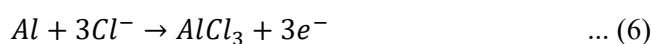
While leveraging the benefits of EC process, current study proposes the use of perforated hollow cylindrical aluminium electrodes for the treatment of oily wastewater. Studies reported significant removal of chemical oxygen demand (COD) by 99%²⁴, 96.5%⁵ from oily wastewater treatment. Different combinations of geometries have been studied such as parallel plate, rod, perforated type etc., and suggested that perforated electrodes have performed very well, because of their high mixing capacity and better release of coagulants²⁵⁻²⁷.

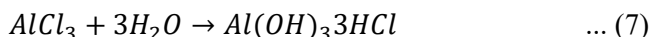
Energy efficiency of the EC process is dependent on multiple operating variables such as initial contaminant concentrations, solution mixability, electrode passivation, current density, and treatment time. Also, the type and shape of the electrode are the significant features in EC process, as it affects the quality, quantity respectively^{28,29}. To enhance the energy efficiency and adaptability of EC process as a decentralized treatment unit, current study proposes the perforated electrode setup in the cylindrical reactor to promote the homogeneity of solutions. The objectives of this study are (1) to analyze the effects of three process parameters namely pH, current density and electrolysis time in EC process; (2) optimization of the process with respect to pH, current density and electrolysis time; and (3) to study the equilibrium adsorption behaviour and chemical kinetics in the process. In addition, the parameters such as economy and energy consumption were studied for the optimum conditions obtained.

Experimental Section

Wastewater sample

The wastewater used in this study is a synthetic oil-in-water emulsion. The synthetic sample is used to avoid variation in the properties of the sample. For the sample preparation, 1 g/L petrol engine oil and 1 g/L sodium dodecyl sulfate as a surfactant were mixed in deionized water. To form a homogeneous mix, the sample was sonicated for ten minutes using an ultrasonication device. 1 g/L sodium chloride (NaCl) was added to the mixture. NaCl serves as a supporting electrolyte to enhance the electrical conductivity of the sample³⁰ and it also reduces electrode passivation by inducing local acidic condition called pitting corrosion³¹, as shown in Eqs (6 to 7).





The micro acidic environment created due to formation of hydrochloric acid, increases the aluminium dissolution and reduces the chance of electrode passivation³².

Electrocoagulation reactor

An EC reactor made of borosilicate material was used in this study for wastewater treatment. Aluminium (Al) was preferred over iron (Fe) as an electrode material, because of its better conductivity, strong hydroxide and formation of stable flocs than iron^{33,34}. A DC power source was used in the experiment to stabilize current and voltage within a range of 0-3A and 0-30V, respectively. A schematic diagram of the reactor is shown in Fig. 1. A magnetic stirrer was used at the rate of 250 rpm to form a better mix and better interaction, between metal ions and oil-water emulsions. The electrodes were cleaned with sandpaper to remove surface dust and then washed with distilled water, ethanol before use. After the test, the sample was left to settle for two hours, and COD tests were conducted to obtain the results.

Electrode arrangement

Aluminium was used as the material for both electrodes. While existing studies have focused on creating holes to improve mixing³⁵, the novelty of the perforated hollow cylindrical electrode lies in its unique design. This design allows for superior mass transfer, mixing, and circulation compared to standard perforated electrodes³⁶ and increases energy efficiency³⁷. Spiral geometries push the coagulants and pollutants toward the centre of the reactor, which

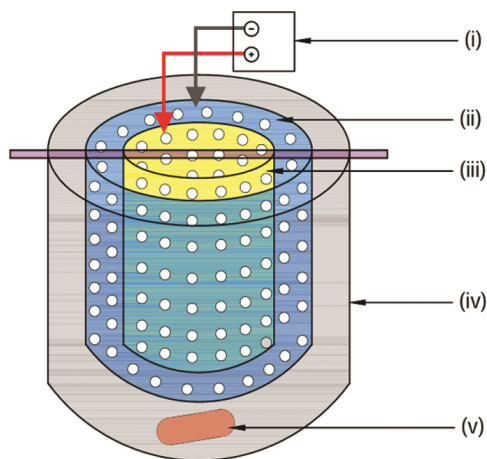


Fig. 1 — Electrocoagulation batch reactor consisting of (i) DC power source, (ii) aluminium cathode, (iii) aluminium anode, (iv) borosilicate cylinder and (v) magnetic stirrer

lead to swirl flow preventing the foam formation and passivation of electrode³⁸.

In this work, the reactor consisted of two concentric perforated aluminium electrode tubes. The inner tube served as the anode, while the outer tube served as the cathode. Both tubes were perforated with holes of 4 mm diameter. The experiments were designed using the response surface methodology (RSM) based Box-Behnken design (BBD) approach to treat wastewater.

