



Assessing the impact of dye characteristics on electrocoagulation efficiency in synthetic textile wastewater: An RSM-based study

Fatima H. Mohammed ^a, Shaymaa A. Ahmed ^{a,*}, Forat Yasir AlJaberi ^{b, c}

^a Chemical Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq

^b Chemical Engineering Department, College of Engineering, Al-Muthanna University, Al-Muthanna, Iraq

^c College of Engineering, Al-Ayen University, Thi-Qar, Iraq

Abstract

This new study investigates the effect that dye type cationic Methylene Blue (MB) and anionic Congo red (CR) that has on the Electro-coagulation (EC) treatment performance of synthetic wastewater by employing Response Surface Methodology-Central composite design (RSM- CCD) optimization technique. Twenty-seven experiments were performed to analyze and optimize the effects of 4 factors: Current Density (mA/cm^2) = 6.67 - 13.33; Initial pH = 2 – 10; Reaction Time (h) = 0.07 – 1.5; and Chemical Oxygen Demand (COD mg/L) = 840 – 4236.67 mg/L . The efficiency of EC treatment is evaluated in terms of COD reduction as primary response variable. The RSM model accomplish an excellent predictive power ($R^2=98.84\%$; adjusted $R^2=97.48\%$); the experimental results illustrated a significant relationship between the estimated and measured values. The ANOVA analysis indicated that both current density and reaction time were primarily responsible for the most considerable effects on COD reduction. Furthermore, the study found that the initial pH had a critical role in forming and maintaining coagulating species. A maximum COD reduction efficiency of 98.14% was obtained under the best operating conditions as follows; current density of 11.11 mA/cm^2 (optimal), pH = 6 (initial) and reaction time = 1.5h and initial COD concentration of 2510 mg/L which also utilized only 8.89Wh / kg COD of the applied electrical energy. Many responses also had been tracked in this study to reflect the complex interaction between the operational variables and the final solution properties and its characteristics. The investigated properties changes were the final temperature, conductivity, voltage of the solution, in addition to the theoretical consumption of anode and specific energy consumption. A complex synergistic effect had been reported during the track of the solution characteristic, and this can be relied on the effect of dyes negative and positive charges that reflect some unusual behavior in comparison to the removal of single dyes, or dyes mixture of the same type.

Keywords: Synthetic wastewater; Electrocoagulation; COD removal; Dye type; Central Composite Design; Process optimization; Response Surface Methodology.

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1- Introduction

The nature of textile wastewater makes it one among the most difficult to treat industrial wastewater. This is because of the difficulty in treating all of the components present in textile effluent, as well as the large amounts of pollutants that are present. A considerable amount of water is used for sizing, desizing (a textile process where sizing agents like starch are removed from the fabric), scouring, bleaching, dyeing, printing and finishing processes, which results in large volumes of wastewater from each operation. Typical constituents of textile wastewater include dyes, surfactants, salts, suspended solids, organic compounds, heavy metals and other chemicals that may be present as auxiliaries [1, 2]. These constituents increase the chemical oxygen demand (COD) biological oxygen demand (BOD), color, salinity and toxicity of textile wastewater. The characteristics of textile wastewater can differ greatly based on the type of fabric being processed, the type of dyes and finishing

treatments used. Because of the recalcitrance of the dye molecules and the complexity of organic contaminants in textile effluent, untreated textile effluent represents a significant threat to the environment and therefore must be effectively treated prior to discharge into surface water bodies [1, 2].

The release of untreated wastewater from textile manufacturing can negatively affect aquatic ecosystems through the reduction of light penetration (which reduces photosynthesis) and introduction of toxins (and potential carcinogens) into the ecosystem. High levels of COD, color, suspended solids and dissolved salts will also degrade water quality and harm aquatic life. Conventional treatment processes are generally inefficient in removing all dye and organic pollutants due to the high degree of chemical stability and resistance to biodegradation exhibited by most synthetic dyes. Therefore, alternative and advanced treatment processes including electrocoagulation (EC), advanced oxidation processes,



*Corresponding Author: Email: shaimaa.ahmed@coeng.uobaghdad.edu.iq

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membrane filtration and adsorption have received a significant amount of interest in their ability to enhance the efficiency of pollutant removal. It is thus crucial to develop sustainable and affordable treatment options that minimize the environmental impact of the textile industry while allowing for the potential use of treated effluent for reuse or resource recovery [2-4].

A variety of treatment technology has evolved in response to the problematic nature of textile wastewaters, which typically exhibit both high color strength and high levels of organic content, and have poor biodegradable properties. The traditional treatments that have been applied to textile waste waters include physical processes, such as adsorption, coagulation-flocculation, membrane filtration, and settling; chemical processes including advanced oxidation processes (AOPs) through ozone and electro-chemistry; and biological processes using aerobic or anoxic microbial populations. Among the various available treatment alternatives for treating textile wastewater, electro-coagulation (EC) presents itself as one potential alternative process since it can produce simultaneous removals of color, suspended solids and organic material without the need to add chemicals to treat the effluent nor does it produce a lot of sludges. Advanced oxidation processes produce very reactive radicals able to degrade non-biodegradable dye compounds. Membrane treatment options are known to produce very effective separations; however, they may be subject to fouling problems and/or high operating expenses. Biological treatment techniques are both environmentally acceptable and relatively inexpensive; however, biological degradation of many commercially synthesized dyes is difficult. Therefore, multi-component treatment techniques utilizing combinations of physical, chemical, and biological treatment technologies have become more popular in order to meet higher treatment performance requirements and stricter regulatory guidelines related to final effluent quality [1, 5, 6].

EC is an electrochemical treatment method that has received increasing interest as it appears to be highly efficient, simple to operate, and environmentally compatible for treating textile wastewater. The EC process involves dissolving sacrificial metal electrodes (commonly aluminum or iron) under the influence of an electric current to generate coagulant species in-situ. The metal hydroxides formed destabilize particulate matter, absorb dissolved contaminants, and promote the flocculation of contaminants into larger aggregates that can be easily removed from the water via sedimentation or flotation. Additionally, hydrogen gas produced at the cathode also enhances contaminant removal via flotation mechanisms. Textile wastewater which often contains contaminants can be treated using the EC process because of the strong adsorption capacity of the generated metal hydroxides and they can treat both soluble and insoluble contaminants [7-9].

Multiple studies have shown that electrocoagulation can be an effective method to significantly reduce color, chemical oxygen demand (COD), turbidity, and toxicity of textile effluent. The performance of EC process is

dependent on numerous operational parameters including; current density, initial pH, type of electrode material, concentration of pollutants, distance between electrodes and time of reaction [10-12]. Amongst all of those above-mentioned factors, current density and pH are the most important parameters that determine the rate of coagulant generation and speciation of metal hydroxides responsible for pollutant removal. In comparison with traditional coagulation methods, electrocoagulation provides benefits that include lower chemical consumption, reduced sludge production, ease of automation and enhanced treatment efficiency for recalcitrant dye compounds. Therefore, electrocoagulation has become a promising and sustainable alternative to treat textile wastewater and facilitate water reuse within industrial applications [3, 10-13].

Due to the gap in researches that investigate the simultaneous effect of cationic and anionic dyes mixture in EC process, the primary goal of this new research is to overcome this gap and assess the effects of various dyes mixtures (anionic and cationic mixture) on the effectiveness of the electrocoagulation (EC) process as applied to the treatment of synthetic textile effluent; and to utilize Response Surface Methodology Type Central Composite Design (RSM-CCD) to optimize EC operational conditions. The CCD design had been used due to their properties of sequential experiments, the addition of axial points that are beyond the factorial boundaries, rotatability that provide consistent predictive performance. Specifically, the research aims to identify the extent to which current density, initial pH, reaction time, and initial COD concentration contribute to COD reduction by evaluating the efficiencies of EC treatment; to formulate an empirical mathematical relationship between variables of interest and COD reduction; and to establish the optimum operational conditions necessary to achieve maximum removals of dissolved organic compounds. Additionally, the research seeks to track the effect of changing the operation variables and enhance the understanding regarding the variability in dye-contaminated wastewaters properties (like acidity, conductivity, and temperature) and their impact upon electrocoagulation efficiencies and on the characteristic of the treated solution, ultimately providing a basis for developing optimized treatment methodologies applicable to dye-contaminated industrial wastewaters.

2- Methodology

2.1. Preparation of synthetic wastewater

Synthetic textile wastewater samples were made by using two types of Methylene Blue (MB) and Congo red (CR) to assess the impact of dyes on the EC treatment process. Anionic dye (Congo Red - $C_{32}H_{22}Na_2N_6O_6S_2$) and cationic dye (Methylene Blue- $C_{16}H_{18}ClN_3S \times H_2O$) had been used to simulate the waste solution. The COD concentration of each synthetic textile wastewater sample varied over a wide range from 840-4236.67 mg/L mixed dye solution, according to the RSM-CCD experimental

design. The pH of each sample was then altered using HCl and NaOH in diluted form prior to the start of testing to be within the desired pH range of 2 – 10, to maintain the desired conductivity (0.75 g) of NaCl salt per liter was used as a supporting electrolyte to maintain the desired conductivity.

2.2. Electrocoagulation experimental setup

Experiments were performed on electrocoagulation using a laboratory scale batch reactor shown in Fig. 1 that had sacrificial metal electrode and a DC power source. Each reactor was filled with the prepared wastewater and the sacrificial metal electrodes (aluminum anode and iron

cathode) with active surface area of 140 *60 mm, thickness of 2 mm, in which their specification including EDS and SEM analysis are shown in Fig. 2 and Fig. 3, the electrodes are placed in the reactor at a set distance apart of 20 mm in 0.75 L solution dye mixture. A pre-determined current density was passed through the electrodes during each run to create coagulants in place through anodic dissolution. The formed metal hydroxide particles destabilized and removed dissolved and particulate contaminants from solution through various processes including adsorption, flotation and coagulation that all happen inside EC. Following each experiment, a water sample was taken and analyzed for COD.

