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Statistical optimization of electrocoagulation for restaurant wastewater treatment using Box–Behnken design

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The discharge of untreated restaurant wastewater into the environment poses significant risks to receiving water bodies due to its high load of organic matter, fats, oils, grease (FOG), and detergent-based chemicals. In this study, electrocoagulation (EC) with aluminium electrodes in batch mode was investigated for the treatment of raw restaurant wastewater under varying operational conditions, namely applied voltage, initial pH, inter-electrode distance, and electrolysis time. A Box–Behnken response surface design (BBD) of RSM with four factors at five levels has been employed to optimize the process variables with the dual objective of maximizing COD removal while minimizing power consumption. ANOVA results and Pareto chart analysis highlighted the relative significance of each factor and their interactions, with voltage and electrolysis time emerging as the dominant contributors. The optimized conditions—15.1 V, pH 7.51, inter-electrode distance 0.83 cm, and 55.32 min—achieved a maximum COD removal of 84.8% and a minimum power consumption of 30.1 kWh/m³. Furthermore, a comparative evaluation with literature on different wastewater streams demonstrated the applicability and competitiveness of EC for restaurant wastewater treatment.

Keywords: COD removal, Electrocoagulation, Restaurant wastewater, RSM, Wastewater treatment

Introduction

India is a home for growing hospitality sector with a divergent range of establishments in many fields. According to the reports as of now it is estimated that, there are over 95,000 hotels in the country, ranging from luxury resorts to budget lodging. Water is an essential natural resource crucial for the survival of humans and all living organisms. However, the waste produced from various activities can be substantial and poses serious health risks[1]. The wastewater that gets discharged from restaurants can cause serious threat to the environment and cause several consequences to the ecosystem. The restaurant wastewater is typically characterized for the high levels of fats, greases (FOGs), oils and other organic matter present in the wastewater, which possess the serious challenges for traditional treatment methods[2]. It is reported that wastewater is the raw sewage which has the elevated amount of the BOD and COD[3]. The one of the most important features of the restaurant wastewater is the presence of the high amount of the FOGs which can cause the blockages in the sewage system[3]. The restaurant wastewater usually warmer in nature than the domestic wastewater due to the continuous use of the hot water during the cleaning and dishwashing processes which it affects the biological treatment. The detergents and disinfectants can leads to the increase the chemical load. The oils and grease contained in the wastewater will start to aggregate over a certain period of time and cause serious of unpleasant smell in and around. The wastewater from the restaurants are sometimes untreated, and cost-effective treatment solutions are crucial applied due to the less profit margins most restaurants operate with it. Ensuring that, both low capital and operating costs is essential to maintain the profit and as the same time. It is necessary to treat and reuse the water in order to reduce the oxygen depletion in the atmosphere[4].

Electrocoagulation (EC), a separation technique offers prominent treatment techniques to treat the wastewater[5]. This process offers a straightforward and the efficient approach for treating the high oil content wastewater. Coagulation is a technique that involves the aggregation of pollutants and suspended particles and insoluble complexes, the process occurs when particles collide together there by leading to agglomeration and subsequent sedimentation. The mechanism of EC follows three steps includes: electrolysis of electrode, coagulant formation, flocculation, electro flotation, sedimentation and separation[6].

EC uses metal electrodes, such as aluminium or iron, hence an electrical current is applied over the electrodes, metal ions such as Al^{3+} or Fe^{2+}/Fe^{3+} are released from the anode side into the wastewater, by the same time water is reduced at the cathode side, producing the hydrogen gas and hydroxyl ions. The metal ions hydrolyse in the water to form metal hydroxides which act as an effective coagulants[7]. These hydroxides usually have a high surface area and can adsorb and neutralize pollutants such as suspended solids (SS), organic compounds in the wastewater, through continuous process they generate metal ions that facilitates the coagulation and subsequent removal of pollutants through sedimentation process. EC can able to treat higher organic, inorganic, and pathogenic contaminants in water and wastewater systems and are to proven to be effective in reducing various pollutants, such as fat, oil, grease (FOGs)[8], chemical oxygen demand (COD), and total suspended solids (TSS)[9].

EC is more advantageous because it does not require any of the external chemicals and additives to be added in reducing the pollutants present in the wastewater and it usually produces less by-products, making it more cost-effective[10]. It can be applied to treat the domestic, seawater and other industrial waste water[11].

The main aim of this paper is to provide the in-depth knowledge of EC for the treatment of restaurant wastewater and its optimization through RSM, to achieve efficient pollutant removal. This works contributes to the growing body of research on sustainable way to treat the wastewater.

