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Evaluating the performance of an electrocoagulation process using response surface methods for textile wastewater treatment

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HIGHLIGHTS

- Electrocoagulation was evaluated for textile wastewater treatment using Response Surface Methodology
- pH, voltage, and electrolysis time significantly affected COD and color removal efficiency
- Optimal removal occurred at pH 7, electrolysis time 60 min, and 11 V, achieving high treatment performance
- Statistical models showed strong predictive accuracy, confirming key influential parameters
- Results supported electrocoagulation as a low-cost, energy-efficient treatment for textile wastewater

Keywords:

Electrocoagulation; Wastewater; Textile; Optimization; Contaminants; Treatment.

ABSTRACT

The textile industry is one of the largest polluters of water resources, producing effluents containing complex mixtures of pollutants such as dyes, heavy metals, and high biological oxygen demand. Electrocoagulation (EC) is an efficient wastewater treatment technique that uses iron or aluminum electrodes to coagulate and adsorb pollutants. This work assesses the performance of EC for textile wastewater treatment to identify the best combination of pH (5-9), electrolysis time (20-60 min), and voltage (5-11 V) on Chemical Oxygen Demand (COD) and color removal. The results show that voltage and electrolysis time had a positive effect on the efficiencies of pollutant removal, reaching the maximum efficiency of 70.06 and 87.36 when pH was 7, electrolysis time 60 min, and 11 V. The quadratic regression models obtained by Response Surface Methodology (RSM) had good predictive ability with the adjusted R^2 of 0.9684 for COD and 0.9843 for color. Statistical significance of the pH, voltage, and their interaction was further verified using the ANOVA test as significant factors that helped to explain the treatment effect. This study also highlights the possibility of using EC as a cost-effective and energy-saving technology compared to conventional chemical coagulation and advanced oxidation processes, with satisfactory treatment obtained at modest voltage and time demands. The study contributes to the knowledge of parameter optimization and enhances the applicability of EC in reducing the effects of textile effluents on the environment.

1. Introduction

The global textile sector alone is heavily responsible for water pollution and uses more than 100,000 different dyes. More than 700,000 tons of dye-rich material are produced annually. The wastewater discharged from textile dyeing industries has a complex waste composition, which differs with fabric type, quality, and finishing steps. Steps involved in textile processing include sizing, scouring, bleaching, dyeing, printing, and finishing. Each of these steps generates immense amounts of effluent that contains a different and complex composition of contaminants. Some of the major contaminants associated with textile dyeing and its effluents are dyes, dissolved and suspended solids, salts, coloring materials, heavy metals, and total phosphates [1]. In Nigeria, there are serious environmental consequences of textile wastewaters that encompass toxic pollutants that negatively affect aquatic life and human health; thus, it becomes necessary to adopt efficient treatment methods like electrocoagulation [2,3]. This study addresses the gap in optimized electrocoagulation parameters for decentralized, small-scale textile dyeing operations that are prevalent in Nigeria and similar developing economies, which are often not regulated by regulatory agencies. Despite the extensive literature on electrocoagulation in various wastewaters, a significant gap remains in achieving

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full optimization of parameters for textile wastewater treatment using simultaneous multi-response optimization, which targets both COD and color removal efficiency. The ecology of these discharges is catastrophic and complicated since dyes in waterbodies decrease penetration of light, disrupt aquatic ecosystems, and cause an increase in chemical oxygen demand. Textile effluents also influence the number of dissolved gases absorbed in large water bodies, adjust the redox potential, and have organic and nutrient contents. They contain carcinogenic compounds, mainly characterized by high color intensity, extreme pH levels 2 and above or 12 and above, high organic content, and low biodegradability.

Traditional techniques, such as biological oxidation, chemical coagulation, and physical filtration, often fail to effectively treat complex pollutants in textile wastewater, particularly synthetic dyes, which are highly persistent and non-biodegradable. Such methods usually lead to inadequate decolorization and produce large amounts of sludge, which is why more advanced methods such as electrocoagulation should be used, as it is more efficient and less harmful to the environment [1,4,5]. Electrocoagulation (EC) has emerged as a promising treatment technology that combines multiple physicochemical processes, including the spontaneous generation of metal hydroxides that subsequently coagulate organic pollutants through charge neutralization, surface complexation, and adsorption. The electrode metal of choice is either iron or aluminum, also used to treat effluents from tanneries or textile mills to bio-digesters [6].