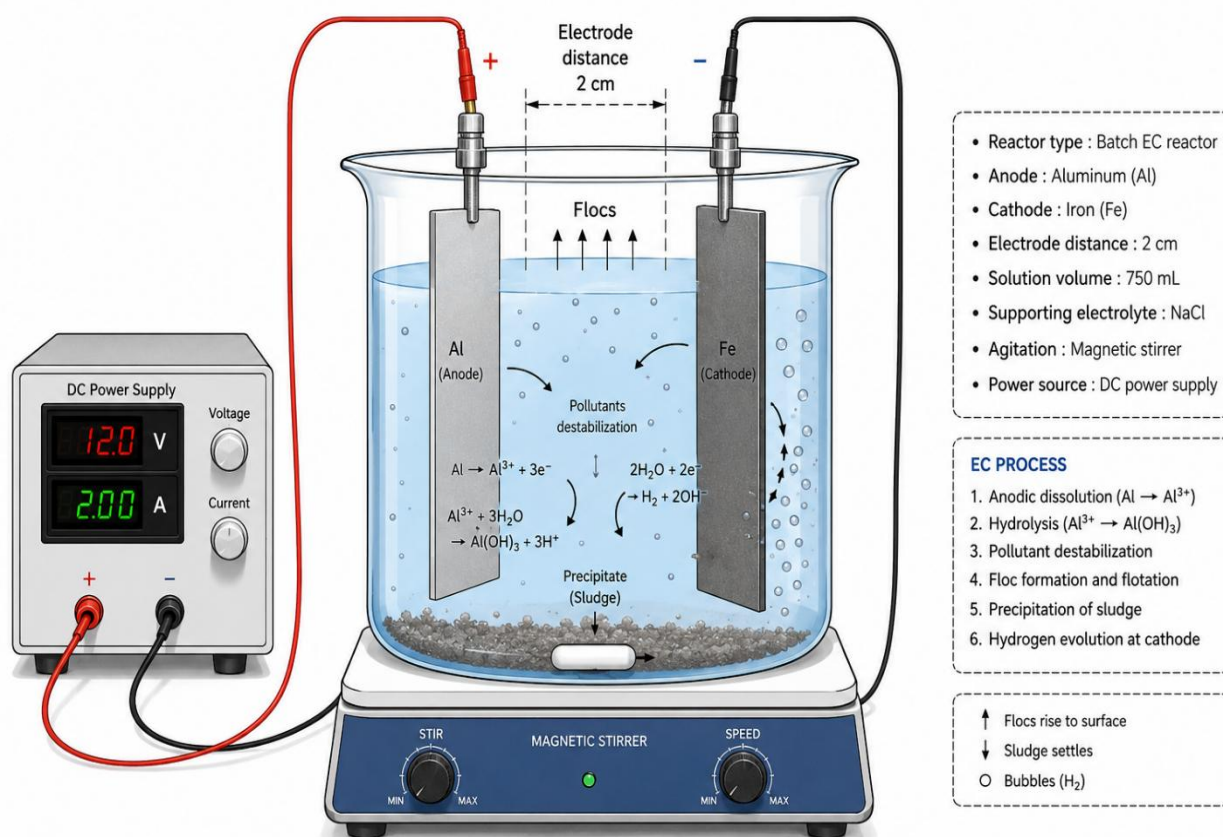


Fig. 1. Electrocoagulation (EC) setup

2.3. Experimental design and statistical analysis

A Response Surface Methodology (RSM) utilizing a Central Composite Design (CCD) was used to investigate the potential to optimize an Electrochemical Coagulation (EC) process. Independent Variables that were studied in this investigation included; current Density (mA/cm^2); initial pH; reaction time (h); and initial chemical oxygen demand (COD) concentration (mg/L). This study also consisted of 27 Experimental Runs generated from the CCD which included Factorial Points, Axial Points and Center Points.

The results of these experiments were then modeled with Minitab Software as a Quadratic Polynomial

Equation that defined how each variable impacted the COD reduction. ANOVA analysis was done to determine the level of statistical significance for the impact of individual factors, interactions between those factors and the overall fit of the model. Finally, response surfaces and optimization tool within Minitab software were used to identify the best operational conditions to maximize COD reduction. Additionally, the study's results identified the relative impacts of the differing in operation variables on the characteristics of the treated solution like its acidity, conductivity and others and how these characteristics change during the removal of COD related to dye mixture.

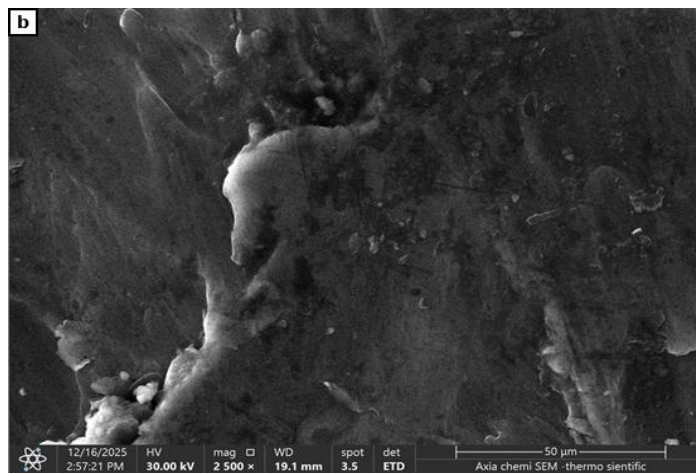
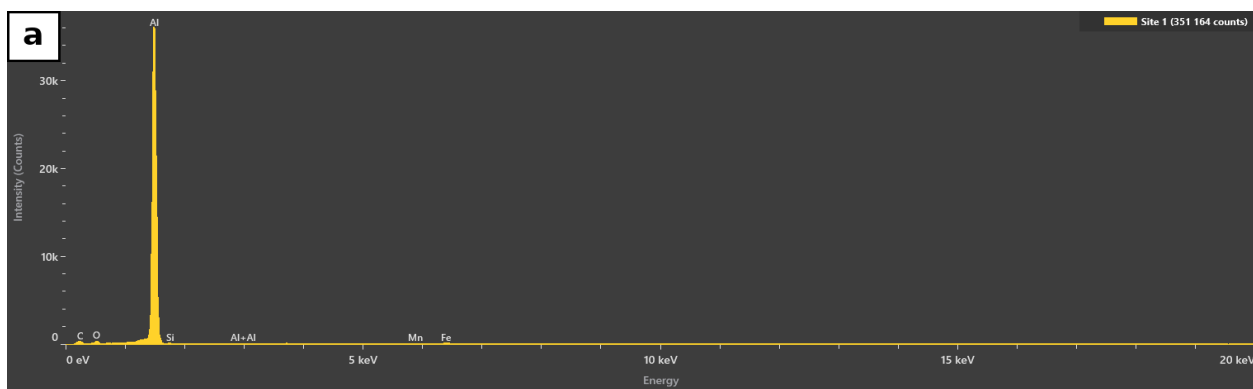


Fig. 2. Al anode (a) EDS and (b) SEM analysis

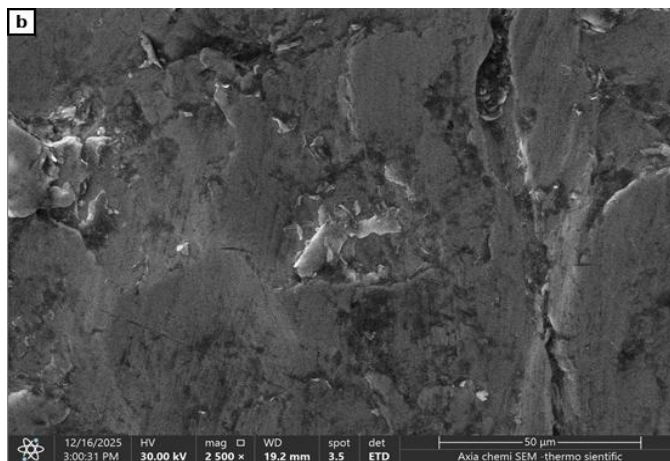
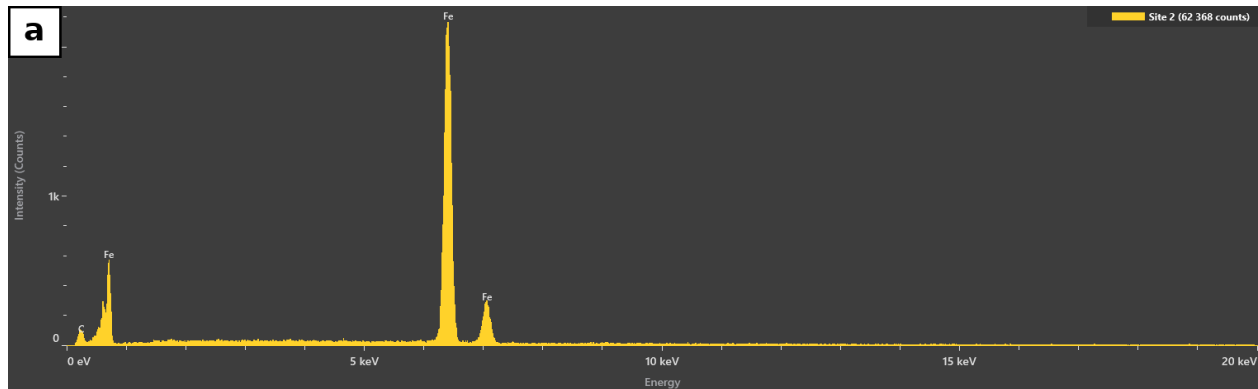


Fig. 3. Fe cathode (a) EDS and (b) SEM analysis

3- Results

3.1. Experimental design matrix and measured responses

The whole RSM – CCD experimental setup as well as response measurements for each of the experimental runs are shown in Table 1 and Table 2. The experimental work was done using 27 runs based on the CCD over four factors: current density (6.67-15.56 mA/cm²); initial pH (2-10); reaction time (0.07-1.50 hours); and initial COD concentration (840-4236.67 mg/L). For each of the 27 runs, six responses were either measured directly or calculated: final COD (mg/L), final pH, final electrical conductivity (μS/cm), theoretical anodic mass loss (g), and specific energy consumption (SEC, Wh/kg COD). Table 1 shows a variability of the treatment performances over the whole experimental area. COD reductions vary

greatly depending on the 27 runs (minimum reduction: Run 19; CD=11.11mA/cm²; pH=2; time=0.78h; COD₀=2510 mg/L): 73.44%; while maximum reduction: Run 22; CD = 11.11mA/cm²; pH=6; t=1.5h; COD₀=2510 mg/L: 98.14%. These differences in COD reduction efficiencies illustrate how sensitive EC treatment can be to the selected parameters.

All three central point replicates (Runs 25-27) showed COD removals of 83.13%, 79.81% and 82.34% respectively, and this demonstrated good reproducibility of the experiment. Values of SEC ranged from 0.658 Wh/kg COD (Run 21; shortest electrolysis time of 0.07 h) to 20.451 Wh/kg COD (Run 23; 0.78h and smallest initial COD of 840 mg/L), clearly showing how much the energy efficiency depends upon both the applied process conditions as well as upon the amount of pollutants present in wastewater.

Table 1. Experimental design ranges of the operating variables

Operating Variables	Values	Operating Variables	Values
X1: Current Density (mA/cm ²)	8.89-15.56	X3: Reaction time (hr)	0.42-1.5
X2: Initial pH	2-10	X4: initial COD (mg/L)	840- 4236

3.2. RSM model development

3.2.1. ANOVA test for final COD

The ANOVA results shown in Table 3 present the analysis of the fit of Equation 1, and it is shown that the obtained model is statistically significant ($F = 72.74$; $p < 0.001$). This indicates that the fourteen terms used in this model have statistically significant impact on the variability in COD after treatment. As can be seen from Table 2, the sum of squares for the model (915,718) is substantially larger than the sum of squares for the residuals (10,791); therefore, the F value (mean square ratio) obtained by dividing these two values exceeds the critical limit for $\alpha = 0.05$.