Experimental Section

Wastewater collection and characterization

Restaurant wastewater was collected from a local restaurant in Coimbatore, Tamil Nadu, India and stored at 4°C until further use. All the chemicals used in the study including potassium dichromate, silver sulphate, concentrated sulphuric acid, ferrous ammonium sulphate, ferrion indicator, sodium hydroxide and acetic acid were of analytical grade and purchased from SD fine chemicals, Mumbai, India. Closed reflux titrimetric method was used for analyzing COD of wastewater samples before and after treatment. The basic physio-chemical characteristics of wastewater including pH, conductivity and Total Dissolved Solids (TDS) were measured using a multiparameter analyzer.

Experimental set-up and procedure

A simple set-up was used for EC process, where a 1 L beaker was placed on a magnetic stirrer with 500 mL of wastewater and two aluminium electrodes (20 cm × 7 cm) were positioned vertically parallel to each other with 1 cm gap from the bottom of the beaker. Though both Al and Fe electrodes are most widely used for electrocoagulation process[12], Al is preferred here as it tends to form lighter and stable flocs compared to Fe. The effective electrode surface area of electrode in the EC set-up was 70 cm^2. A DC power supply was connected to the electrodes, offering adjustable output with a voltage range of 0 to 30 V. The magnetic stirrer was operated with a speed of 300 rpm to maintain uniformity during the EC operation.

Statistical experimental design

Response surface methodology (RSM) is a popular statistical approach for designing experiments and is helpful for optimizing many processes. Using the Box-Behnken design (BBD) technique under RSM, the experimental settings for the treatment of restaurant wastewater by electorcoagulation were optimized in this study[13]. BBD is preferred here over CCD (Central Composite Design), as it requires fewer experiments, keeps factor levels within practical ranges and avoids extreme operating conditions[14]. A BBD with four components and two responses was designed. The four factors include voltage, pH, inter-electrode distance and reaction time. The responses include COD removal and power consumption. Table 1 presents the specified ranges and levels of variables for the four factor three level BBD. According to the conditions of each run, initial pH of wastewater was adjusted either using sodium hydroxide or acetic acid, inter electrode distance adjusted, voltage supplied and EC process was carried out for the specific time.

Table 1 — Range and levels of independent components

Variable	Unit	Symbol	-1	0	+1
Voltage	V	A	10	15	20
pH		B	4.5	6.25	8
Inter electrode distance	cm	C	0.5	1.5	2
Time	min	D	15	37.5	60

Results and Discussion

Characteristics of restaurant wastewater

The collected wastewater was mixed thoroughly before taking sample for analysis. The COD of the wastewater was found to be 5600-5950 mg/L using closed reflux titrimetric method. The average pH of the wastewater was 4.05 - 4.84. The restaurant wastewater had an average conductivity of 2.9 mS/cm and a TDS of 1450 ppm.

EC for restaurant wastewater treatment - Optimization by RSM based BBD

In order to maximize the COD removal efficiency with least power consumption, and to analyze the relationship between the four factors - initial pH, initial voltage, inter electrode distance and electrolysis time, RSM - BBD was utilized in this study. According to the run table generated by RSM, electrocoagulation experiments were conducted and the two responses - COD removal percentage and power consumption were measured. Table 2 presents the details of the runs and the responses.

The BBD results were subjected to multiple regression analysis. Table 3 represents the fit summary of COD removal efficiency for EC process, while Table 4 represents the fit summary of power consumption for the process. They both suggest that quadratic model is the best fitting one for the acquired data. Eq. (1) illustrates the impact of four factors—Voltage (A), pH (B), inter-electrode