Some research indicated potential cost benefits of EC compared to conventional treatment methods, though comprehensive comparative studies are limited [3,7]. Research indicates that operational parameters during electrolysis, particularly electrolysis time, significantly affect the efficiency of contaminant removal. These parameters have been optimized using Response Surface Methodology (RSM) for high removal of chemical oxygen demand (COD) level, as stated by Gündüz, and Atabey [8]. The initial pH level is crucial, as it determines the efficacy of the EC across the textile wastewater pH spectrum, as identified by Hanako and Bagastyo [7]. In a previous study on the treatment of Batik wastewater, an initial pH level of 3 – 11 influenced the outcome of the experimental study in the removal of COD and color [9]. Moreover, factors such as voltage settings and the type of electrodes (aluminum or iron) affect the efficiency of pollutant removal. Research has also been done to increase the performance of both the Fe-Al anodes [10].

RSM is used to assess EC efficiency to enhance textile wastewater treatment independently, making it feasible to optimize the processes' parameters toward contaminant elimination [11]. The objective of this study is to assess the EC performance based on RSM and determine the effect of the process parameters, including electrolysis time, pH, and voltage, on color and COD reduction. EC technology has the advantage of being capable of operating under very high current densities. Still, the most important aspect of the EC method is that the operating conditions can be tailored towards achieving high treatment efficiency at the lowest possible energy cost. Appropriate conditions for practical utilization in the textile wastewater treatment are the knowledge that is sought after in the study [12].

2. Materials and methods

2.1 Characterization and sampling of textile wastewater

Textile wastewater was collected from a local dyeing center located at Asero in Abeokuta, Nigeria, after textile processing activities. Initial parameters such as pH, chemical oxygen demand (COD), color intensity, and electrical conductivity were determined on the wastewater samples. New samples were taken in polyethylene bottles and kept at 4 ºC to avoid degradation. Preliminary characterization indicated that the textile wastewater had typical properties of textile wastewater with high COD values of 730-1500 mg/L, strong coloration, and alkaline pH conditions typical of dyeing processes.

2.2 Electrocoagulation process

The electrocoagulation system was composed of aluminum and iron electrodes placed in a circular reactor. The experimental system was run in batch mode, with the main operating parameters being voltage (5-11 V), initial pH adjustment (5-9), and electrolysis time (20-60 minutes). Before each experiment, the electrodes were cleaned with a dilute HCl solution and washed with distilled water. In operation, the anode released aluminum ions by oxidation, which formed different hydroxide species that destabilized the pollutants by charge neutralization and sweep coagulation processes. Figure 1 shows the electrocoagulation experimental system.

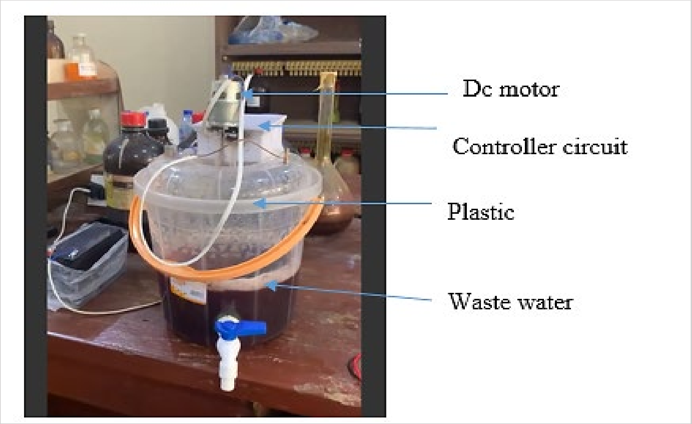

Figure 1: The electrocoagulation experimental system

2.3 Analytical methods

Water quality parameters were evaluated using standard methods as per (APHA 5220D). The Chemical Oxygen Demand (COD) was determined by the closed reflux colorimetric method using a spectrophotometer with a wavelength of 600 nm [13]. The efficiencies of color removal were determined by measuring the changes in absorbance at the maximum wavelength of the dye using UV-Vis spectrophotometry. Also, the pH was measured using a calibrated digital pH meter. The removal efficiency was calculated using the Equation 1. The removal efficiencies were determined by Equation (1):

$$\text{Removal Efficiency } (\%) = \frac{C_o - C_t}{C_o} \times 100 \tag{1}$$

where C_o is the initial concentration and C_t is the concentration at time t.