The coefficient of determination $R^2 = 98.84\%$ confirms that the model accounts for 98.84% of the total variance in the final COD response across all 27 runs in Table 1. The adjusted R^2 (97.48%) corrects for the number of model terms relative to observations, while the predicted R^2 (94.68%) estimates the model's out-of-sample predictive accuracy. The small difference between $R^2(\text{adj})$ and $R^2(\text{pred})$, less than 3%, confirms that the model is not overfitted and will perform reliably for interpolative predictions within the studied experimental domain. The root mean square error $S = 29.99$ mg/L represents the average absolute deviation of experimental from model-predicted COD values, which is acceptably small relative to the COD response range (46.67–666.67 mg/L) observed in Table 2. The Lack-of-Fit test necessary to evaluate the model validity, a value of 0.885 (larger than 0.05) indicates it is not statistically significant compared to pure-error, and that demonstrates that the proposed model describes the experimental data with high adequacy.

$$\begin{aligned} \text{Final COD (mg/L)} = & 144 + 188.3 X_1 - 229.9 X_2 - 326 X_3 + 0.2231 X_4 - \\ & 7.15 X_1^2 + 11.90 X_2^2 - 258.7 X_3^2 - 0.000043 X_4^2 - 3.89 X_1 X_2 - \\ & 17.01 X_1 X_3 - 0.00536 X_1 X_4 + 86.9 X_2 X_3 + 0.02183 X_2 X_4 - \\ & 0.0004 X_3 X_4 \end{aligned} \quad (1)$$

The 14 terms in Eq. 1 are 4 linear, 4 quadratic and 6 two-way interactions. The negative signs of the linear coefficients for initial pH (-229.9) and reaction time (-326) indicate that increasing either of these parameters throughout the study results in a decrease in final COD. Conversely, the positive linear coefficient for current density (188.3) suggests that current density has a non-monotonic effect on COD reduction. The main contribution to this non-monotonicity is from the quadratic term with respect to current density. The insignificant variables shown in Table 1 can be theoretically omitted from Equation 1, but practically cannot, because they are important to be taken into consideration, especially the initial COD variable.

3.2.1.1. Effect of current density

As shown in Fig. 4, COD reduction as a function of current density showed a non-linear characteristic in the range of study, 6.67–15.56 mA/cm². At first, the final COD was found to be increasing with increasing current density from 6.67 mA/cm² to around 9 mA/cm², which meant that the treatment efficiency was decreasing. This behavior can be caused by restabilization phenomenon caused by the presence of the anionic and cationic dyes at the same time alongside the presence of aluminum hydroxide, this causes the lack of generation of coagulants and the lack of complete destabilization of organic pollutants during the passage from the low to the moderate current densities, thus reducing the

effectiveness of the removal of the pollutants. The final COD, however, gradually decreased as the current density continued to rise beyond 9 mA/cm², indicating better treatment efficacy. The higher the current density, the faster the rate of dissolution of the sacrificial electrodes, the more coagulants of metal hydroxide will be formed, and the more hydrogen bubbles will be produced, which will increase the effect of coagulation and flotation. These

effects promote the aggregation and separation of organic contaminants, leading to greater COD reduction. However, the rate of reduction is relatively low, indicating that raising current density helps to remove pollutants, but not at a high current density because of potential mass-transfer limitations and the emergence of diminishing returns with coagulant utilization efficiency.

Table 2. Experimental design matrix with all measured responses RSM-CCD

Run	X1	X2	X3	X4	Final COD (mg/L)	SEC (Wh/kg COD)	Final Cell Voltage (volt)	Final conductivity (Micro-S)	Final pH	Theo. Consumption (g)	Anode-Consumption
1	8.89	4	0.42	1663.33	623.333	3.596	11.0	1371	8.00	0.114	
2	13.33	4	0.42	1663.33	590.000	5.844	12.3	982	5.29	0.171	
3	8.89	8	0.42	1663.33	390.000	3.017	11.3	1318	8.30	0.114	
4	13.33	8	0.42	1663.33	296.667	6.269	16.8	1203	7.40	0.171	
5	8.89	4	1.14	1663.33	196.667	7.224	11.6	1353	6.66	0.307	
6	13.33	4	1.14	1663.33	153.333	13.065	14.4	1277	7.29	0.460	
7	8.89	8	1.14	1663.33	280.000	8.055	12.2	1517	7.85	0.307	
8	13.33	8	1.14	1663.33	133.333	13.969	15.6	1383	7.25	0.460	
9	8.89	4	0.42	3486.67	663.333	1.252	10.4	1767	7.25	0.114	
10	13.33	4	0.42	3486.67	620.000	3.149	17.7	1910	8.61	0.171	
11	8.89	8	0.42	3486.67	646.667	1.508	12.6	1556	8.30	0.114	
12	13.33	8	0.42	3486.67	523.333	3.029	17.6	1710	7.15	0.171	
13	8.89	4	1.14	3486.67	326.667	3.873	13.4	2080	8.41	0.306	
14	13.33	4	1.14	3486.67	183.333	5.433	13.1	1432	5.26	0.460	
15	8.89	8	1.14	3486.67	490.000	3.231	10.6	1518	8.44	0.307	
16	13.33	8	1.14	3486.67	313.333	4.663	10.8	1780	8.68	0.460	
17	6.67	6	0.78	2510.00	406.667	2.145	9.6	1757	8.91	0.157	
18	15.56	6	0.78	2510.00	250.000	7.910	16.3	1527	7.46	0.368	
19	11.11	2	0.78	2510.00	666.667	3.697	8.7	2410	4.50	0.263	
20	11.11	10	0.78	2510.00	653.333	5.738	13.6	1426	8.05	0.263	
21	11.11	6	0.07	2510.00	626.667	0.658	18.6	1836	8.75	0.022	
22	11.11	6	1.50	2510.00	46.667	8.890	14.6	1582	7.09	0.504	
23	11.11	6	0.78	840.00	223.333	20.451	16.1	1723	7.87	0.263	
24	11.11	6	0.78	4236.67	476.667	3.083	14.8	1868	8.32	0.263	
25	11.11	6	0.78	2510.00	423.333	5.105	13.6	1887	8.47	0.263	
26	11.11	6	0.78	2510.00	506.667	5.670	14.5	1705	8.05	0.263	
27	11.11	6	0.78	2510.00	443.333	4.814	12.7	1663	8.04	0.263	

3.2.1.2. Effect of initial pH

The pH curve, revealed in Fig. 4, for the first phase of the process shows that there is a slight rise or a very gentle slope from pH 2 through to pH 10. The lowest final COD values are recorded at an approximately near-neutral pH range of pH 5-7. In contrast, the higher the acid level (pH=2), the higher will be the final COD value because the majority of soluble Al species (such as Al³⁺) will be present. However, they will form fewer solid flocs that have fewer sites available for adsorption of solubilized pollutants by comparison with amorphous Al(OH)₃. On the other hand, when high levels of alkalinity prevail (i.e. above pH 8), the soluble species formed during this stage of the process (such as Al(OH)₄⁻) will inhibit the formation of insoluble Al species and therefore reduce the effectiveness of the coagulant. These results are in agreement with Hakizimana et al., which described the behavior of Al hydroxide species in relation to pH. They found that maximum amounts of precipitate occur over a narrow pH range (5.5-7.5). This results in a larger number of adsorption sites on the floc surfaces for dyes and other organic pollutants [8].

3.2.1.3. Effect of reaction time

Fig. 4, shows an inverted U (concave down) curve with an evident maximization in final COD at intermediary times between about (0.5 to 0.85 hours) followed by a steep decline towards the minimum final COD of about 46mg/L at 1.50h. Non-linearity of this trend is due to two counteracting processes; insufficient Al(OH)₃ flocs have been developed to bind and coalesce dye molecules and organic contaminants within a very limited electrolyzing period, which will result in higher than expected residual COD values. Subsequently, followed by increasing number of flocs formed throughout the course of electrolysis accelerate adsorption, charge-neutralization, and sweep-coagulation processes to reduce the COD over time. A significant decrease in COD values for longer treatment periods (more than 1 hour) supports that treatment duration is among the major contributors to the highest degree of COD reduction achievable in this system, about 98.14 % removal of COD was observed after 1.50 hours of electrolysis (Run 22). This finding aligns with other researches, which illustrated that

extended electrolysis time greatly increases pollutant removal efficiencies in EC systems treating multi-component industrial effluent streams, and research by Ebba et al., which demonstrated that reaction time is one of the key factors influencing RSM-optimized EC of hospital effluents [12-14].

3.2.1.4. Effect of initial COD

The initial COD plot had a broad, shallow downward shape with a maximum final COD at about 2500 – 3000 mg/L and decreasing final COD values at both ends. This unusual behavior represents the relationship between the amount of pollutants applied and the constant amount of coagulant used. When the initial COD value is small (i.e.,

about 850 mg/L), the floc formed will have a larger ratio to pollutant mass, so it can remove a larger percentage of the pollutant load, while producing a lower absolute pollutant load in the final effluent. In contrast, when the initial COD value is extremely high (about 3500 mg/L), there is little space on the surface of the flocs for additional pollutant loads. Therefore, the ratio of pollutant load removed per unit coagulant decreases. The non-linear character of this response was proven to be statistically significant ($p < 0.01$ for COD^2) in the ANOVA as well as being similar to those observed by Faheem et al., for the optimized EC of landfill leachate using RSM [15].

Table 3. Response surface regression: final COD (mg/L) analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Signification status
Model	14	915718	65408.4	72.74	<0.0001	Highly
Linear	4	88484	22120.9	24.60	<0.0001	Highly
Current Density (mA/cm2)	1	2000	2000.0	2.22	0.162	Not
Initial pH	1	61480	61479.5	68.37	<0.0001	Highly
Reaction time (hr)	1	24378	24377.5	27.11	<0.0001	Highly
Initial COD (mg/L)	1	73	73.0	0.08	0.781	Not
Square	4	164815	41203.8	45.82	<0.0001	Highly
Current Density (mA/cm2)*Current Density (mA/cm2)	1	27031	27031.2	30.06	<0.0001	Highly
Initial pH*Initial pH	1	49153	49153.2	54.66	<0.0001	Highly
Reaction time (hr)*Reaction time (hr)	1	23935	23935.3	26.62	<0.0001	Highly
Initial COD (mg/L)*Initial COD (mg/L)	1	21368	21367.7	23.76	<0.0001	Highly
2-Way Interaction	6	97082	16180.4	17.99	<0.0001	Highly
Current Density (mA/cm2)*Initial pH	1	4784	4784.0	5.32	0.040	Acceptable
Current Density (mA/cm2)*Reaction time (hr)	1	2934	2934.0	3.26	0.096	Not
Current Density (mA/cm2)*Initial COD (mg/L)	1	1893	1893.4	2.11	0.172	Not
Initial pH*Reaction time (hr)	1	62084	62084.0	69.04	<0.0001	Highly
Initial pH*Initial COD (mg/L)	1	25387	25386.6	28.23	<0.0001	Highly
Reaction time (hr)*Initial COD (mg/L)	1	0	0.3	0.00	0.985	Not
Error	12	10791	899.3			
Lack-of-Fit						Highly acceptable, i.e., not significant
	10	7006	700.6	0.37	0.885	
Pure Error	2	3785	1892.6			
Total	26	926509				

S=29.9877; R²=98.84%; R²(adj)=97.48%; R²(pred)=94.68%

3.2.2. Secondary responses investigation

The following sections reflect the effect of the studied variables on the treated solution properties and characteristic at the mean value of the other studied variables.