Experimental design

To design the experiments, RSM was used, which is a powerful statistical technique used in industry, academia, and research for experimental design and data analysis. RSM-based BBD was used to design experiments with complex parameters and to reduce the experimental runs. BBD helps in finding complex relations between independent variables and dependent variables. RSM uses a second-order polynomial equation as shown in Eq. (8) to establish a relation between the variables.

$$Y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{1 \leq i < j}^k b_{ij} x_i x_j + \sum_{i=1}^k b_{ii} x_i^2 + \epsilon \dots (8)$$

Here, Y represents the predicted or dependent variable, which is COD in our case, b_0 is the intercept, b_i , b_{ij} , and b_{ii} represent the linear coefficient, interaction coefficient and quadratic coefficient, respectively, x_i , x_j are the independent variables, and ϵ is the random error term³⁹.

In this work, three independent operating variables namely pH, current density (mA/cm^2) and electrolysis time (minutes) were considered for removal efficiency of oil in EC process. The three independent variables with their coded values and levels are shown in Table 1. Design expert software version 13 was used for the design and proposed seventeen experimental runs and fitted into a second order polynomial equation. Higher regression coefficient R-squared values and analysis of variance (ANOVA) were used to verify the quality of the model.

Table 1 — Independent variables with their coded levels

Independent variables	Coded variables	Units	Levels of each variable		
			-1	0	+1
pH	A		5	7	9
Current density	B	mA/cm^2	1	3	5
Electrolysis time	C	min	5	15	25

Analytical methods (pH meter, turbidity meter, COD closed reflux method)

The COD value was considered to evaluate the oil removal performance of the EC process, as the COD and oil concentration removal trends are the same⁴⁰. COD test was conducted using closed reflux method. COD experiments were performed by using APHA 5220C method. All the experiments were performed in triplicate. The removal efficiency of COD was obtained by using Eq. (9):

$$R\% = \frac{\text{COD}_f - \text{COD}_i}{\text{COD}_i} \times 100 \quad \dots(9)$$

Economic analysis

The economy of the process depends on the cost of materials used and energy consumed in the treatment process. The cost of the EC process depends on the electrode material consumed by the electrical energy used. Total operating cost can be calculated using Eq. (10):

$$\text{Treatment cost} = (a \times C_{\text{electrode}}) + (b \times C_{\text{energy}}) \quad \dots(10)$$

where, "a" and "b" are the coefficients representing cost of electrode (1500₹/ kg or 18.10\$/ kg for Al), and energy rate (6.38₹/ kW h or 0.0719\$/ kW h), respectively. C_{energy} (kWh/ kg COD) and $C_{\text{electrode}}$ (kg/ kg COD) represent the consumption of energy and electrode, respectively, calculated from Eqs (11 and 12):

$$C_{\text{energy}} = \frac{U \times I \times t_{\text{EC}}}{V \times C_i \times R_e} \quad \dots(11)$$

$$C_{\text{electrode}} = \frac{I \times t \times M \times \phi}{z \times F \times V \times C_i \times R_e} \quad \dots(12)$$

where U is cell potential (V), V is volume of wastewater (m^3), I is applied current (A), t_{EC} is electrolysis time (min), C_i is initial COD concentration in (kg/m^3), R_e is COD removal efficiency, M is molecular mass of Al (26.98 g/mol), z is valency of electrons for Al which is 3 and F is Faraday's constant which is 96,485 C/mol, ϕ is current efficiency given by Eq. (13):

$$\phi = \frac{\text{ACE}}{\text{TCE}} \times 100 \quad \dots(13)$$

In Eq. (13), ACE represents the actual consumption of electrode calculated by taking the difference of W_1 , W_2 , where W_1 and W_2 are the weights of electrodes before and after the treatment process, TCE represents

the theoretical consumption of electrode, which is calculated by Faraday's law in Eq. (14):

$$Z = \frac{ItM}{eF} \quad \dots(14)$$

where, t is the electrolysis time in seconds, M is the molecular weight of the material used in g/mol and e is the number of electrons involved in oxidation and reduction reactions of the EC process (for $\text{Al}^{3+}=3$).