2.3.1 Experimental system configuration

The electrocoagulation reactor was a 1-liter cylindrical vessel with aluminum and iron electrodes placed vertically with 3 cm inter-electrode spacing. A DC power supply supplied a constant voltage, and magnetic stirring was done at 120 rpm. The experiments were carried out at ambient temperature (27 °C).

2.3.2 Experimental design parameters

The paper adopted Box-Behnken experimental design (BBDOE) with three factors at three levels to study how process variables influenced the removal of both chemical oxygen demand (COD) and color in the treatment of textile wastewater.

The variables examined were: Electrolysis time: 20-60 minutes, Voltage: 5-11 volts, and pH: 5-9, as shown in Table 1.

Table 1: Levels of the investigated factors in the box behnken design

Factors	**Symbols**	**Levels**		
		-1	**0**	**+1**
pH	**B**	5	7	9
Electrolysis Time (Mins)	**C**	20	40	60
Voltage (V)	**A**	2	4	6

A second-order polynomial model Equation 2 was adopted to assess the correlation between input and output variables:

$$Y_i = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{j=1}^{k-1} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 \tag{2}$$

where: $\mathrm{Y_i}$ = the predicted responses, β_0, β_{i}, β_{I}, and β_{ij} depict constant, linear, quadratic, and cross-factor interaction coefficients respectively; X_i and X_j depict the independent variables and k and C are the number of factors and residual terms, respectively [14]. This approach aimed to comprehensively analyze how changes in input variables influenced the effectiveness of electrocoagulation in treating textile wastewater. By employing BBDOE, the study sought to determine optimal conditions for maximum removal of COD and color, providing valuable insights for improving the EC process.

3. Results and discussion

The factors affecting COD and color removal from textile wastewater were evaluated using a Box-Behnken experimental design. The BBD model with three factors at 3 levels was used to optimize the parameters for color and COD removal. Fifteen (15) experimental runs were implemented using Design Expert version 13 software, and the independent variables were replaced in the BBDOE as $A, B,$ and C. The developed models for COD and color removal were of the second-order polynomial type and are shown in Equations 3 and 4:

$$\%COD = 60.38 - 1.72A + 3.66B + 5.84C + 0.1150AB - 2.68AC + 2.61BC - 18.33A^2 - 2.17B^2 - 0.3300C^2 \tag{3}$$

$$\%COLOR = 66.85 - 1.92A + 5.239B + 10.40C - 1.37AB - 3.09AC - 1.26BC - 1.26\mathrm{BC} - 21.98A^2 - 0.2017B^2 + 6.01C^2 \tag{4}$$

where A, B, and C represent the independent variables, A^2, B^2 and C^2 represent the quadratic terms and AB, AC and BC represent the cross-factor interaction coefficients.

4. Main effects

pH (A) had a negative linear correlation with removal efficiency, with coefficients of -1.72 (COD) and -1.92 (color). These adverse indicators are indicative of the decreased availability or effectiveness of metal hydroxide flocs at extreme pH. The best pH, as confirmed by experimental data, was close to neutral (pH 7), at which iron hydroxide precipitated most efficiently, and the redox potential was optimal. The effect of electrolysis time (B) was positive and consistent with coefficients of +3.66 (COD) and +5.39 (color). Longer treatment times enabled greater degradation and aggregation of pollutants.

Voltage (C) in both models exerted the greatest positive effect on pollutant removal, with coefficients of +5.84 (COD) and +10.40 (color). This implied that the higher the applied voltage, the more the coagulant species (e.g., Fe^{2+}/Fe^{3+} ions) were formed, the faster the electrochemical oxidation process, and the more the gas bubbles were generated to float the pollutants. This effect was particularly large in the case of color removal, indicating that dye molecules were more effectively destabilized electrochemically at higher voltages.