3.2.2.1. Final solution temperature

The tracking of the final temperature of the treated wastewater is shown in Table 1. The final temperature reflects a lot of information under the studied variables that can affect the contaminants removal. Due to the effect of flocks' structure and their adsorption ability and the passivation behavior of electrodes. The contribution of

the investigated variables is summarized below, and are shown in Fig. 5.

a- Effect of current density

As depicted in Fig. 5, the solution temperature has shown a nearly monotonically increasing relationship with the current density across the investigated range of values (6.67 – 15.56 mA/cm²). The final solution temperature increased from approximately 28°C to 34°C. This behavior is directly related to Joule (or ohmic) heating; where the power lost to the electrolyte resistance ($P = I^2R$) will be converted into thermal energy. Because the amount of heat generated per unit time due to Joule heating is directly proportional to the square of the

applied current at constant resistance, it explains why there are greater rates of increases in solution temperatures as applied currents increase. It has been demonstrated the importance of monitoring temperature increases within electrocoagulation systems by

researchers and they concluded that when solutions reach temperatures in excess of $\sim 40^{\circ}\text{C}$, it negatively affects both the floccule formation structure and reduces their pollutant adsorption capabilities [12].

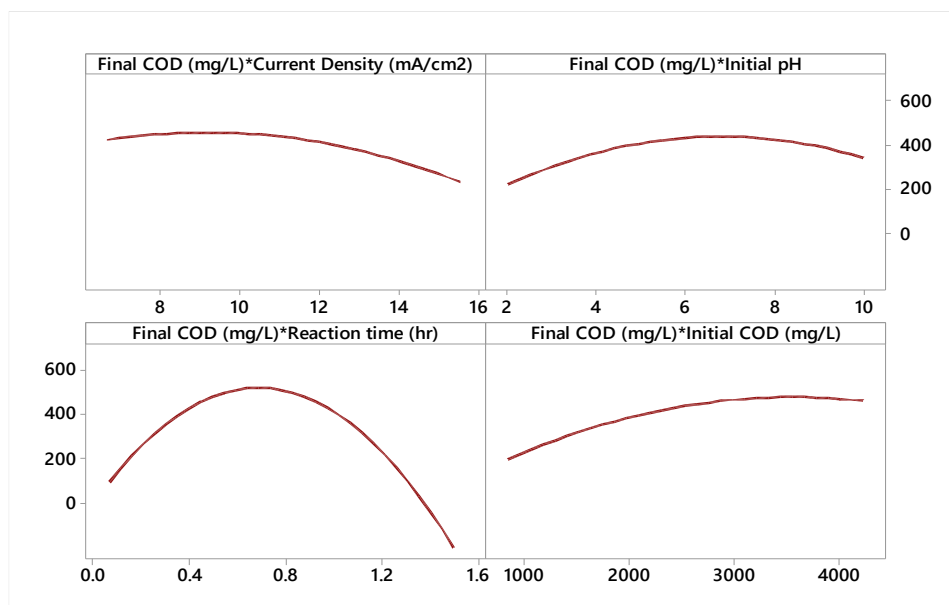


Fig. 4. Represent the effects of; reaction time, initial pH, and Initial COD on the final COD at the mean value of the other studied variables

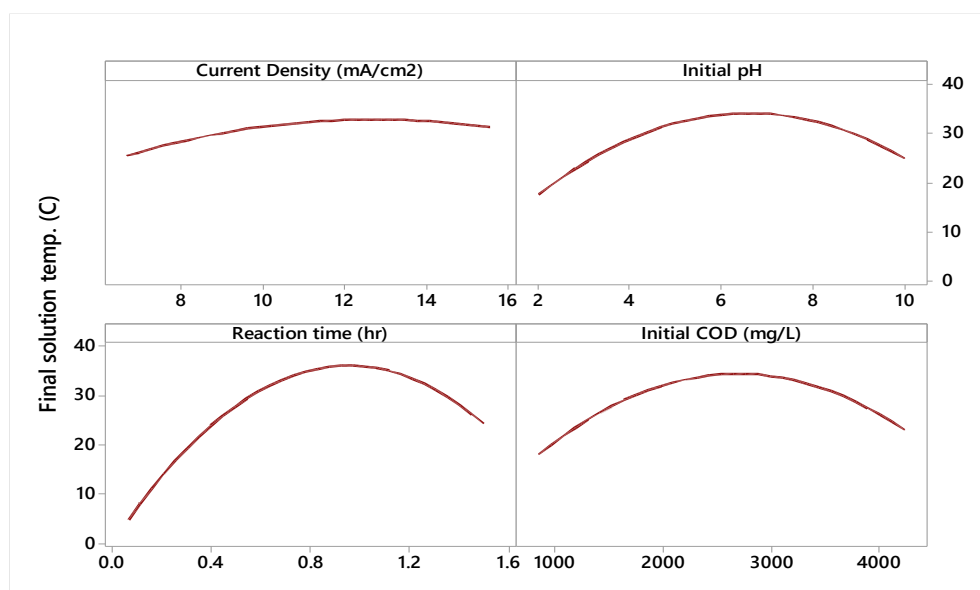


Fig. 5. Represent the effects of: current density, initial pH, reaction time and initial COD on the final sol. temperature, at the mean value of the others

b- Effect of initial pH

Curves shown in Fig. 5 indicate that there is a strong maximum in final temperature value of at an acidity level of approximately pH 5 to 7. However, there are lower temperatures recorded as well at both, very low pH (approximately pH 2), and at very high pH (pH 10). These trends can be understood through a deeper insight into how ionic speciation affects the conductivity of solutions.

Specifically, when a solution has a neutral pH, all ions present (e.g., Al^{3+} , OH^- , species associated with buffers, plus the background electrolyte (NaCl) contribute to the total ionic strength and therefore the total conductivity of the solution. When these factors combine at near neutral pH to produce the greatest amount of ionic strength possible, they create the greatest amount of Joule heat produced per unit of electric current. Conversely, when either excessive amounts of H^+ or OH^- ions are present

due to a low or high pH respectively, the presence of additional ions in the solution slightly reduces the distribution of ions within the solution with respect to their mobility; however, it does so to such a degree that it results in slightly less resistance to the passage of electrical current and thus slightly less resistive heating. These agrees with the conductivity - temp. relation described by Marri et al. in systems works with aluminum electrodes [16].

c- Effect of the reaction time

Fig. 5 also exhibits an obvious increase in the solution's temperature with respect to temperatures - starting near-ambient conditions, $\sim 6^\circ\text{C}$ above room temperature at a reaction time of 0.07 hours - and increasing to approximately 32°C at a reaction time of 1.50 hours; after which there is a slight leveling off. The shape of this curve is concave down indicating a continued reduction in the rate of the initial rapid temperature rise due to Joule heating as the solution continues towards a thermal steady state where the amount of heat generated within the system is equal to the amount of heat lost to its environment. So, this is an indicative of the cumulative impact of ohmic heat input during the duration of the electrochemical process; similar response was observed by other researchers who used Al electrodes for industrial wastewater treatment in their experimental EC study [11].

d- Effect of initial COD

Fig. 5 shows a wide-concave down trend with final temperature on around 2500-3000 mg/L. Increasing in COD will have increasing in ionic strength and dissolved organic load that increases solution conductivity which cause an increase Joule Heating. Decline at elevated value of initial COD (>3500 mg/L) is thought to be due to partial saturation of the ionic conductivity effect as electrolyte ion concentration plateau. Temperature increase during EC is important operational consideration, noted by Shahedi et al. in their review. Elevated final temperatures may increase rate of passivation of the electrode and change floc morphology potentially affecting long-term process performance [17].

3.2.2.2. Final cell voltage

Cell voltage is an important operational parameter for the EC reactor because it is related to the electrical energy that is used to maintain electrochemical reactions in a wastewater treatment process. In general, the final cell voltage rises as the current density increases, because of the higher electrical resistance that is faced in the electrolyte and the increased potential required to force the reactions for dissolution of the electrodes and evolution of gases. But this behavior can be conflicted depending on electrodes type, stability of the adsorbed passive layer, the number of formed bubbles, and others. Increased cell voltage can increase the production of coagulant species and hydrogen bubbles that may

improve the efficiency of pollutant removal. But too high a voltage can result in increased energy consumption and lower process economy. The cell voltage at the end of the reaction is also affected by cell conductivity, electrode separation, metal ion composition of wastewater, and passivation of the electrodes. Thus, the final cell voltage monitoring and optimization are crucial to ensure optimum treatment performance and energy efficiency in electrocoagulation systems. The response to the change in the variables examined is discussed below:

a- Effect of current density

Fig. 6 illustrates how the current density affects cell voltage. As can be seen, the voltage continues to grow as the current density increases (the voltage grows from 10 Volt to 15 Volt when the current density rises from 6.67 mA/cm^2 to 15.56 mA/cm^2). There are two reasons for the growth of the cell voltage as the current density increases. First, if a consideration of a fixed geometric configuration of electrodes and solution resistance is applied, then the required driving voltage will be directly proportional to the increased current according to Ohm's Law (Ohm's Law states that the voltage developed across a conductor is equal to the product of the resistance and the flow of electric current or $I = V/R$). Second, in addition to the above-mentioned reason, at higher currents there is also a larger overpotential required to maintain the anodic dissolution reaction of aluminum ($\text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^-$), thus further increasing the cell voltage. The reports results in literature are conflicting depending on used metal, contaminant, and passivation, but our findings support similar reported results which demonstrated that voltage and current density show a direct linear relationship in batch EC reactors [18].

b- Effect of initial pH

Fig. 6 also demonstrates a clear maximum increase in final cell voltage occurring at an initial pH ranging from 5–7 and this voltage tend to decrease as pH approaches either an acid (pH 2) or base (pH 10) value. The pH dependence of the cell voltage indicates a strong influence of pH on solution conductivity and therefore ohmic resistance. Solutions having a nearly neutral pH are of slight conductivity due to their modest ionic free content. Therefore, it is expected that higher voltages would be required to force the desired amount of current through the inter-electrode space. In contrast, at pH 2, the high concentration of H^+ ions allow protons to move through the solution rapidly via the Grotthuss mechanism thereby increasing conductivity. Similarly, at pH values greater than 10, excess amount of OH^- ions decrease electrolyte resistance allowing a reduction in the required cell voltage. Thus, the pH dependency on cell voltage identified in this study is in accordance with previous studies performed in treatment systems using EC [8].

c- Effect of reaction time

The treatment reaction time and their impact on final cell voltage is identified in Fig. 6, which displays a non-monotonic profile where the cell voltage peaks early (~0.7–0.9 hours) before decreasing at longer electrolysis times. Initially, an increase in cell voltage is observed as dissolved Al ion concentrations build up within solution. This may attributably lead to the formation of passive layers due to accumulation of aluminum oxide/hydroxide deposits on the electrode surfaces leading to an increase in surface resistance. Subsequently, after extended electrolysis times (>0.9 hours) a decrease in cell voltage is observed and this can be primarily caused by progressive increase of Al ions that may increase the solution conductivity. Also, this decline can be attributed to the de-attachment of passive layer, and the mechanical effect of formed bubbles, causing this de-attachment. Electrochemical passivation and its effects on cell voltage during electro-coagulation have been thoroughly examined by many researchers, they all reported an increase in cell voltage within the first 30 min of operation, followed by slight increase or stability in values over time [8,12].

d- Effect of initial COD

As shown in Fig. 6, cell voltage exhibits a concaved down shape with a peak around 2500–3000 mg/l of initial COD resembling temperature trend. On the left side, the increase in final cell voltage with the increase in initial COD can be related to the accumulation of organic loads in solutions increases the resistance of solutions as many ionic species related to dye molecules contribute to overall conductivity of electrolyte, and some may cause an organic fouling on electrode surface. At highest initial COD ranges >3500 mg/l, sufficient excess ionic strength may lower bulk resistance enough to decrease required cell voltage resulting in observed decrease. Also, it is known that some organics can be ionized at high concentration causing buffering that affect pH - passivation relation causing an elevation in conductivity. The changes in conductivity during electrolysis are influenced by initial concentrations of pollutants as indicated by Espinoza-Quiñones et al. for conductivity-time curves in batch EC reactors [19].