Results and Discussion

Model design and statistical analysis

The RSM approach was used to analyze and study the effects of operating variables on COD removal efficiency. A total of 17 experiments were conducted for the design of experiments obtained from the RSM-BBD approach. The quadratic regression model was fitted into experimental outcomes to derive the mathematical equation as shown in Eq. (15), and achieved an R^2 value of 0.9845, which suggests that 98.45% of the total variations in COD removal can be explained with the help of the developed model.

$$\text{COD removal (\%)} = 63.53 - 4.93A + 10.96B + 11.13C - 6.84A^2 - 3.43AB - 2.77AC - 4.10B^2 + 6BC - 2.43C^2 \quad \dots(15)$$

It can be inferred from the equation that the coefficient terms for current density (B) and electrolysis time (C) are positive and largest, hence suggesting these two the most dominant factors in improving the removal efficiency. In the equation, the term BC has synergistic effects which means that by increasing both B and C simultaneously, the removal (%) increases, while AB and AC are antagonistic which suggests that their interaction have negative effects on COD removal (%). In the equations, the terms B, C, A^2 , A, B^2 and BC are the significant terms, while the terms AB and AC are insignificant. The adjusted and predicted R^2 values for the model are 0.9646 and 0.9204, respectively. The difference between adjusted and predicted R^2 value is less than 0.2, which further added value to the quality of the model. Table 2 shows experimental and predicted COD removal efficiency. The experimental findings of removal efficiency are ranged from 40% to 84%, while the predicted value ranged from 40.12% to 85.09%.

The line as shown in Fig. 2(a) represents the predicted value, while the dotted point represents the actual value obtained in the experiment. Hence, the

Table 2 — Design of experiment using RSM with actual and predicted response

Run	pH (A)	Current Density (mA/cm ²) (B)	Electrolysis Time (min) (C)	Actual COD Removal (%)	Predicted COD Removal (%)	Residual	Absolute Residual	Relative Error (%)
1	5	3	25	74.06	73.08	0.97	0.97	1.31
2	9	3	25	59	57.70	1.295	1.295	2.19
3	9	3	5	40	40.97	-0.97	0.97	2.42
4	7	1	5	42	40.90	1.095	1.095	2.61
5	9	5	15	55	55.2	-0.2	0.2	0.36
6	7	3	15	63.33	63.52	-0.196	0.196	0.31
7	7	3	15	65.99	63.52	2.454	2.454	3.72
8	7	5	5	52	50.83	1.17	1.17	2.25
9	5	3	5	44	45.29	-1.295	1.295	2.94
10	7	3	15	66.67	63.52	3.134	3.134	4.70
11	7	1	25	50	51.17	-1.17	1.17	2.34
12	7	5	25	84	85.09	-1.095	1.095	1.30
13	5	5	15	72.03	71.9	0.125	0.125	0.17
14	7	3	15	61.67	63.52	-1.866	1.866	3.03
15	7	3	15	60	63.52	-3.526	3.526	5.88
16	5	1	15	43.33	43.13	0.2	0.2	0.46
17	9	1	15	40	40.12	-0.125	0.125	0.31

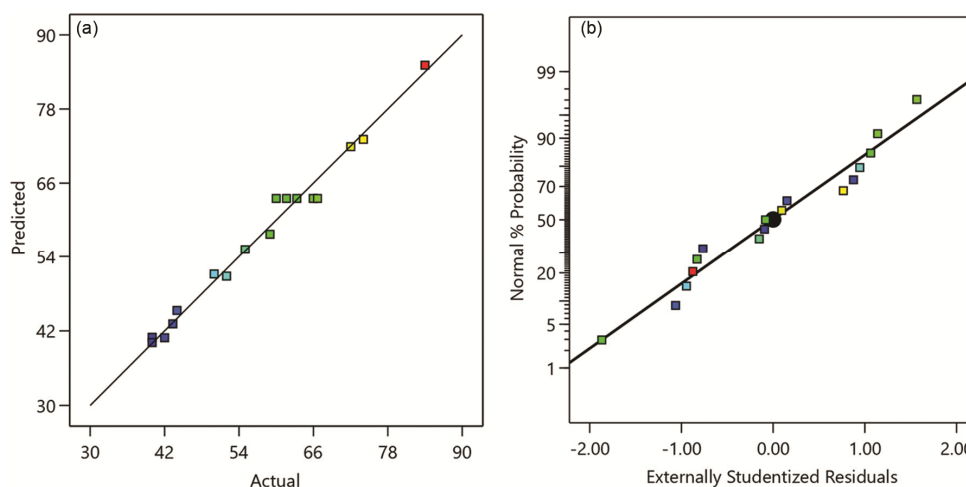


Fig. 2 — (a) Actual vs predicted value and (b) normal percentage probability versus external studentized residuals for % COD removal

actual values have significantly low deviations from the predicted values. It suggests that the random error or residual value is less between actual values and predicted values. Points as shown in Fig. 2(a) located above the dotted line have values greater than the predicted value and hence known as positive residuals. On the other hand, the points below the dotted line have values less than the predicted values and are negative residuals. The normal probability graph as shown in Fig. 2(b) confirmed that the residuals are normally distributed, the slight deviation at extremes are acceptable as they are still within the range of +2 with no outliers demonstrating the quadratic model assumptions.