4.1 Interaction effects

The interaction terms showed complicated interdependencies of variables. As an example, the AC (pH x voltage) term was negative in both models (-2.68 COD and -3.09 color), which indicated that the advantages of higher voltage are reduced at sub-optimal pH. On the same note, BC (time x voltage) had a positive impact on COD (+2.61), implying that the longer the treatment time, the more the voltage enhances COD removal. However, its low color value (-1.26) suggests that it may be over-saturated or ineffective for floc formation when time and voltage are high together in dye removal.

4.2 Quadratic terms and curvature

The quadratic terms (A^2, B^2, and C^2) give crucial information about the non-linear behavior of each factor, which is of great importance to process optimization:

1) **A^2 (pH^2):** The negative coefficients are strong (18.33 for COD, 21.98 for color), which means that the curvature is sharp, and indeed, both removal efficiencies are maximized at a narrow range of pH around 7. Any deviation causes a reduction in floc formation and charge neutralization efficiency.
2) **B^2 ($Time^2$):** Slightly negative in both models (-2.17 in COD, -0.2017 in color), indicating that there is a diminishing returns effect when the treatment time is too long. This may be due to the re-stabilization of flocs or increased electrode passivation.
3) **C^2 ($Voltage^2$):** It is interesting to note that C_2 is negative in COD (-0.3300) and positive in color (+6.01). This implies that COD removal stagnates or even reduces at higher voltages. In contrast, color removal continues to increase, indicating the high electrochemical sensitivity of dye molecules to the rising voltage levels.

Table 2 presents the results from 15 experimental runs, evaluating the influence of pH, electrolysis time (in minutes), and voltage (V) on the removal efficiency of Chemical Oxygen Demand (COD) and color. RSM was used to build second-order polynomial regression models of the process variables on the removal efficiency.

The percentages confirmed how critical the pH was to the treatment outcome. In the present work, all conductors showed the best performances under a neutral pH level (pH =7) for both COD and color reduction. This indicates that the electrochemical reactions that could lead to the degradation of pollutants are most efficient at near-neutral pH, probably because of optimal formation of active oxidizing agents. As expected, electrolysis time was another variable that indicated better treatment efficiency of the system. The overall COD and color removals, as parameters of treatment efficiency, were found to be higher for longer treatment times (60 minutes). This pattern of interaction was the most conspicuous at the neutral pH and higher voltage, which also suggests a cross-generative effect between these factors. In addition, there was a direct effect of voltage on the treatment process. Preliminary results showed that higher voltages of 11 V increased the COD and color removal efficiencies, indicating that higher generations of oxidizing agents and efficient electron transfers existed at the higher voltages.

Table 2: Box behnken experimental designs depicting effect of pH, electrolysis time, and voltage

Run	pH	Electrolysis time	Voltage	% Cod	% Colour
1	7	20	11	56.42	78.6
2	9	40	11	44.8	57.76
3	7	40	8	58.66	66.66
4	5	60	8	45.74	54.5
5	9	60	8	40.22	45.1
6	5	40	11	51.26	64.98
7	9	40	5	37.52	42.98
8	7	60	11	70.06	87.36
9	5	20	8	39.76	41.5
10	7	40	8	61.18	67.8
11	7	60	5	54.12	69.26
12	7	20	5	50.92	55.44
13	5	40	5	33.28	37.82
14	7	40	8	61.3	66.1
15	9	20	8	33.78	37.58

From the experiments conducted in this study, the most effective operating conditions were found to be a pH of 7, electrolysis time of 60 minutes, and Voltage of 11 V. The highest COD reduction was 70.06% and the color removal was 87.36% in Run 8. This aligns with previous studies where the EC experiments achieved color removal rates for RB5 at 98.60 % while COD removal rates were up to 95.06 %, respectively [9]. This work serves to underscore the value of parameter optimization in the processes of electrochemical wastewater treatment. However, the impact of both higher electrolysis time and voltage was less expressed at low (4) or high (10) pH. This observation suggests that pH significantly influences treatment effectiveness, potentially negating the benefits of prolonged treatment periods or higher voltages when the pH is suboptimal.