Table 2 — Experimental design matrix as suggested by BBD

Run	Factor 1 A:Voltage	Factor 2 B:pH	Factor 3 C:Inter electrode distance	Factor 4 D:Time	Response 1 COD removal		Response 2 Power Consumption	
					Actual Value	Predicted Value	Actual Value	Predicted Value
Units	V		cm	minutes	%	%	kWh/m^3	kWh/m^3
1	10	8	1.25	37.5	52.6	56.79	8.1	6.80
2	20	6.25	2	37.5	53.62	53.35	17.5	19.01
3	10	6.25	1.25	15	43.3	41.37	2.5	3.81
4	10	6.25	2	37.5	58.71	59.15	5.38	5.53
5	15	4.5	1.25	60	65.67	64.92	21.2	23.43
6	15	8	2	37.5	53.84	51.41	10.3	9.75
7	15	4.5	0.5	37.5	45.5	48.48	17.7	18.62
8	15	6.25	1.25	37.5	64.45	64.45	11.75	11.06
9	15	6.25	1.25	37.5	63.4	64.45	10.5	11.06
10	10	4.5	1.25	37.5	49.6	50.03	6.88	5.00
11	15	6.25	1.25	37.5	65.5	64.45	10.92	11.06
12	15	4.5	1.25	15	37.8	37.67	6.05	7.60
13	10	6.25	1.25	60	72.78	70.92	11.9	13.29
14	15	6.25	2	15	38.71	39.22	9.86	10.64
15	20	6.25	1.25	60	76.2	78.69	42	41.06
16	20	6.25	1.25	15	35	37.42	14.9	13.89
17	20	4.5	1.25	37.5	53.3	50.09	25.63	24.72
18	15	8	0.5	37.5	72.5	72.38	19.38	21.66
19	15	6.25	0.5	60	79.85	80.32	41.83	38.84
20	15	8	1.25	15	38.9	38.12	6.49	6.10
21	20	8	1.25	37.5	60	60.55	25.25	24.92
22	15	4.5	2	37.5	57.4	58.08	12.69	10.79
23	20	6.25	0.5	37.5	68.71	66.74	32.63	34.32
24	15	6.25	0.5	15	46.1	46.01	9	6.76
25	15	6.25	2	60	74.67	75.74	15.2	15.22
26	10	6.25	0.5	37.5	58.38	57.12	9.63	9.96
27	15	8	1.25	60	83.1	81.69	26.63	26.92

Table 3 — Fit summary and fit statistics of COD removal for EC process

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.0309	0.8264	0.7810	
2FI	0.0216	0.0493	0.8963	0.8439	
Quadratic	0.0013	0.1375	0.9658	0.9108	Suggested
Cubic	0.1209	0.2331	0.9572	0.7812	Aliased

Table 4 — Fit summary and fit statistics of power consumption for EC process

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.0170	0.8045	0.7520	
2FI	0.0045	0.0342	0.9068	0.8667	
Quadratic	0.0042	0.0783	0.9620	0.8999	Suggested
Cubic	0.5799	0.0457	0.9596	0.1445	Aliased

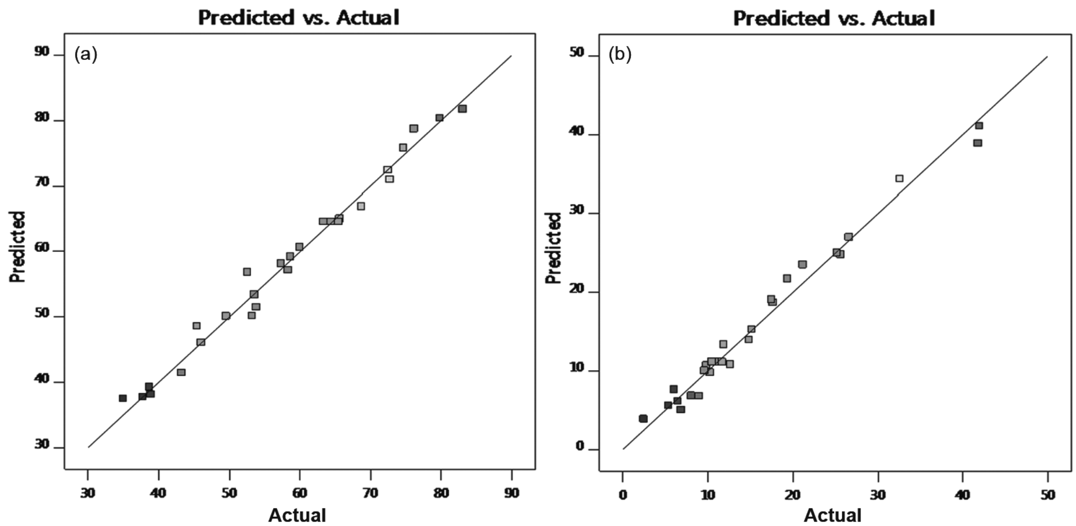

Fig. 1 — Relationship between expected and actual values for (a) COD elimination percentage and (b) power consumption, for EC

distance (C), and time (D)—on the response of COD removal (R1).

$$\text{COD removal (\%)} = 64.45 + 0.9550A + 4.31B - 2.84C + 17.71D + 0.9250AB - 3.85AC + 2.93AD - 7.64BC + 4.08BD + 0.5525CD - 4.29A^2 - 5.79B^2 - 1.07C^2 - 3.06D^2 \quad \ldots (1)$$

Eq. (2) illustrates the impact of four factors—Voltage (A), pH (B), inter-electrode distance (C), and time (D)—on the response of power consumption (R2).

$$\text{Power Consumption (kWh/m}^3\text{)} = 11.06 + 9.46A + 0.5000B - 4.94C + 9.16D - 0.4000AB - 2.72AC + 4.42AD - 1.02BC + 1.25BD - 6.87CD + 3.15A^2 + 1.15B^2 + 3.00C^2 + 3.81D^2 \quad \ldots (2)$$

Assessing the suitability of the suggested model is a crucial phase in the analytical process. A decent approximating model ensures that the results are not misleading or erroneous by providing a sufficient approximation. The expected and actual values from the model are compared in Fig. 1 (a) and (b). It was found that the diagonal line centered the data points, and that the experimental values and the model predictions agreed with each other.