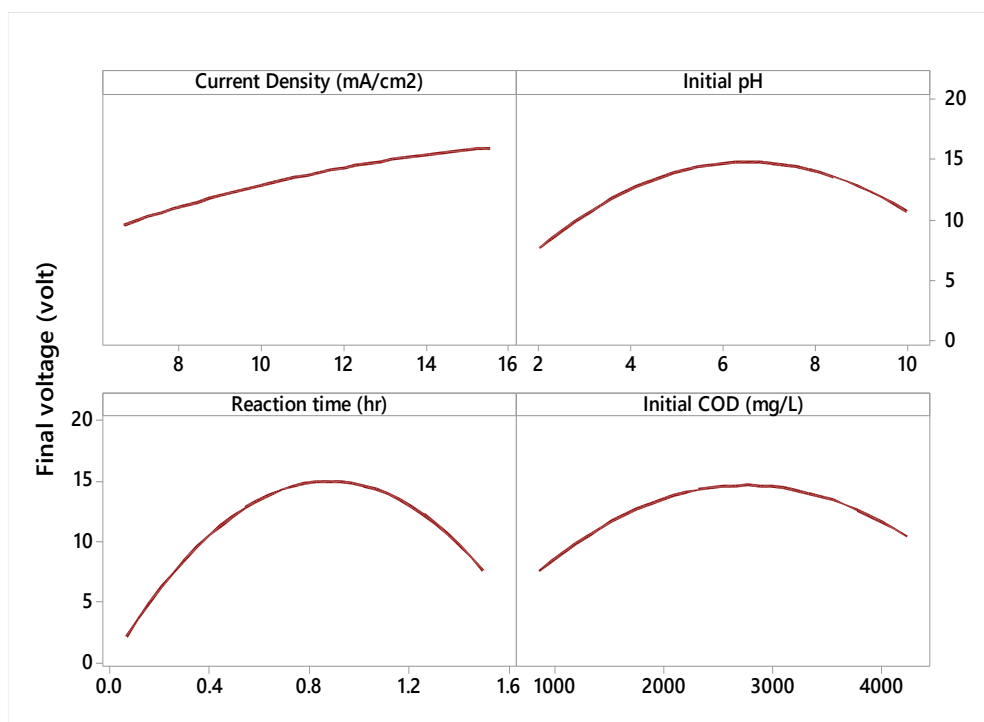


Fig. 6. Represent the effects of: current density, initial pH, reaction time and initial COD on the final voltage at the mean value of the others

3.2.2.3. Specific energy consumption

Specific Energy Consumption (SEC) is one of the most important economic and operational criteria to evaluate the EC process. SEC have to be related to the contaminants removal to decide the efficacy of the process. The following describe how the SEC changes as the operational variables varies:

a- Effect of current density

In Fig. 7, the top left panel illustrates the increasing specific energy consumption (SEC) as current density increases. Due to the proportionality of SEC with both current and cell voltage ($SEC \propto I \cdot V \cdot t / \Delta COD$), as both current and voltage are increased simultaneously, there is a substantial escalation of energy used per unit COD removed at current densities above the optimal 11

mA/cm². The reason for this is due to the decreasing marginal returns on the reduction of pollutants as the current density continues to increase. As an example, although additional coagulant will be generated through higher current densities, the ratio of COD reduction gain to energy use costs will decrease, due to the exponentially increasing energy costs associated with elevated current densities. This relationship between current density and

energy consumption is clearly illustrated within the literature. For example, Das et al. have documented that energy consumption increases disproportionately with current density in EC systems. Similarly, Aryanti et al., have found that the primary method for minimizing SEC in EC based wastewater treatment systems is through optimizing the current density [12, 20].

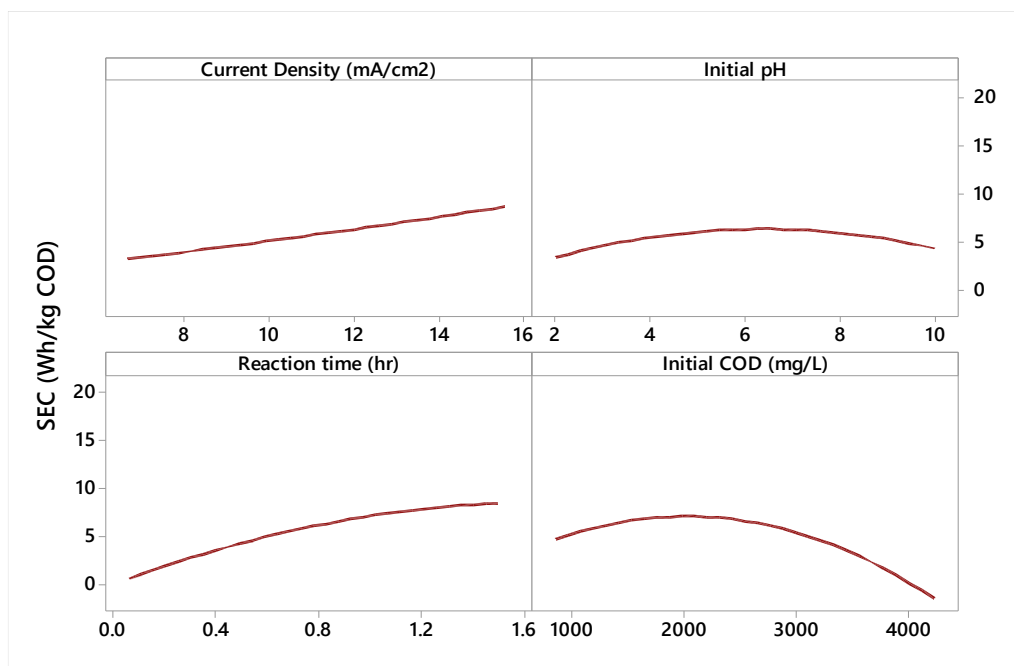


Fig. 7. Represent the effects of: Current density, initial pH, reaction time and Initial COD on the SEC, at the mean value of the others

b- Effect of initial pH

The flatness of the curve shown in Fig. 7 indicates that pH has a relatively minimal impact upon SEC in comparison to other variables. However, its main impact is on the coagulation efficiency (and therefore Δ COD) rather than on energy input (which is primarily influenced by current and voltage). Therefore, the slight SEC peak at intermediate pH values can be attributed to two factors. First, the area where the highest cell voltage exists for the same current density (as shown in Fig. 3). Second, the intermediate pH value is the point where the greatest amount of COD reduction occurs, which would counteract some of the excess voltage. This result was also obtained by researchers during their response surface methodology (RSM) investigation into electrochemical treatment of textile dyeing wastewater [21].

c- Effect of reaction time

Fig. 7 illustrates the monotonic increase of specific energy consumption (SEC) with reaction time. At very short electrolysis times, the SEC approaches zero, but increases sharply up to a maximum of approximately 8.9 Wh/kg COD at an electrolysis time of 1.5 hours. This is expected behavior because energy input increases linearly with time ($E = V \cdot I \cdot t$), while the COD reduction rate

decreases over time as the most reactive fraction of pollutants is quickly removed initially in the process. With continued time, the rate of COD reduction slows down significantly. Consequently, each successive unit of energy added yields progressively less COD reduction - a type of "energy utilization diminishing returns." This kinetic behavior is consistent with second order pollutant removal kinetics reported by Acharya et al. for electrocoagulation systems. Initially, rapid pollutant removal occurs, followed by slow diffusion limited pollutant removal after prolonged periods of operation [22].

d- Effect of initial COD

The relation between initial COD and SEC is clearly non-monotonic as demonstrated in Fig. 7. Specifically, a sharp maximum of SEC value (about 20.5 Wh/kg COD at the optimum level of the studied variables) occurred at the lowest initial COD concentration (840 mg/L) as shown in table 1. On the other hand, a dramatic decline in SEC to a minimum (of about 3 Wh/kg COD) occurred at high initial COD concentrations (4236 mg/L) (Table 1). The underlying mechanism for this hyperbolic relationship between SEC and initial COD concentration shown in figure 4 is simple. When the initial COD concentration is low, a given quantity of electrical energy input into the

system results in a large quantity of electrical energy being spread out over a small mass of COD removed resulting in extremely high SEC. Conversely, when high levels of initial COD concentrations exist in the system and a corresponding large amount of COD is reduced using the same electrical energy, the SEC decreases dramatically. This type of hyperbolic relationship between SEC and initial pollutant load is a common feature among many electrochemical processes including those involving electrocoagulation [11,12], and it presents significant practical advantages. Electrochemical treatment systems are most efficient when treating concentrated effluent streams; therefore, these systems have significant potential application for treating concentrated textile dye house effluent streams.