4.3 Model selection and adequacy

Statistical indicators shown in Tables 3 and 4 were used to check the adequacy of the model of the dependence between inputs (pH, electrolysis time, and voltage) and outputs (COD and color removal efficiencies). The quadratic model was the most appropriate model based on the sequential $p < 0.0001$ from the analysis. The p-values for all of the fits are COD: 0.3220, which suggests a good model fit, and color: 0.1229, which also shows a good fit for the model. The adjusted R^2 values for color removal (0.9843) and COD removal (0.9684) indicate high explanatory accuracy. The high predicted R^2 values of 0.9169 for color and 0.8549 for COD indicate strong predictive performance of the model, demonstrating excellent correlation between predicted and observed values.

Table 3: Model statistics for COD

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	0.3840	0.0150	0.0244	-0.4259	
2FI	0.9472	0.0105	-0.2847	-2.0027	
Quadratic	< 0.0001	0.3220	0.9684	0.8549	Suggested
Cubic	0.3220		0.9820		Aliased

Table 4: Model statistics for color

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	0.1742	0.0032	0.1748	-0.3189	
2FI	0.9750	0.0022	-0.1061	-2.0732	
Quadratic	< 0.0001	0.1229	0.9843	0.9169	Suggested
Cubic	0.1229		0.9967		Aliased

4.4 Analysis of variance (ANOVA)

The quadratic models and their terms were compared using Analysis of Variance (ANOVA) for both COD and color removal efficiencies as shown in Tables 5 and 6, respectively. The results revealed that both models were highly significant (COD: The model data reveals the significance of the independent variables on the removal efficiencies as measured by the F-statistic; the values obtained are F-value = 48.70, p-value = 0.0002 for pH and F-value = 98.71, p-value < 0.0001 for color. In the present study, the F-value was higher in the color removal model than in other models, indicating that the model may be sound in its prediction. For both COD and color removal, the experimental exposure time and the applied voltage were established to be very significant ($p < 0.005$). The impact of pH level was found to be significant on color removal ($p = 0.0350$) while it was of marginal significance in relation to COD removal ($p = 0.0574$). It is also strongly suggested that all three factors are significant, although the pH may be relatively more significant in color removal processes.

However, the interaction effect of pH and voltage (DC) was significant for both COD and color ($p < 0.05$), which suggests that the influence of voltage on the removal efficiency depends on the pH level. In this respect, the time-voltage interaction (BC) was significant only for the COD removal ($p =0.0457$), indicating that the relationships between time and voltage are different for other removal processes. The quadratic effect for pH (A^2) had a rather highly significant level, $p < 0.0001$, yielding a strong non-linear effect on both COD and color removal efficiencies. This tends to support the previous positive note that any form of neutral pH situation led to higher removal rates. For color removal, the quadratic term, C^2 voltage, was significantly different at $p = 0.0017$, but that of COD removal was not significantly different, suggesting that at higher levels, fluctuations of voltage may significantly affect color removal efficiency than COD removal efficiency. The lack of fit was not significant for both models (COD: Fitting the quadratic equation, the model validity was proven as there were no systematic deviations in the relationship between the factors and the removal efficiencies ($p = 0.3220$ in pH; $p = 0.1229$ in Color).

4.5 Analysis of three-dimensional response surface plots

To understand the relationship between pH, electrolysis time, and the applied voltage for the removal of COD and color, a three-dimensional response surface plot was established for each, as shown in Figures (2-7). These plots are useful for explaining and supporting our statistical results and for further analyzing our data. In the context of COD removal, all the plots Figures (2-4) depicted a dome-shaped response with regard to pH and maximum COD removal at a near-neutral pH (pH ≈ 7). This visualization is consistent with the strong quadratic effect of pH detected in our statistical model. Both electrolysis time and applied voltage increase with COD removal, and their effects are best seen when the pH is at its optimum. The difference in slope of the response surfaces across the range of pH values demonstrates this. Color removal shares the same general trends Figures (5-7), but there were some differences. Color removal was less sensitive to pH changes than for COD removal, which was evident from the comparison between the two responses, as the dome shape of surface plots depicting the response for color removal is more coherent than that for COD. This is in line with the earlier stated statistical results that showed a better quadratic fit of pH with color removal than with the COD removal. User-study results show that the direction of the effect of the applied voltage on color removal is true to the highly significant quadratic term for the voltage coefficient in the model. Both COD and color removal efficiencies peak under similar conditions: lower hydrogen ion concentration, longer electrolysis time, and increased voltage. Nevertheless, the steepness of the plots of color removal appears to accentuate the dependence of color removal on variation from optimum conditions, especially concerning pH.