The analysis of variance for these two quadratic equations were extremely significant ($p<0.0001$) as can be observed from the ANOVA tables (Table 5 & Table 6). The experiment showed that these second-order polynomial equations may be used to forecast the COD elimination % and power consumption by the EC process in a satisfactory manner. The quadratic equation was validated by looking at the regression coefficients R^2, which show how well the equation fits data. The predicted R^2 of 0.9108 and adjusted R^2 of 0.9658 confirm the quadratic model's suitability for predicting COD removal efficiency. Similarly, the predicted R^2 of 0.8999 and adjusted R^2 of 0.9620 confirm the quadratic model's suitability for predicting power consumption.

Table 5 — EC - Analysis of variance (ANOVA) and regression model validation for Quadratic model of COD removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4720.92	14	337.21	53.51	< 0.0001	significant
A-Voltage	10.94	1	10.94	1.74	0.2122	
B-pH	222.48	1	222.48	35.30	< 0.0001	
C-Inter electrode distance	96.84	1	96.84	15.37	0.0020	
D-Time	3761.60	1	3761.60	596.89	< 0.0001	
AB	3.42	1	3.42	0.5431	0.4753	
AC	59.44	1	59.44	9.43	0.0097	
AD	34.34	1	34.34	5.45	0.0378	
BC	233.48	1	233.48	37.05	< 0.0001	
BD	66.67	1	66.67	10.58	0.0069	
CD	1.22	1	1.22	0.1938	0.6676	
A^2	98.31	1	98.31	15.60	0.0019	
B^2	178.92	1	178.92	28.39	0.0002	
C^2	6.10	1	6.10	0.9682	0.3446	
D^2	49.88	1	49.88	7.92	0.0156	
Residual	75.62	12	6.30			
Lack of Fit	73.42	10	7.34	6.66	0.1375	not significant
Pure Error	2.21	2	1.10			
Cor Total	4796.54	26				

Table 6 — EC - Analysis of variance (ANOVA) and regression model validation for Quadratic model of power consumption

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2798.20	14	199.87	47.97	< 0.0001	significant
A-Voltage	1073.90	1	1073.90	257.72	< 0.0001	
B-pH	3.00	1	3.00	0.7200	0.4128	
C-Inter electrode distance	292.45	1	292.45	70.18	< 0.0001	
D-Time	1007.60	1	1007.60	241.81	< 0.0001	
AB	0.6400	1	0.6400	0.1536	0.7020	
AC	29.59	1	29.59	7.10	0.0206	
AD	78.32	1	78.32	18.80	0.0010	
BC	4.14	1	4.14	0.9938	0.3385	
BD	6.23	1	6.23	1.49	0.2451	
CD	188.93	1	188.93	45.34	< 0.0001	
A^2	52.91	1	52.91	12.70	0.0039	
B^2	7.05	1	7.05	1.69	0.2178	
C^2	47.99	1	47.99	11.52	0.0053	
D^2	77.30	1	77.30	18.55	0.0010	
Residual	50.00	12	4.17			
Lack of Fit	49.19	10	4.92	12.16	0.0783	not significant
Pure Error	0.8093	2	0.4046			
Cor Total	2848.21	26				

Effect of operating parameters of EC on COD removal and power consumption

In general, when any of the four independent variable is increased, it leads to an increase in COD removal efficiency[15]. But the pattern is observed only till an optimum value is reached. After that, decline in COD removal could be observed. With respect to power consumption, voltage and time has a similar effect as COD removal, while the pH does not have any significant effect on it. Regarding inter electrode distance, decrease in power consumption was observed as the distance between the cathode and anode is increased[16]. As the effect of individual parameters - voltage, initial pH, inter electrode distance and electrolysis time during EC of restaurant wastewater have been assessed in detail already by many researchers[17], the interaction between operating parameters will be discussed in detail here.