Analysis of variance (ANOVA) and lack of fit

ANOVA results were considered to check the quality of the model; if the quality of the model is not checked, it may lead to incorrect reporting. Therefore, ANOVA was considered as a tool to check the quality of the model. The results of the analysis of variance for COD removal efficiency are shown in Table 3. The models with a p-value less than 0.05 are considered as significant, while the model value greater than 0.05 are insignificant. The F-ratio (Fisher variance) verified the quality of the model and confirmed that the model is highly significant with the following parameters (F-value-49.45, p-value<0.0001). The R-squared value of 0.9845

Table 3 — ANOVA results for the COD removal using RSM

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value	Significance
Model	9	2688.31	298.70	49.45	< 0.0001	significant
A-pH	1	194.24	194.24	32.16	0.0008	significant
B-CD	1	961.41	961.41	159.17	< 0.0001	significant
C-ET	1	991.46	991.46	164.15	< 0.0001	significant
A ²	1	46.92	46.92	7.77	0.0270	significant
AB	1	30.58	30.58	5.06	0.0592	
AC	1	144.00	144.00	23.84	0.0018	
B ²	1	196.73	196.73	32.57	0.0007	significant
BC	1	70.80	70.80	11.72	0.0111	significant
C ²	1	24.77	24.77	4.10	0.0825	
Residual	7	42.28	6.04			
-Lack of Fit	3	10.48	3.49	0.4396	0.7373	not significant

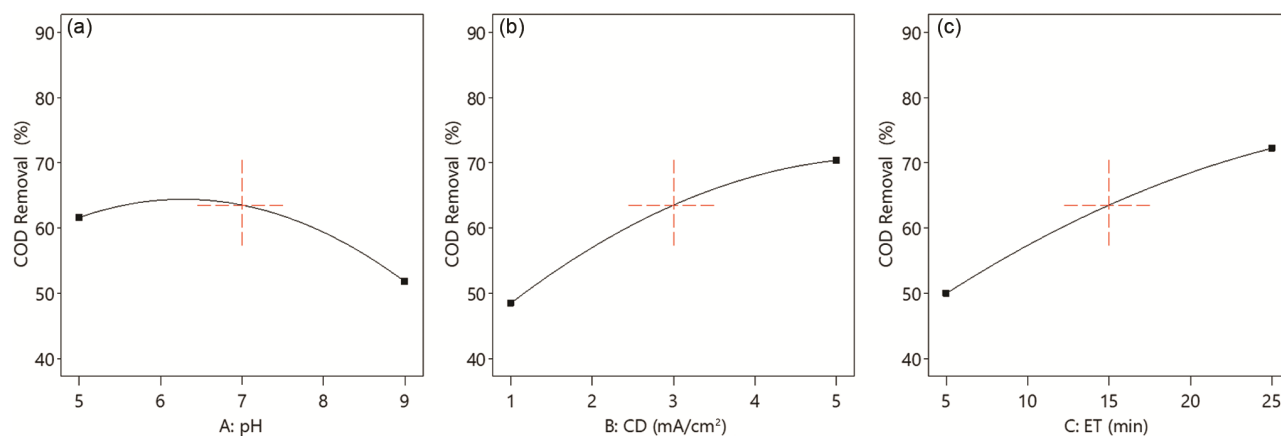


Fig. 3 — Perturbation plots showing effects of each procedure parameter on COD removal

explained that the 98.45% variation can be explained with the model. The adjusted R-squared with a value of 0.9646 showed good agreement with R-squared. The p-value for the lack of fit is 0.7373 greater than 0.05, suggesting that the model is significant and obtained model explained the data well. The signal noise ratio of 23.85 confirmed that the model possesses adequate precision for prediction and optimization, as the required signal-to-noise ratio must be greater than 4.