Table 5: Analysis of variance (ANOVA) for the quadratic model for COD

Factors	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1707.28	9	189.70	48.70	0.0002	significant
A-pH	23.53	1	23.53	6.04	0.0574	
B-Electrolysis time	107.02	1	107.02	27.47	0.0033	
C-Applied voltage	272.61	1	272.61	69.99	0.0004	
AB	0.0529	1	0.0529	0.0136	0.9118	
AC	28.62	1	28.62	7.35	0.0422	
BC	27.25	1	27.25	7.00	0.0457	
A^2	1241.25	1	1241.25	318.67	< 0.0001	
B^2	17.39	1	17.39	4.46	0.0883	
C^2	0.4021	1	0.4021	0.1032	0.7610	
Residual	19.48	5	3.90			
Lack of Fit	15.03	3	5.01	2.25	0.3220	not significant
Pure Error	4.44	2	2.22			

Table 6: Analysis of variance (ANOVA) for quadratic model for color

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3187.13	9	354.13	98.71	< 0.0001	significant
A-pH	29.57	1	29.57	8.24	0.0350	
B-Electrolysis time	232.20	1	232.20	64.72	0.0005	
C-Applied voltage	865.28	1	865.28	241.19	< 0.0001	
AB	7.51	1	7.51	2.09	0.2076	
AC	38.32	1	38.32	10.68	0.0222	
BC	6.40	1	6.40	1.78	0.2392	
A^2	1784.10	1	1784.10	497.30	< 0.0001	
B^2	0.1502	1	0.1502	0.0419	0.8460	
C^2	133.51	1	133.51	37.22	0.0017	
Residual	17.94	5	3.59			
Lack of Fit	16.44	3	5.48	7.30	0.1229	not significant
Pure Error	1.50	2	0.7505			
Cor Total	3205.06	14				

4.6 Economic and environmental impact analysis

Electrocoagulation (EC) generates iron hydroxides, which are notably less voluminous and more environmentally benign compared to traditional chemically dosed sludge treatment methods. These characteristic underscores the potential of EC in sustainable sludge management, promoting eco-friendly practices that mitigate environmental impacts while effectively treating wastewater [15, 16]. Moreover, the reduced sludge volume from iron hydroxides helps avoid many challenges associated with conventional sludge disposal, illustrating the efficiency of electrocoagulation as a superior sludge management technology. This method presents innovative and sustainable practices that align with contemporary environmental goals, promoting resource recovery and energy efficiency in sludge processing systems [15,16]. Electrocoagulation (EC) presents several environmental and sustainability advantages in wastewater treatment.

Firstly, EC effectively destabilizes and aggregates a wide range of contaminants, including heavy metals and organic compounds, leading to their efficient removal from wastewater without the need for harmful chemical coagulants. This characteristic minimizes the introduction of additional pollutants into the environment, making it an eco-friendlier alternative compared to traditional chemical coagulation methods [17, 18]. Secondly, electrocoagulation operates at a broader range of pH levels and generates less sludge compared to conventional treatment techniques. This allows for simpler disposal options and lower operational costs, facilitating a sustainable approach to wastewater management [19]. Moreover, the production of valuable by-products from the electrocoagulated sludge can further enhance the sustainability of the process [20]. Lastly, EC's potential for integrating renewable energy sources, such as solar power, enhances its sustainability profile. The adaptability of this technology to varying wastewater characteristics makes it suitable for diverse applications, from industrial to municipal wastewater treatment, thus promoting resource conservation and energy efficiency across sectors [21,22].