Impact of interaction between factors for COD removal

As can be observed from the Fig. 2, among the six parameters interaction - AB, AC, AD, BC, BD and CD for response 1 COD removal, the most significant interaction is between pH and inter electrode distance (BC). For the least inter electrode distance and maximum pH, the best COD removal efficiency has been attained[18]. The factors pH and electrolysis time

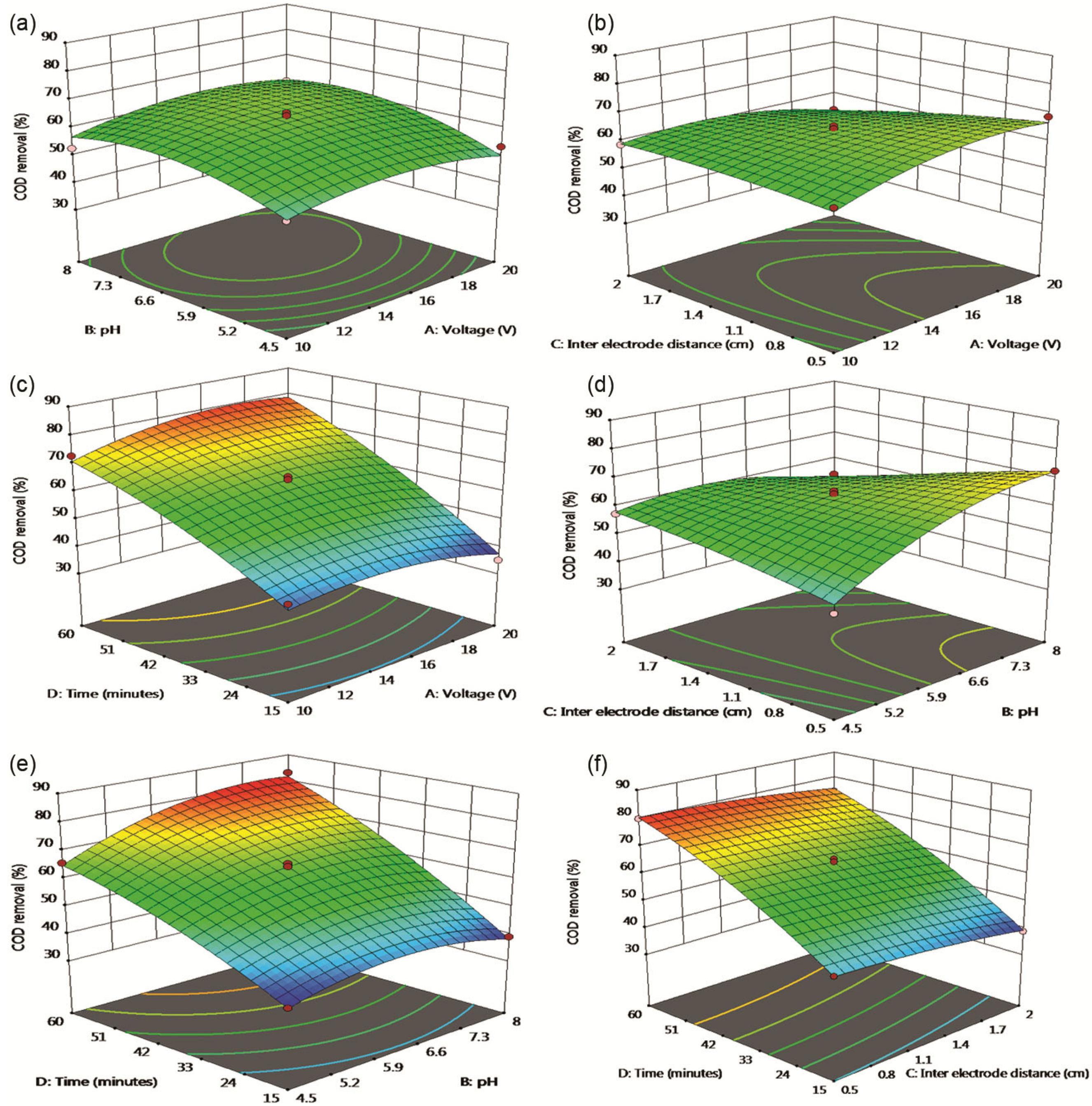

Fig. 2 — Effect of interaction between factors on COD removal: (a) voltage and pH, (b) voltage and inter electrode distance, (c) voltage and time, (d) pH and inter electrode distance, (e) pH and time and (f) time and inter electrode distance

(BD) also have significant interaction effect as increase in pH as well as time gives a steady increase in COD removal[19]. Similarly, the factors voltage and inter electrode distance (AC) also have a significant interaction effect on, as least inter electrode distance and highest voltage has attained maximum COD removal[20]. Comparatively, a less interaction is observed between the factors time and voltage (AD), even though both of them influences COD removal percentage positively[21]. On the other hand, insignificant interaction is observed between the factors pH and voltage (AB) as well as inter electrode distance and time (CD) as the p value is more than 0.05[22].