Effects of procedure parameters on COD removal efficiency

Effect of pH

The impact of pH influences COD removal, as it affects conductivity and electrode consumption. The COD removal with pH followed a reverse trend ranged from 61% to 51% when the pH changed from 5 to 9 respectively, at mean values of current density and electrolysis time. During the EC process near neutral pH, the Al^{3+} ions react with OH^- ions to form aluminium hydroxides. These hydroxides neutralize colloidal charges and adsorb excess pollutants from

wastewater. At alkaline pH, due to excess number of hydroxyl ions, the dissolution of aluminium hydroxides takes place, which results in the formation of aluminate ions $\text{Al}(\text{OH})_4^-$. Dissolution of aluminium hydroxides reduces floc formation, and hence a sharp decrease in COD removal efficiency from 61% at pH 5, to 51% is obtained at pH of 9.

$$\text{COD Removal (\%)} = 73.68 - 2.56A + 0.0043A^2 \dots (16)$$

The COD removal rate can be explained from Eq. (16), that the COD removal rate follows a declining trend as the pH increases. Also, the negative coefficient indicates that the increasing pH decreases COD removal efficiency. Fig. 3(a) clearly demonstrates that the COD removal decreases from 61% to 51% as the pH changes from 5 to 9, respectively. This behaviour revealed that the COD removal favours the acidic condition. Also, the literature suggested that the pH range of 5-7 has more COD removal efficiency than the alkaline condition^{24,41}.

Effect of current density

The quantity of ions released from the metal cation is based on the applied current density. When an electric current is applied to electrodes, the metal ions are released from the electrode, which acts as a coagulant in the EC process. The dissociation of electrode follows Faraday's law, which is given by the Eq (14), which describes that the metal ions released is proportional to current applied. In the experiments, the current density parameter ranged from 1 to 5 mA/cm² to know its effect on the performance of EC reactor. The rate of oil removal and the number of different ions released from the electrodes are based on this parameter, hence making it one of the most important parameters in the EC process. The effect of current density on oil removal is shown in Fig. 3(b) for the electrolysis time of 15 min and pH of 7. The COD removal efficiency has increased from 49% to 70%, when the current density varied from 1 to 5 mA/cm², respectively, at the electrolysis time of 15 min and pH of 7. The findings revealed that there is an improvement of 21% for the tested range. The findings revealed that the unique design of the anode provided enough coagulants to release into wastewater and helped in the COD removal with the increase in current density. The enhanced cathode area helped in the release of hydroxyl ions, which further helped in the formation of metal hydroxides and led to significant removal of COD. Eq. (17) represents the mathematical relation of COD removal with current density and the mean values of pH, electrolysis time.

$$\text{COD Removal (\%)} = 43.63 + 5.30B - 0.0061B^2 \dots (17)$$

The Eq. (17) consists of both linear as well as quadratic change, which suggests that during initial current densities, the COD removal rate increases but as it approaches optimum value it favours a curvature effect with a concave down. The higher current densities helped in the removal of COD, with the formation of flocs generated in-situ. The mixture of air bubbles helped in the formation of scum layer, which was floating on the surface, which confirmed that COD removal involved two phenomena i.e. electro-coagulation and electro-flocculation.

Effect of electrolysis time

Electrolysis time refers to the duration during which an electric current is applied to a volume of the solution. During this period, the electric current causes chemical changes in the solution, leading to

oxidation and reduction phenomena. According to Eq. (14) of Faraday's law, electrolysis time is proportional to the amount of metal ions released into the solution. The results demonstrated that the COD removal efficiency increased from 50% to 72% when the electrolysis time changed from 5 to 25 min, respectively. It has been confirmed from Fig. 3(c) that a longer duration aids in COD removal. Eq. (18) confirmed that COD removal had a linear effect during the initial stages and, later at optimum conditions, followed a curvature pattern. At mean values of current density and pH, the maximum COD removal was achieved with an electrolysis duration of 25 min.

$$\text{COD Removal (\%)} = 43.36 + 1.115C + 0.0010C^2 \dots (18)$$

After the mean electrolysis time, the COD removal rate declined due to an excess number of coagulants released and formation of metal oxide layer on the electrodes. These layers limit the COD removal efficiency, as the interaction of coagulants with the pollutant decreases. The adsorption and desorption process occurs simultaneously, the COD removal rate declined after the mean electrolysis time, due to the excess number of ions and metal oxides in the solution. Eq (18) depicts the relation between COD removal rate and electrolysis time at mean values of pH and current density.

3D surface and 2D contour plots shown in Fig. 4 reveals the effect of pair of procedure parameters on COD removal efficiency. The effect of each pair of procedure parameters on COD removal efficiency was studied by varying them as per the designed range, while remaining parameter was fixed at central value i.e. 7 pH, 3 mA/cm² current density and 15 min electrolysis time. Fig. 4(a), shows the effects of pH and current density on COD removal at central value of electrolysis time for 15 min. In Fig. 4(b), the current density was fixed at central value of 3 mA/cm², while pH and electrolysis time was changed as per the designed ranges. In Fig. 4(c), the pH was kept at central value of 7, while the effect of current density and electrolysis time was studied for all values ranging from lower to higher as per the designed range.