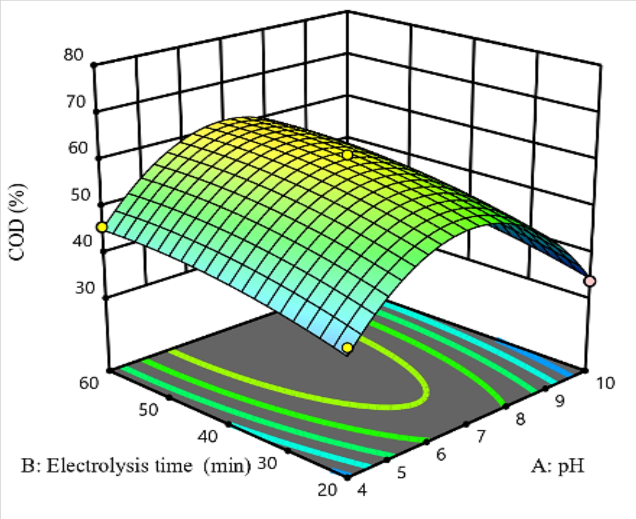

Figure 2: Influence of pH and electrolysis time on COD removal efficiency

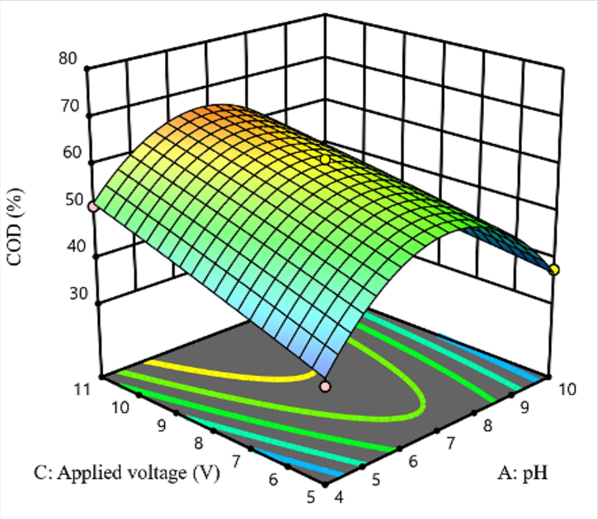

Figure 3: Interactive effect of applied voltage and pH on COD removal efficiency

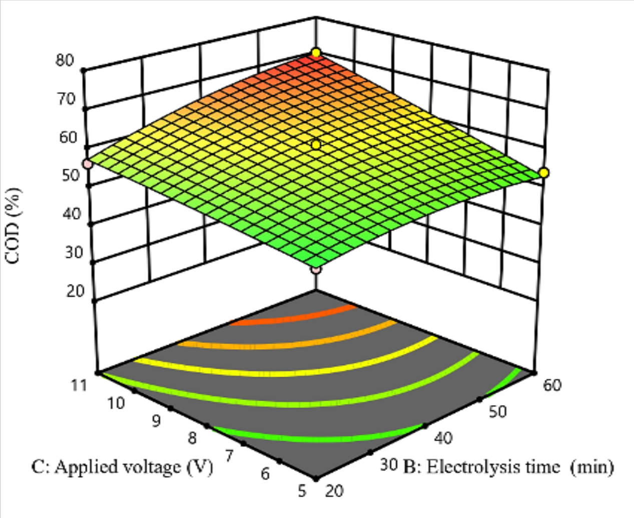

Figure 4: Influence of applied voltage and electrolysis time on COD removal efficiency