Impact of interaction between factors for power consumption

For the response 2 power consumption, the effects of interaction between parameters are all depicted in the Fig. 3. As observed from the figures and ANOVA table, the most significant interaction effect is between the factors inter electrode distance and time

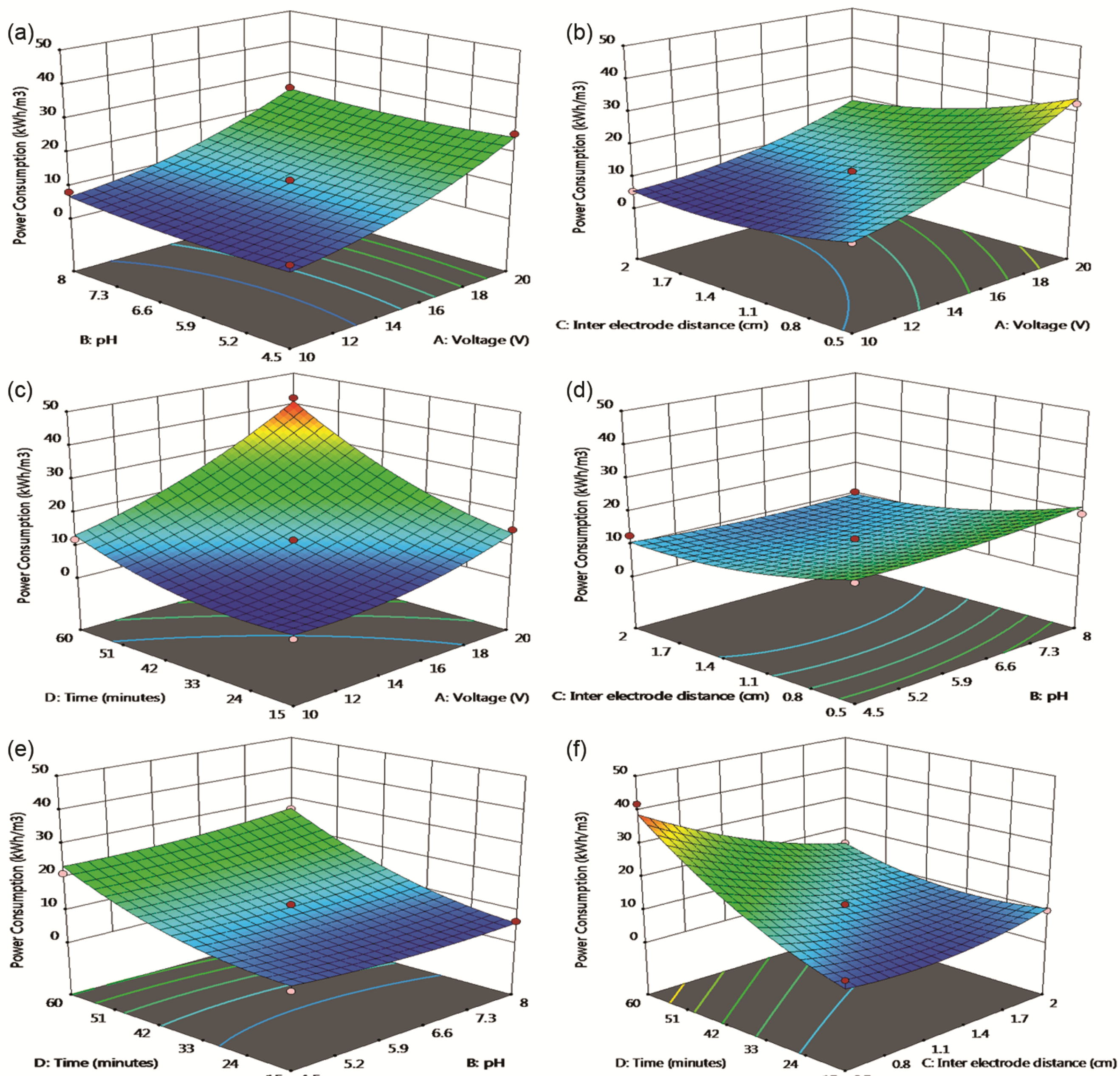

Fig. 3 — Effect of interaction between factors on power consumption (a) voltage and pH, (b) voltage and inter electrode distance, (c) voltage and time, (d) pH and inter electrode distance, (e) pH and time and (f) time and inter electrode distance