3.2.3. Other studied responses

3.2.3.1. Electrical conductivity

The electrical conductivity in the electrocoagulation reactor is an important parameter that indicates the conductivity of the treated wastewater and its direct effect on the efficiency and energy consumption of the electrocoagulation process. This helps ions to pass between the electrodes, decreasing the electrical resistance of the solution and, therefore, the cell voltage necessary to sustain a certain current density. This enhances energy efficiency and coagulant species generation by the dissolution of the electrodes. The electrical conductivity can vary throughout the electrocoagulation process due to a number of contributing factors, including the removal of pollutants, consumption or production of ions, and the creation of metal hydroxide flocs. Supporting electrolyte (sodium chloride) is added to improve conductivity and treatment efficiency in many cases. Consequently, it is necessary to keep an appropriate level of electrical conductivity in electrocoagulation systems to guarantee effective pollutant removal, stable reactor operation, and low operating costs.

a- Effect of current density

Fig. 8 illustrates a fairly level to somewhat reduced conductivity profile over the examined range. Conductivity does not significantly change as the current density increases. This can be accounted for the creation of more aluminum ions (increase ionic concentration) with increasing the current density, yet it will also enhance floc precipitation and co-precipitation, which will take away ions from solution using adsorption and sweep-coagulation of ionic species related to dye molecules. The net result is little to no improvement in final conductivity. Similar stabilization of conductivity at high current densities was reported by Espinoza-Quñones et al., in which the report that the dynamic equilibrium between ion release and ion removal due to floc development determine the final conductivity in batch EC reactors [19].

b- Effect of initial pH

As illustrated in Fig. 8, there is a wide maximum in final conductivity about pH 4–7 and decline at low (pH 2) and high level of acidity (pH 10). Low pH (of about 2), the elevated H-ion concentration in the original sample provides increased conductivity, but once EC has driven pH towards neutral by generating cathode OH-ion, H-ion are consumed. High pH (of about 10), the alkaline environment enhances rapid $\text{Al}(\text{OH})_3$ precipitation and incorporates a greater portion of dissolved ionic species within the floc phase, thus lessening ionic strength of the supernate. The maximum found near pH 4–7 represents a condition where the initial ionic environment and EC induced ionic equilibrium combine to produce the greatest remaining conductivity; consistent with findings by Hakizimana et al., on how pH affected distribution of ionic species in aluminum EC processes [8].

c- Effect of reaction time

As illustrated in Fig. 8, conductivity rapidly increases during the first 0.8 hours of electrolysis and then quickly drops off at longer times, displaying a clear concave down peak. This can be related to complex competition among many simultaneous phenomena that takes place during EC process. The early conductivity increases stems from accumulation of $\text{Al}(\text{OH})^{2+}$, Al^{3+} , etc., being generated from anodic dissolution. Once electrolysis continues, these species undergo hydrolysis forming insoluble $\text{Al}(\text{OH})_3$ precipitates and remove themselves from the ionic pool and decrease solution conductivity. This decrement can be related to ion retention in the growing flocs, hydrogen and oxygen gas bubbles that reduce their mobility due to increasing resistance and viscosity. Thus, the net conductivity reaches its peak when rates of generation of ions and removal of ions through precipitation are equivalent. This conductance behavior was modeled quantitatively by Espinoza-Quñones et al., as they created a model describing conductance vs time for batch EC system that described both increasing and decreasing phases of conductance behavior [19].

d- Effect of initial COD concentration

Fig. 8 shows that conductivity increased continuously with initial COD to approximately 3000 mg/L after which the final conductivity remained constant or slightly decreased. Textile dye samples having higher COD have greater amounts of dissolved organic compounds, surfactants and auxiliary materials, contributing to ionic strength. The continued increase in final conductivity with initial COD is representative of retaining residual ionic species (dye molecules, products, inorganic ions) in the treated effluent. A saturation point of high initial COD would indicate that floc surface area became saturated, reducing fraction of ionic dye removed resulting in more residual ions. Influence of initial organic load on final conductivity in EC-treatment of textile wastewater were

reported by Kobya et al. and Naje et al.; who indicated residual conductivity as a significant factor to assess

complete treatment [11, 23].

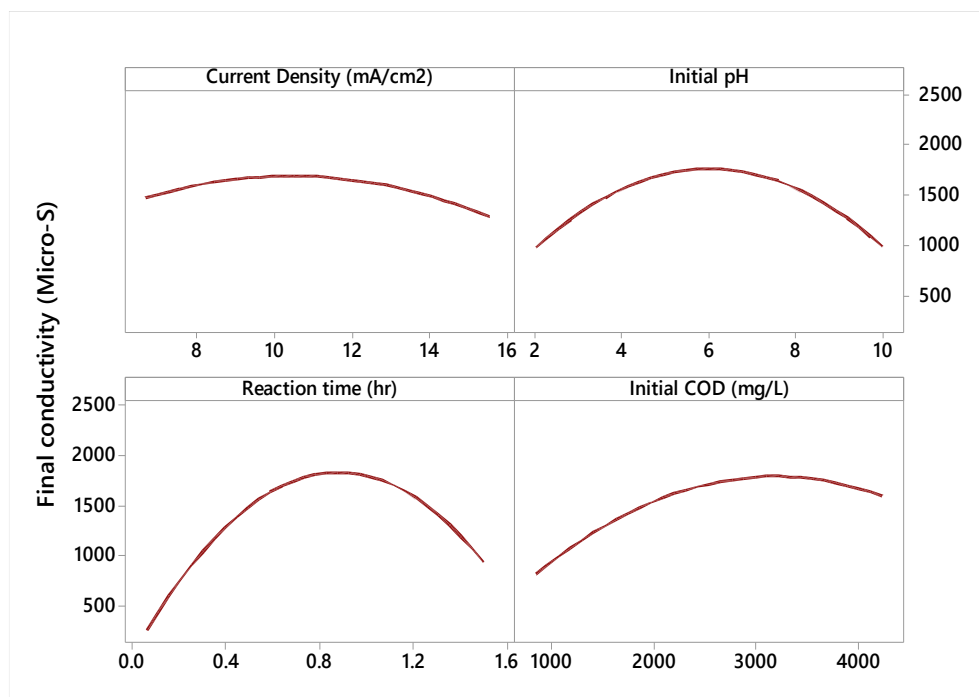


Fig. 8. Represent the effects of: Current density, initial pH, reaction time and Initial COD on the final conductivity, at the mean value of the others

3.2.3.2. Final pH

The final pH of the electrocoagulation (EC) reactor is an important indicator of the chemical conditions during the electrocoagulation treatment and has a great impact on the formation and stability of coagulant species. Water reduction reactions also formed hydroxide ions (OH^-) at the cathodes, which can cause the pH to rise during the electrocoagulation process. At the same time, the dissolution process of the sacrificial electrodes (Al or Fe) generates metal ions that hydrolyze to metal hydroxides, which are used for the removal of pollutants by coagulation and adsorption mechanisms. The amount of pH shift is influenced by many factors, such as initial pH, current density, electrolysis time, composition of wastewater, and electrode material. The final pH is typically best for the formation of insoluble metal hydroxide flocs and increased removal of contaminants in the neutral to slightly alkaline pH range. Hence, measuring the final pH gives a good idea of the efficiency of the reactor and allows for maintaining optimum pH during the electrocoagulation treatment to reduce the need for pH correction after treatment.

a- Effect of current density

As depicted in Fig. 9, final pH plots a gentle, concave-down curve showing a broad peak (maximal pH ~ 7.8) over the intermediate range of current densities (10–12 mA/cm^2) and then gently declines with increasing current density. Regardless of the initial pH (range 2–10), the

final pH remains within the narrow pH range 7–9 across all samples demonstrating the well-documented self-regulatory nature of aluminum electrocoagulation (EC) systems. As OH^- ions are produced at the cathode ($2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$), they will continue to buffer the solution towards neutral-to-alkaline conditions. At high enough rates of OH^- ion production however, this may cause the pH to exceed the optimal condition for the formation of $\text{Al}(\text{OH})_3$ and lead to aluminate formation. This self-buffering characteristic of EC systems is a major advantage of EC and has previously been well-documented by both Hakizimana et al. and Mollah et al. [7, 8].

b- Effect of initial pH

Fig. 9 shows that when treating wastewater at acidic pH levels, the final pH will always be higher than the initial pH. When treating wastewater at basic pH levels, the final pH will generally be the same as or slightly less than the initial pH. However, this "convergence" effect is especially prevalent. In fact, regardless of if the initial pH was 2, 6 or 10, the final pH remained in the 7–9 pH range following EC treatment. These effects result from two mechanisms: i) hydroxide ions (OH^-) being generated at the cathode during the EC process; ii) subsequent hydrolysis of dissolved aluminum (III) ions ($\text{Al}^{3+} + 3\text{OH}^- \rightarrow \text{Al}(\text{OH})_3$), where these ions will consume hydrogen ions (H^+) present in acidic solutions while simultaneously producing additional hydroxide ions (OH^-). One major practical benefit of this natural pH convergence to neutral

is that it eliminates the need for adjusting the pH level as a post-treatment step for EC treated water. Convergence to a neutral pH has been shown repeatedly throughout the literature regarding Al based electrocoagulation processes [7, 12].

c- Effect of reaction time

Fig. 9 presents a nearly linear increase in final pH from ~1.5 (close to initial pH at very early electrolysis times) through approximately 6.5 – 8 at 1.50 hours. The data presented on this panel supports that the self-buffering of EC system pH is a function of time: at very short electrolysis times ($< 0.07\text{h}$), there is inadequate OH^- generation to effectively buffer the solution away from its initial acid-based set points. Over time, increased OH^- generation continues to alkalize the solution and drives it into the stability optimum for $\text{Al}(\text{OH})_3$. The practical implication of this is that sufficient time for electrolysis should be provided so that not only is coagulant generated, but also sufficient time has passed to allow the pH to adjust to the optimal range for $\text{Al}(\text{OH})_3$ formation

and pollutant adsorption. The observed kinetic development of pH in this study is consistent with findings made by both Ebba et al., and Mao et al., [14,18].

d- Effect of initial COD concentration

As seen in Fig. 9, final pH increases as a function of initial COD concentration up to approximately 3000 mg/L and then slightly decreases. At higher concentrations of organic compounds, there is an increased ability of the solution to act as a buffer due to organic acids and dissolved dye intermediates competing against OH^- generation to elevate pH levels. Additionally, there are a larger number of organic substrates available for Kolbe-type reactions at the anode and adsorptive reactions consuming OH^- . The overall trend therefore indicates that the self-regulation of EC system pH is influenced by the buffering capacity of organic compounds in the wastewater matrix, a concept discussed extensively by Naje et al. in their review article examining electrochemical treatment of textile wastewaters [23].

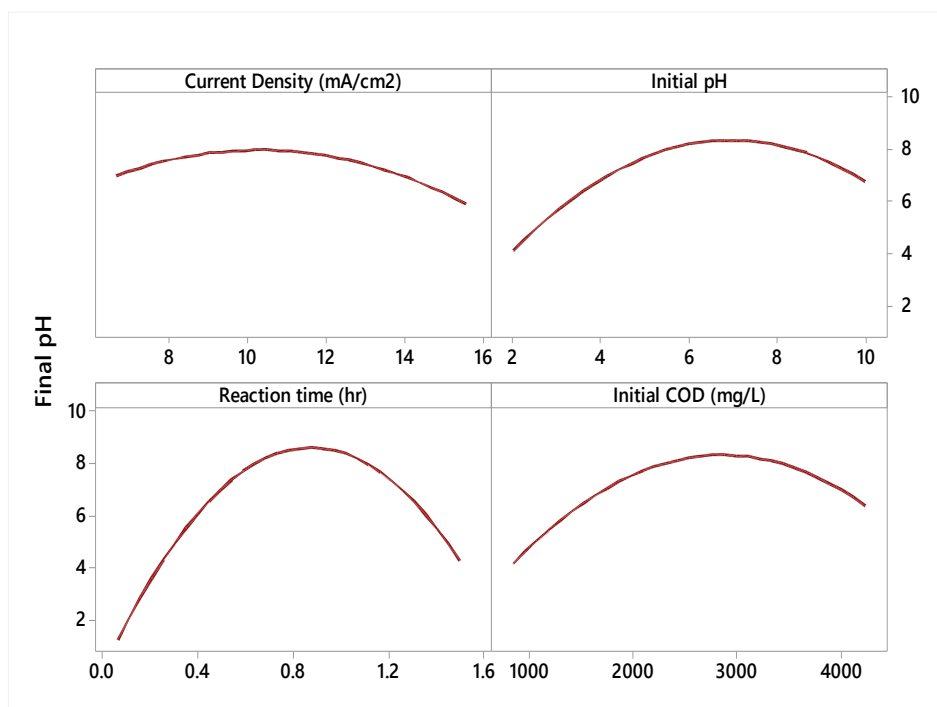


Fig. 9. Represent the effects of: Current density, initial pH, reaction time and initial COD on the final pH, at the mean value of the others