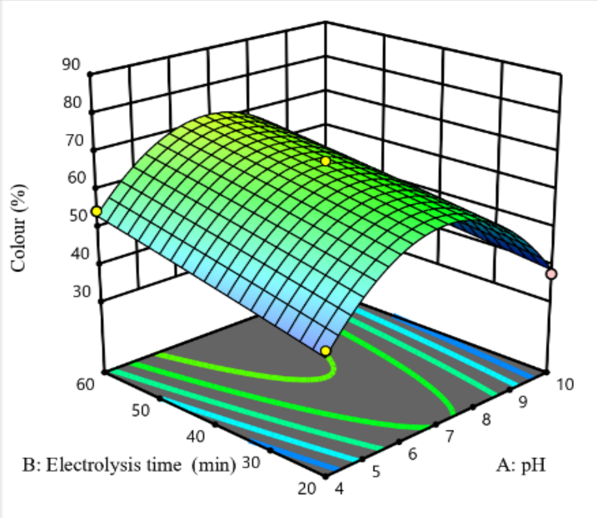

Figure 5: Effect of pH and electrolysis time on color removal efficiency

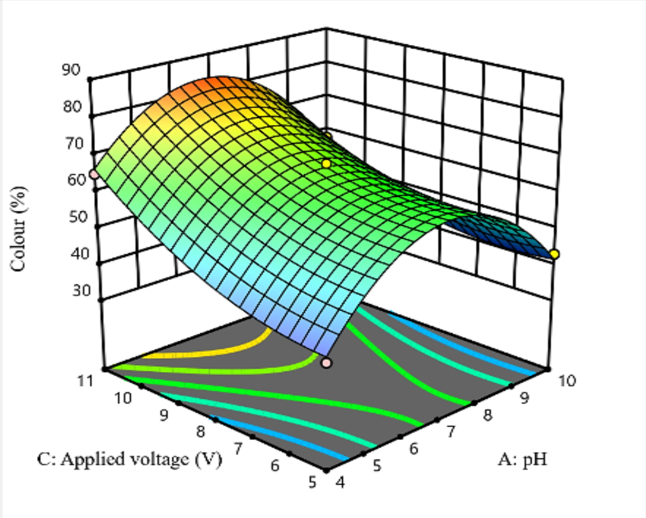

Figure 6: Effect of applied voltage and ph on color removal efficiency

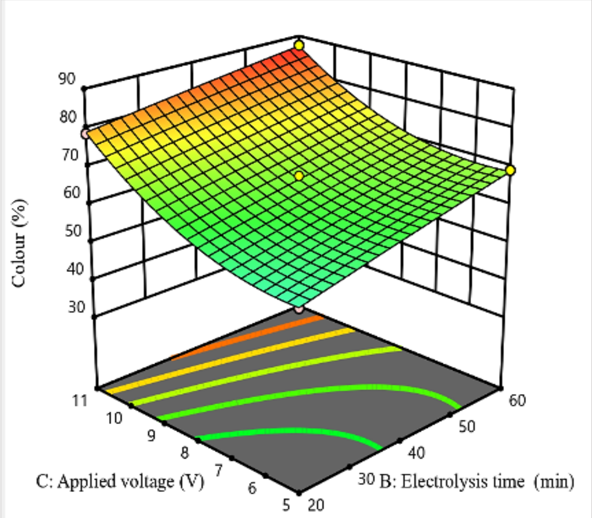

Figure 7: Effect of applied voltage and electrolysis time on color removal efficiency

5. Conclusion

This study successfully evaluated the performance of the electrocoagulation process for textile wastewater treatment using Response Surface Methodology. The effects of pH, electrolysis time, and voltage on COD and color removal were investigated, revealing that optimum removal efficiency was achieved at pH 7, 60 minutes of electrolysis time, and 11 V. The statistical models developed demonstrated high predictive accuracy, and analysis confirmed voltage and electrolysis time as significant contributors to treatment efficiency. These findings affirm the potential of electrocoagulation to be a cost-effective and energy-saving technology compared to conventional chemical coagulation and advanced oxidation processes, with satisfactory treatment obtained at modest voltage and time demands, offering valuable guidance for optimizing operational parameters in real-world applications.

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Author contributions

Conceptualization, **A. Badejo** and **B. Bada**; data curation, **A. Olanipekun**.; formal analysis, **F. Nkeshita**.; investigation, **F. Nkeshita** and **A. Olanipekun**.; methodology, **A. David**.; project administration, **A. Badejo, B. Bada,** and **W. Kupolati**.; resources, **A. Badejo**.; software, **F. Nkeshita**.; supervision, **J. Ndambuki**.; validation, **A. Badejo, B. Bada**. and **W. Kupolati**.; visualization, **A. Olanipekun** and **A. David**.; writing—original draft preparation, **F. Nkeshita**.; writing—review and editing, **A. Badejo**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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