(CD). The least time of 15 min and least inter electrode distance of 0.5 cm has consumed the least power. Similarly, many authors have reported that increasing the time, increases metal dissolution during the EC process, thus consuming more power[23]. Next to it, the interaction effect between the factors time and voltage (AD) is also significant. Increasing the voltage to the maximum value of 20 V leads to a power consumption of 14.9 kWh/m^3 and increasing the time to its maximum value of 60 min leads to a power consumption of 11.9 kWh/m^3. But together, when time and voltage are maximized, a peak power consumption of 42 kWh/m^3 is attained[24]. Another significant effect is found on the interaction between parameters inter electrode distance and voltage (AC). The other three combinations AB, BC and BD, corresponding to the pH with all other 3 parameters voltage, inter electrode distance and time had insignificant effect on each other. This case was expected as pH itself did not have any significant effect on the power consumption[25].

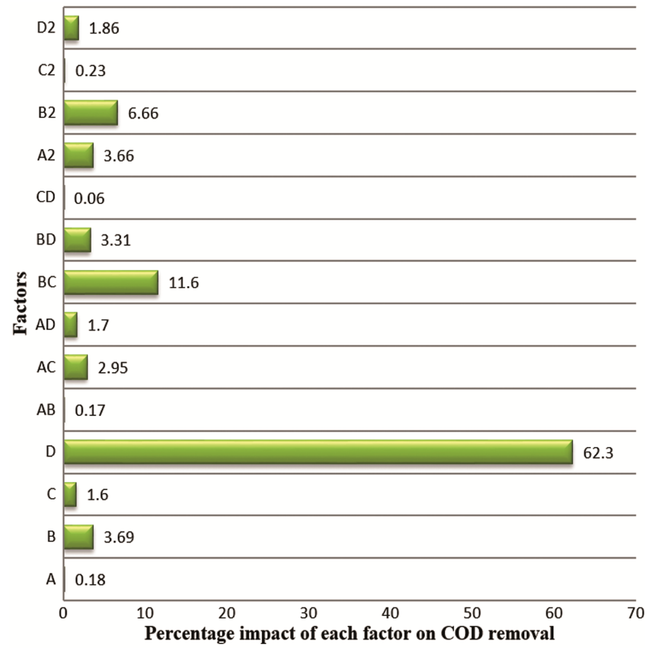

Fig. 4 — Pareto analysis of impact of factors and their interaction on COD removal

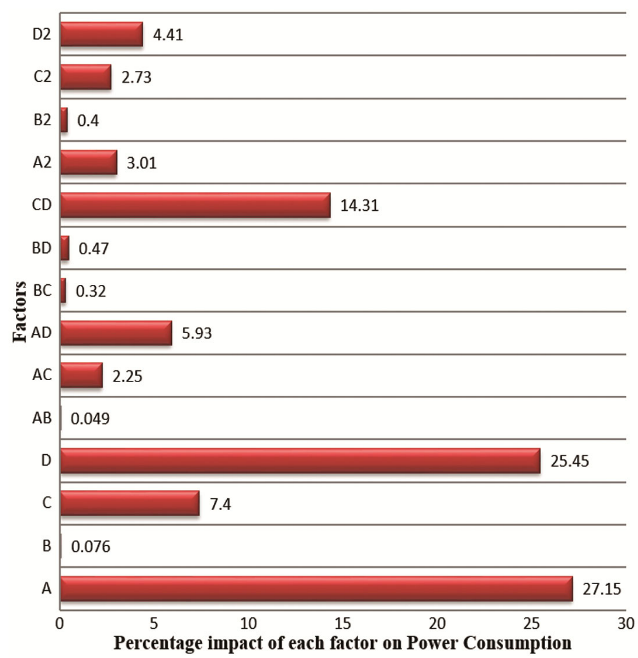

Fig. 5 — Pareto analysis of impact of factors and their interaction on power consumption

Pareto analysis

The Pareto chart analysis was carried out to evaluate the relative significance of the operating variables and their interactions on COD removal efficiency and power consumption[26]. For COD removal, the quadratic and interaction terms were considered along with the linear factors to assess their overall contribution. The analysis revealed that electrolysis time (D) was the most influential factor, followed by pH (B) and the interaction between pH and time (BD). The contributions of voltage (A) and inter-electrode distance (C) were comparatively lower (Fig. 4).

In contrast, the Pareto analysis of the power consumption model indicated that voltage (A) and electrolysis time (D) were the dominant factors, significantly affecting the energy requirements of the EC process (Fig. 5). Among the interaction and quadratic terms, A^2, D^2, and AD showed noticeable effects, while pH and inter-electrode distance had only minor influence.

Overall, the Pareto charts clearly demonstrate that optimizing time and voltage is critical, as these parameters jointly govern both the treatment efficiency and the operational cost of the EC process.