3.2.3.3 Theoretical anode consumption

The theoretical anode consumption in an electrocoagulation (EC) reactor is the amount of the material of the sacrificial electrode, which is dissolved during the treatment process and is usually calculated according to Faraday's law of electrolysis. Its value is directly proportional to the applied current and the time of electrolysis, thus indicating the amount of metal ions discharged into the solution to produce coagulant species. During the dissolution of the anode, metal ions like Al^{3+}

or $\text{Fe}^{2+}/\text{Fe}^{3+}$ are released, which react with water to form metal hydroxides that can help remove pollutants by coagulation, adsorption, and sedimentation processes. The higher the current density, the more rapid the electrode dissolution rate and the greater the theoretical consumption of the anode. This may lead to more efficient treatment with increased coagulant production. Over-consumption of the anode, however, can increase the operating costs and sludge generation, which can decrease the economic viability of the process. Therefore, it is necessary to consider the theoretical anode

consumption to optimize the electrocoagulation performance in terms of the removal efficiency of the pollutants and in terms of the utilization of the electrodes and the sustainability of the whole process.

a- Effect of current density

As shown in Fig. 10, theoretical anode consumption increases almost linearly with current density from around 0.16g at 6.67mA/cm² to about 0.37g at 15.56 mA/cm². The reason for this is because Faraday's Law states that if

you keep the same time and surface area of electrodes, the amount of material that dissolves will be proportional to the current ($m \propto I$). Therefore, the approximately straight line is evidence that there was little or no passivation of the electrodes during the study that would have affected the Faradaic efficiency of Al dissolution. Both Mouedhen et al., and Gu et al., found that Al dosing rates followed Faraday's Law well for both solutions containing chlorides and for a wide range of solution compositions respectively [24, 25].

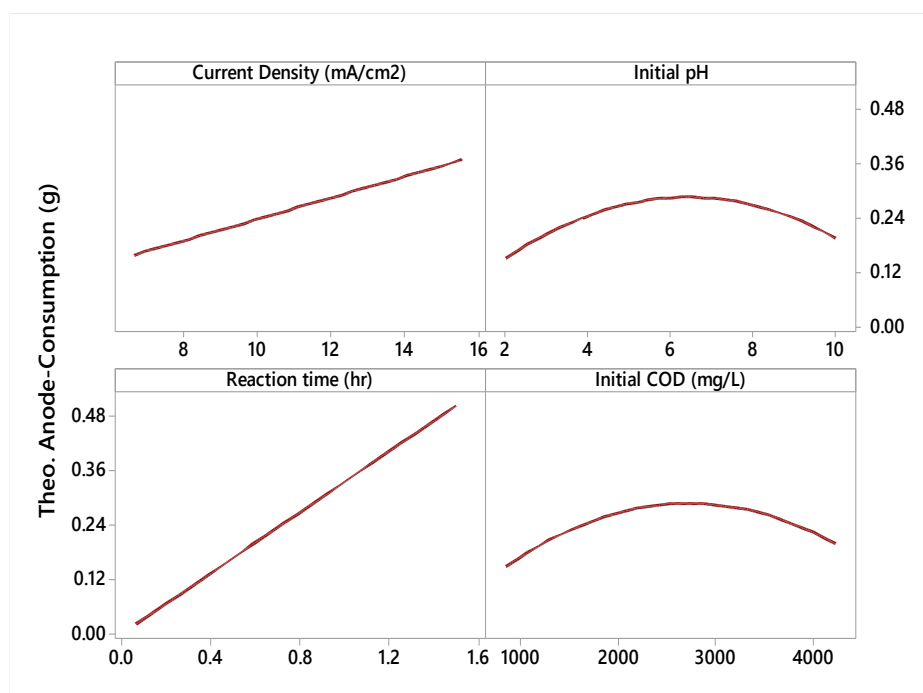


Fig. 10. Represent the effects of: Current density, initial pH, reaction time and initial COD on theoretical anode-consumption, at the mean value of the others

b- Effect of initial pH

Fig. 10 shows a parabola shaped curve, where the theoretical anode consumption peaks in the pH region of 4-7 and decreases significantly towards both strongly acidic (pH 2) and strongly alkaline (pH 10) regions. Although Faraday's Law states that the rate of dissolution of anodes should be independent of pH at a particular point in time, it can be seen from the diagram that there is a pH effect. It had been calculated depending on the measured instance current value, that changes slightly at extreme level of acidity. When the pH becomes too acidic or alkaline, a layer may form on the surface of the electrode, composed of either oxide or hydroxide. These layers inhibit chemical corrosion of the Al, thereby reducing the overall measured current and this may also affect the (faradaic + chemical) Al consumption. Gu et al., and Al-Marri et al., amongst others, have conducted extensive studies into this phenomenon and they have shown that chemical corrosion can lead to excesses of up to 83% in Al dissolution over what is theoretically possible through Faradaic reactions [16,25].

c- Effect of reaction time

As shown in Fig. 10, the reaction time has a linear increase in theoretical anode consumption from essentially zero at 0.07h to ~0.5g at 1.5h. This perfect linear trend is simply a direct mathematical consequence of Faraday's Law whereby the mass of metal consumed by the anode increases linearly with the quantity of charge passed through it ($Q = It$). The gradient of this line ($\Delta m / \Delta t$) is equal to $I_m/z/F$ and therefore the lack of curvature in this line demonstrates that the Al dissolution rate remained constant over all times examined under the conditions studied —i.e., no significant passivation occurred in the time frame studied. This linear relationship has been utilized to estimate costs associated with operational procedures in EC processes and has also been used to determine when anodes need to be replaced in industrial-scale EC applications [18].

d- Effect of Initial COD Concentration

As depicted in Fig. 10, theoretical anode consumption exhibits a concave down maximum in the vicinity of

2500–3000mg/L initial COD after which it declines as COD concentration continues to increase. In theory, according to Faraday's Law, there should be no dependency upon COD concentration since m is dependent only on I , t , M , z and F . However, this apparent dependency exists because in the RSM model employed here; center-point conditions were established using fixed current densities and times as reference points and so the model equations capture statistically based relationships between initial COD concentration and experimental measurements taken from anodic dissolution. There appears to be some indication that intermediate COD concentrations may enhance chemical corrosion of the Al electrodes via pitting corrosion mechanisms that are promoted by Cl^- and assisted by organic acids present in intermediate COD concentrations. High COD concentrations appear to diminish the relative electrochemical driving forces for Al dissolution. This

interpretation supports previous findings concerning extra-Faradaic dissolution mechanisms described by Mouedhen et al., and Hakizimana et al. [8, 24].

3.3. FESEM analysis

The performance of any electrode can be concluded from its morphological structure. In Fig. 11, FESEM surface test for the electrode anode performed at best run (experiment 22) exhibits the most significant surface degradation. At a high current density of 11.11 (mA/cm^2) and a prolonged electrolysis time of 1.5 hr, acidity level of 6 and initial COD concentration related to dyes mixture of 2510 mg/L, the aluminum surface shows deep pitting corrosion and a highly porous, sponge-like structure. The high current density accelerates electron transfer, leading to a honeycomb morphology. This indicates a high rate of coagulant generation.

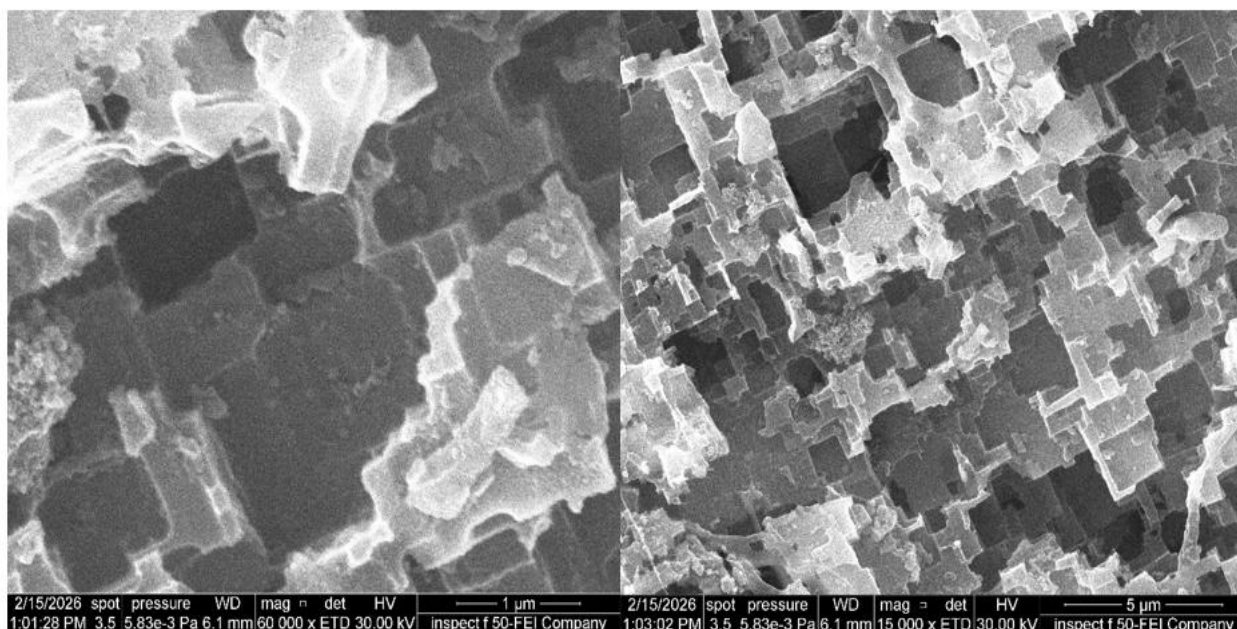


Fig. 11. Al anode FESEM at highest COD reduction experiment 22

4- Conclusions

The present study achieved the successful assessment of the performance of electrocoagulation (EC) treatment of synthetic wastewater using the Response Surface Methodology–Central Composite Design (RSM–CCD) approach in terms of dye effects. The established statistical model showed good predictive ability with a high coefficient of determination ($R^2 = 98.84\%$ and adjusted $R^2 = 97.48\%$), which indicates the reliability of the model for predicting COD removal under different operating conditions. Consequently, the study identified current density and reaction time as the most crucial parameters affecting COD reduction and initial pH as significantly influencing the formation and stability of the coagulating species formed during the EC process. The optimum conditions were a current density of 11.11 mA/cm^2 , an initial pH of 6, a reaction time of 1.5 h, and

an initial COD concentration of 2510 mg/L, for which maximum COD removal efficiency (98.14%) was achieved with minimum specific energy consumption (8.89 Wh/kg COD). The findings also showed that the kind of dyes being used is also an important parameter that affects the efficiency of the EC because the molecular structure and it is different electrochemical characteristics of each dye affect the pollutant destabilization and pollutant removal process. The study also demonstrates the complex effect of the studied operational variables on the properties and the characteristic of the solution after treatment, which can be related to the complexity of the dye mixture solution. The results of this research will help in designing and up-scaling such EC systems for wastewater treatment applications in industry using various dye contaminants.

steps.