The pH range plays a vital role in the COD removal, the efficiency of the process changes significantly as the pH changes from 5 to 9. It is observed from the contour plot in Fig. 4(a), that in the pH range of 5 to 7, the COD removal efficiency is

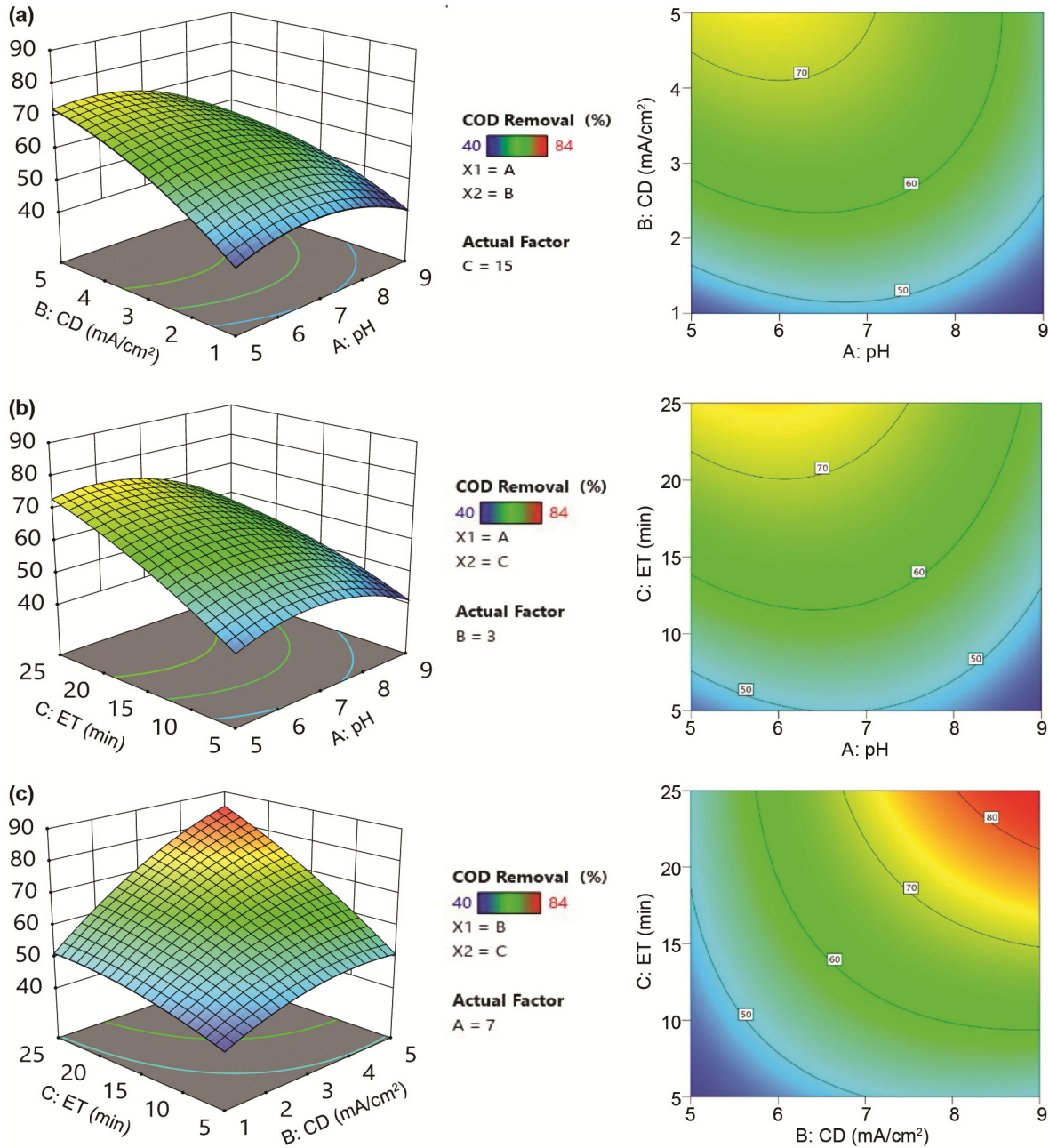


Fig. 4 — 3D surface plots and 2D contour plots for COD removal

greater than 70% at a current density of 4 mA/cm² and the efficiency reached near 80% at current density of 5 mA/cm², at a fixed electrolysis of 15 min.

In EC, when pH range is 5 to 7, the metal ions (Al³⁺) and hydroxide ions (OH⁻) generate the most reactive hydroxide Al(OH)₃ species, these species have strong adsorption affinity for the pollutants which helps in destabilization of contaminants and removes the contaminant. However, when pH value exceeds pH 7, the Al(OH)₄⁻ are the dominant species,

which leads to precipitation and less availability of hydroxide complexes for pollutant removal. In Fig. 4(a), the contour plot depicts that when pH value exceeds 8, the COD removal falls below 60%. Fig. 4(b), reveals that at constant current density, on increasing the electrolysis time at lower pH, the COD removal % increases. The increased electrolysis time provided enough time for the interaction of coagulant species and contaminants.