Optimization and validation

Using the BBD of RSM, optimal conditions for achieving maximum COD removal efficiency and minimum power consumption were determined through the numerical optimization tool in Design Expert software[27] and the resulted are shown in Fig. 6. The software predicted a maximum COD removal efficiency of 83.2%, with a minimum power consumption of 29.9 kWh/m^3. This prediction was

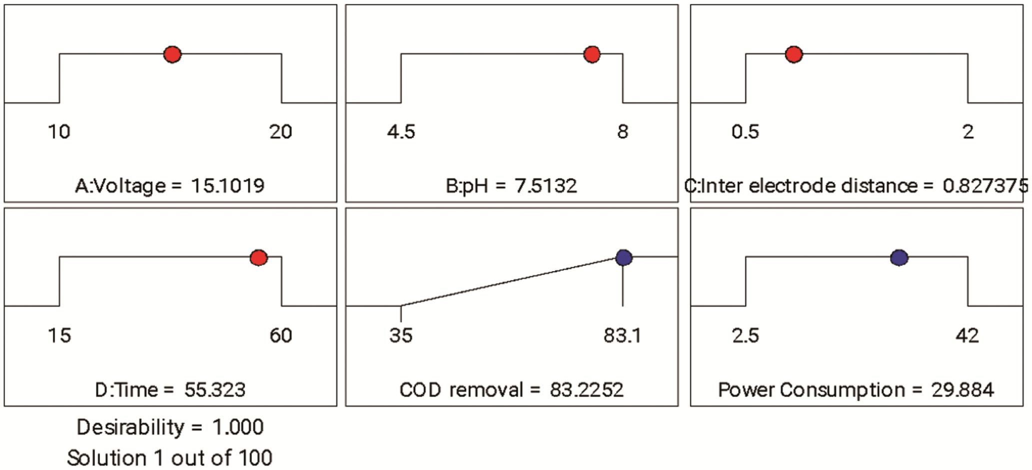

Fig. 6 — Optimized treatment conditions and predicted responses

Table 7 — Comparison of treatment efficiency of different wastewaters by electrocoagulation process under optimized conditions

Type of Wastewater	Electrode Combination	Optimized operating conditions	COD Removal Efficiency	Energy Consumption/ Cost	References
Corrugated box industrial effluent	SS-SS	Current density of 15 mA/cm^2, stirring speed of 700 rpm, treatment time of 28 min	80.9% COD removal	6.7 Wh/g	16
Real graywater	Fe-Fe	Voltage of 14 V, pH of 7.35, treatment time 47 min	75.6% COD removal	0.7 US$/kg COD	28
Rainwater	Al-Al	Current density of 3.26 mA/cm^2, treatment time of 11.38 min	70.83% COD removal	1.04 and 5.25 USD/m^3	29
Hospital wastewater	Fe-Fe	Electric current of 0.09 A, electrolyte concentration of 3 g/L, pH of 7	97.02% COD removal	36kWh/m^3	17
Landfill leachate	Fe-Fe	Current density 16 mA/cm^2, pH of 8.05, inter-electrode distance of 9 mm, treatment time of 60 min	72.13% COD removal	1.41 US$ /kg COD	30
Restaurant wastewater	Al-Al	Voltage of 15.1 V, pH of 7.51, inter-electrode distance of 0.83 cm, and an electrolysis time of 55.32 minutes	84.8% COD removal	30.1 kWh/m^3	This study

validated with additional experiments, confirming a mean Chemical oxygen demand removal of 84.8% and energy usage of 30.1 kWh/m^3 for EC of restaurant wastewater under the specified conditions.

Table 7 summarizes various studies on COD removal efficiency from different types of wastewater using the EC process under optimized conditions. The obtained optimized conditions and the response values align with those reported in the literature as can be seen from the table.

Conclusion

The present research has thus investigated the COD removal efficiency of electrocoagulation process for treating restaurant wastewater with least energy consumption. An empirical relationship between the output and independent variables was established from the experimental data and expressed through a quadratic model using RSM. The results indicated that the maximum colour removal of 84.8% and minimum power consumption of 30.1 kWh/m^3 were achieved at the optimal conditions: voltage of 15.1 V, pH of 7.51, inter-electrode distance of 0.83 cm, and an electrolysis time of 55.32 minutes. Electrocoagulation, being a simple physio-chemical technique can reduce COD very efficiently in a eco-friendly way. Future research could investigate the long-term stability of this system and its effectiveness with other types of industrial effluents, further enhancing the method for wider industrial-scale applications.

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Conflict of interest

The authors declare no conflict of interest.

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