The current density is one of the most important parameters in the COD removal process, as it directly affects the rate of release of coagulant species from the sacrificial electrode and the formation of bubbles at cathode. Fig. 4(c), explains that at constant pH, on increasing the current density and electrolysis time simultaneously, the COD removal is greater than 80%. The interaction of these two parameters provided enough time for release of coagulant species and interaction with the pollutants. In this study, on increasing the current density to 5 mA/cm² and electrolysis time to 25 minutes, the COD removal reaches between 80-90%. Also, it can be observed from Fig. 4(b), that on increasing the electrolysis time at constant current density, the COD removal % increases. The increased residence time assists in better interaction among the coagulants and pollutant species.

Optimization of process parameters

The quadratic model suggested the optimal conditions of pH at 5.42, current density at 5 mA/cm², electrolysis time at 25 min, at a desirability score of 1.0. At optimum conditions, the predicted value is 89.61% for COD removal, while the average experimental value for COD removal is 91.81±4.81%. So, it can be concluded that the average experimental reading of 91.81% exceeded the predicted value of 89.61% for COD removal from the RSM model. At the optimal conditions, the energy consumed was 0.363 kW h/kg oil content. The findings demonstrated that oily wastewater can be treated successfully using a newly designed perforated EC reactor. However, there is an error rate of 2.2% between the predicted and experimental

results. It suggests that the accuracy of the model can be improved with the help of advanced deep learning techniques.

Adsorption kinetics and isotherms

The findings were fitted into the concentration-based kinetics, as in electrocoagulation the goal is to optimize the pollutant removal. However, in adsorption-based kinetics which fits the data into pseudo first order and pseudo second order, as shown in Fig. 5, the goal is to optimize the adsorbent dosage⁴².

In addition, the experimental data were fitted into the Langmuir and the Freundlich adsorption isotherms. The adsorption isotherm findings suggested that the Langmuir isotherm provided the best fit an R-squared value of 0.972 while Freundlich model fitted with an R-squared value of 0.90 as shown in Fig. 6, which confirmed the presence of a monolayer adsorption process for COD removal from oily wastewater.

Electrode consumption and energy consumption

To find the electrode consumption and energy consumption, Eqs (3-6) were used. According to Eq. (12), the theoretical consumption of electrodes is directly proportional to current and electrolysis time, whereas the actual consumption of electrodes depicts the real behaviour of electrodes in the treatment process. In this study, at optimal conditions of pH at 5.6, current density of 5 mA/cm² and electrolysis time of 25 min, the energy and electrode consumption for COD removal were 0.363 kW h/kg and 36.91 g/kg respectively, which lead to the total cost of 57.68 ₹/kg COD or 0.80 \$/kg COD removed. Table 4, compares the research conducted on treatment of different wastewater by using the electrocoagulation. The table shows the comparison of

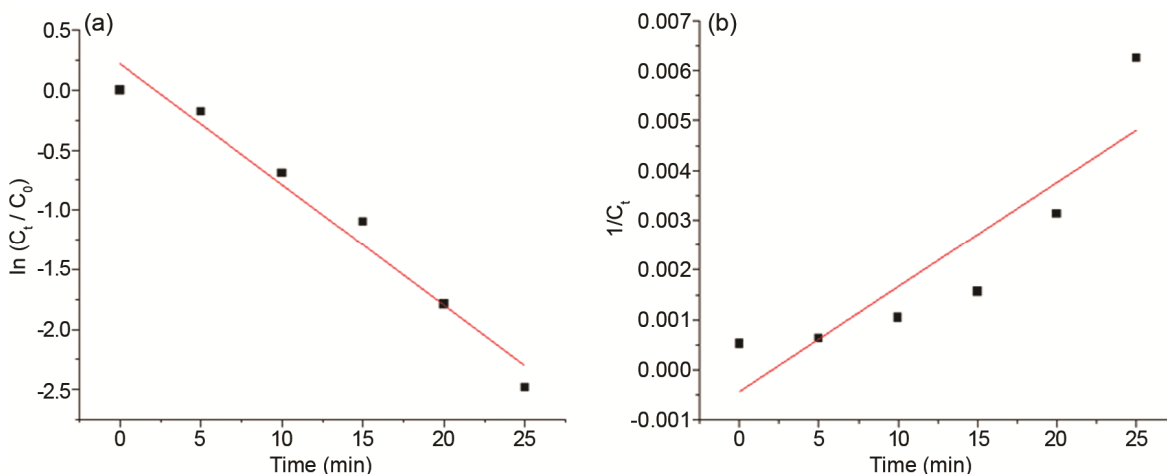


Fig. 5 — Chemical kinetics for (a) first order (b) second order

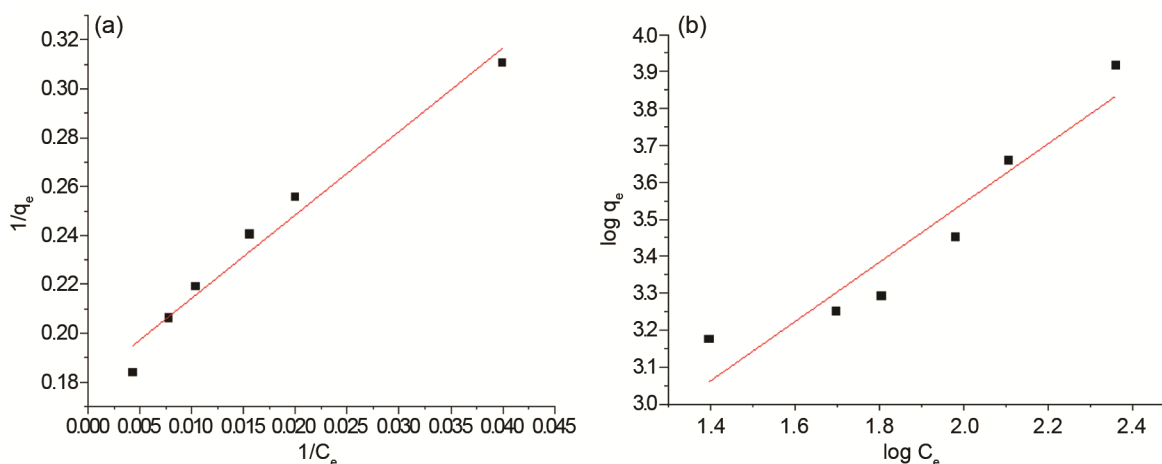


Fig. 6 — Isotherm plots for (a) Langmuir and (b) Freundlich model

Table 4 — Comparison of various EC processes for treatment of different wastewater

Wastewater Type	Removal Efficiency	Energy Consumption (kW h/m ³)	Operating Cost (USD/m ³)
Oil-Water Emulsion	97.15% (COD) ⁴³	26.71	2.39
Oil-Water Emulsion (EPS Electro Per Sulfate)	87.94% (COD) ⁴³	13.84	1.27
Automobile Wash Water	95.7% (COD) ⁴⁴	0.2859	5.17
Carwash Wastewater	88% (COD) ⁴⁵	1.46-2.71	N/A
Tannery Wastewater	95% (COD) ⁴⁶	6	N/A
Cattle slaughterhouse	95% (COD) ⁴⁷	0.88	1.5
Metalworking wastewater	77.7%(COD) ⁴⁸	1.98-17.11	1.37-4.74
Produce wastewater	92.6%(TOC) ⁴⁹	1.5	0.5
Petroleum wastewater	94.02 % (COD) ⁵⁰	31.2	N/A

COD removal efficiency, energy consumption, operating cost in the treatment of different types of wastewaters. According to the results, the energy and electrode consumption was near the value obtained for treating the industrial wastewater. The COD removal efficiency in this study is 91.81% and energy consumed is 1.835 kWh/m³ which aligns with other studies, as shown in the Table 4.

Conclusion

This study effectively analyzed the treatment of oily wastewater by the EC process. The optimum values obtained for maximum COD removal are pH 5.42, current density 5 mA/cm², and electrolysis time 25 min. The optimum condition leads to the COD removal of 91.81%, which aligns with the predicted value of 89.61%. In addition, the adsorption kinetics proved that the COD removal followed a first-order concentration kinetics with an R-squared value of 0.969 compared to an R-squared value of 0.79 for a second-order kinetic model. The adsorption isotherm

model was best fitted to the Langmuir isotherm with an R-squared value of 0.972 compared to the Freundlich model with an R-squared value of 0.90. The electrolysis time remained the significant parameter in COD removal from oily wastewater followed by current density and pH. Furthermore, the energy and electrode consumption were determined as 0.363 kWh/kg COD and 36.91 g/kg COD, respectively under optimum condition. The total treatment cost was found as 0.80 \$/kg COD removed. The graphical charts were considered to show the effects of procedural parameters on COD removal. The study found that this perforated reactor has the potential to treat oily wastewater.

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Conflict of interests

The authors declare no conflict of interest.

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