References

- [1] D. A. Yaseen and M. Scholz, "Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review," *International Journal of Environmental Science and Technology*, vol. 16, no. 2, pp. 1193–1226, Nov. 2018, <https://doi.org/10.1007/s13762-018-2130-z>
- [2] X. Wang, J. Jiang, and W. Gao, "Reviewing textile wastewater produced by industries: characteristics, environmental impacts, and treatment strategies," *Water Science & Technology*, vol. 85, no. 7, pp. 2076–2096, Mar. 2022, <https://doi.org/10.2166/wst.2022.088>
- [3] M. M. Hassan and C. M. Carr, "A critical review on recent advancements of the removal of reactive dyes from dyehouse effluent by ion-exchange adsorbents," *Chemosphere*, vol. 209, pp. 201–219, Jun. 2018, <https://doi.org/10.1016/j.chemosphere.2018.06.043>
- [4] Y. Liu et al., "Environmental Impacts and Biological Technologies Toward Sustainable Treatment of Textile Dyeing Wastewater: A review," *Sustainability*, vol. 16, no. 24, p. 10867, Dec. 2024, <https://doi.org/10.3390/su162410867>
- [5] Y. Zhang, K. Shaad, D. Vollmer, and C. Ma, "Treatment of Textile Wastewater Using Advanced Oxidation Processes—A Critical Review," *Water*, vol. 13, no. 24, p. 3515, Dec. 2021, <https://doi.org/10.3390/w13243515>
- [6] G. Crini and E. Lichtfouse, "Advantages and disadvantages of techniques used for wastewater treatment," *Environmental Chemistry Letters*, vol. 17, no. 1, pp. 145–155, Jul. 2018, <https://doi.org/10.1007/s10311-018-0785-9>
- [7] M. Y. A. Mollah, R. Schennach, J. R. Parga, and D. L. Cocke, "Electrocoagulation (EC) — science and applications," *Journal of Hazardous Materials*, vol. 84, no. 1, pp. 29–41, Jun. 2001, [https://doi.org/10.1016/s0304-3894\(01\)00176-5](https://doi.org/10.1016/s0304-3894(01)00176-5)
- [8] J. N. Hakizimana et al., "Electrocoagulation process in water treatment: A review of electrocoagulation modeling approaches," *Desalination*, vol. 404, pp. 1–21, Oct. 2016, <https://doi.org/10.1016/j.desal.2016.10.011>
- [9] S. K. Ajjam, B. H. Hlih, and H. H. Alwan, "Enhancing lead ion removal from simulated wastewater through continuous electrocoagulation process: investigating operating parameters and adsorption behavior," *Chemical Papers*, vol. 78, no. 18, pp. 9569–9579, Nov. 2024, <https://doi.org/10.1007/s11696-024-03771-1>
- [10] A. Badejo et al., "Evaluating the performance of an electrocoagulation process using response surface methods for textile wastewater treatment," *Engineering and Technology Journal*, vol. 0, no. 0, pp. 1–9, Aug. 2025, <http://doi.org/10.30684/etj.2025.161784.1974>
- [11] M. Kobya, E. Gengec, M. T. Sensoy, and E. Demirbas, "Treatment of textile dyeing wastewater by electrocoagulation using Fe and Al electrodes: optimisation of operating parameters using central composite design," *Coloration Technology*, vol. 130, no. 3, pp. 226–235, Apr. 2014, <https://doi.org/10.1111/cote.12090>
- [12] P. P. Das, M. Sharma, and M. K. Purkait, "Recent progress on electrocoagulation process for wastewater treatment: A review," *Separation and Purification Technology*, vol. 292, p. 121058, Apr. 2022, <https://doi.org/10.1016/j.seppur.2022.121058>
- [13] S. K. Ajjam, M. A. Aljaleel, B. H. Hlih, and H. H. Alwan, "Nitrate removal from simulated wastewater by electrocoagulation: Impact of operating parameters on removal efficiency and energy consumption," *South African Journal of Chemical Engineering*, vol. 55, pp. 1–10, Oct. 2025, <https://doi.org/10.1016/j.sajce.2025.10.002>
- [14] M. Ebba, P. Asaithambi, and E. Alemayehu, "Development of electrocoagulation process for wastewater treatment: optimization by response surface methodology," *Heliyon*, vol. 8, no. 5, p. e09383, May 2022, <https://doi.org/10.1016/j.heliyon.2022.e09383>
- [15] K. Faheem, S. U. Khan, M. Washeem, and S. U. Khan, "Energy efficient removal of COD from landfill leachate wastewater using electrocoagulation: parametric optimization using RSM," *International Journal of Environmental Science and Technology*, vol. 19, no. 5, pp. 3625–3636, Apr. 2022, <https://doi.org/10.1007/s13762-021-03277-3>
- [16] J. S. Al-Marri, A. B. Abouedwan, M. I. Ahmad, and N. Bensalah, "Electrocoagulation using aluminum electrodes as a sustainable and economic method for the removal of kinetic hydrate inhibitor (polyvinyl pyrrolidone) from produced wastewaters," *Frontiers in Water*, vol. 5, Dec. 2023, <https://doi.org/10.3389/frwa.2023.1305347>
- [17] A. Shahedi, A. K. Darban, F. Taghipour, and A. Jamshidi-Zanjani, "A review on industrial wastewater treatment via electrocoagulation processes," *Current Opinion in Electrochemistry*, vol. 22, pp. 154–169, Jun. 2020, <https://doi.org/10.1016/j.coelec.2020.05.009>
- [18] Y. Mao, Y. Zhao, and S. Cotterill, "Examining current and future applications of electrocoagulation in wastewater treatment," *Water*, vol. 15, no. 8, p. 1455, Apr. 2023, <https://doi.org/10.3390/w15081455>
- [19] M. Romani, F. R. Espinoza-Quiñones, A. N. Módenes, and C. E. Borba, "New insights into the improvement of electrocoagulation performance on the basis of a time-integrated performance index: The pivotal role of electrical conductivity," *Journal of Environmental Chemical Engineering*, vol. 8, no. 4, p. 103902, Apr. 2020, <https://doi.org/10.1016/j.jece.2020.103902>

- [20] P. T. P. Aryanti, F. A. Nugroho, C. Phalakornkule, and A. Kadier, "Energy efficiency in electrocoagulation processes for sustainable water and wastewater treatment," *Journal of Environmental Chemical Engineering*, vol. 12, no. 6, p. 114124, Sep. 2024, <https://doi.org/10.1016/j.jece.2024.114124>
- [21] D. Selvaraj and M. Arivazhagan, "An Integrated (Electrocoagulation and Adsorption) approach for the treatment of textile industrial wastewater: RSM and ANN based optimization," *Water Air & Soil Pollution*, vol. 235, no. 1, Dec. 2024, <https://doi.org/10.1007/s11270-023-06840-5>
- [22] N. Acharya, C. Thakur, and P. K. Chaudhari, "Dataset on statistical reduction of COD by electrocoagulation process using RSM," *Data in Brief*, vol. 28, p. 104944, Dec. 2020, <https://doi.org/10.1016/j.dib.2019.104944>
- [23] A. S. Naje, S. Chelliapan, Z. Zakaria, M. A. Ajeel, and P. A. Alaba, "A review of electrocoagulation technology for the treatment of textile wastewater," *Reviews in Chemical Engineering*, vol. 33, no. 3, Nov. 2016, <https://doi.org/10.1515/revce-2016-0019>
- [24] G. Mouedhen, M. Feki, M. De Petris Wery, and H. F. Ayedi, "Behavior of aluminum electrodes in electrocoagulation process," *Journal of Hazardous Materials*, vol. 150, no. 1, pp. 124–135, Apr. 2008, <https://doi.org/10.1016/j.jhazmat.2007.04.090>
- [25] Z. Gu, Z. Liao, M. Schulz, J. R. Davis, J. C. Baygents, and J. Farrell, "Estimating dosing rates and energy consumption for electrocoagulation using iron and aluminum electrodes," *Industrial & Engineering Chemistry Research*, vol. 48, no. 6, pp. 3112–3117, Feb. 2009, <https://doi.org/10.1021/ie801086c>

تقييم تأثير خصائص الصبغة على كفاءة التخثير الكهربائي في مياه الصرف النسيجي الاصطناعية: دراسة قائمة على منهجية سطح الاستجابة

فاطمة حسين محمد علي^١، شيماء عبدالرحمن احمد^{١*}، فرات ياسر الجابري^{٢,٣}

^١ قسم الهندسة الكيميائية، كلية الهندسة، جامعة بغداد، بغداد، العراق

^٢ قسم الهندسة الكيميائية، كلية الهندسة، جامعة المثنى، المثنى، العراق

^٣ كلية الهندسة، جامعة العين، دبي، الإمارات العربية المتحدة

الخلاصة

تبحث هذه الدراسة الجديدة في تأثير نوع الصبغة - الصبغة الكاتيونية الميثيلين الأزرق (MB) وصبغة الكونغو الأحمر الأنيونية (CR) - على أداء معالجة التخثير الكهربائي (EC) لمياه الصرف الصناعية، وذلك باستخدام تقنية التحسين القائمة على منهجية سطح الاستجابة بتصميم مركب مركزي (Response Surface Methodology - Central Composite Design, RSM-CCD). تم إجراء سبع وعشرون تجربة لتحليل وإيجاد الافضلية تحت تأثير أربعة عوامل، هي: كثافة التيار (ملي أمبير/سم²) ضمن المدى ٦,٦٧ - ١٣,٣٣؛ والرقم الهيدروجيني الابتدائي (pH) ضمن المدى ٢ - ١٠؛ وزمن التفاعل (بالساعة) ضمن المدى ٠,٠٧ - ١,٥؛ والاحتياج الكيميائي للأكسجين (COD، ملغم/لتر) ضمن المدى ٨٤٠ - ٤٢٣٦,٦٧ ملغم/لتر. وقد تم تقييم كفاءة معالجة التخثير الكهربائي من خلال نسبة إزالة الاحتياج الكيميائي للأكسجين (COD) بوصفها متغير الاستجابة الأساسي. حقق نموذج منهجية سطح الاستجابة (RSM) ذو قدرة تنبؤية ممتازة (معامل التحديد $R^2 = 98,84\%$ ؛ ومعامل التحديد المعدل $= 97,48\%$)؛ وأظهرت النتائج التجريبية وجود علاقة ملحوظة بين القيم المقدرة والقيم المقاسة. وأشار تحليل التباين (ANOVA) إلى أن كثافة التيار وزمن التفاعل هما العاملان الرئيسيان المسؤولان عن أكبر التأثيرات في إزالة الاحتياج الكيميائي للأكسجين. كما توصلت الدراسة إلى أن الرقم الهيدروجيني الابتدائي يؤدي دوراً حاسماً في تكوين الأنواع المخترقة والحفاظ عليها. تم الحصول على أقصى كفاءة لإزالة الاحتياج الكيميائي للأكسجين بلغت ٩٨,١٤٪ في ظل الظروف التشغيلية المثلى التالية: كثافة تيار مثلى قدرها ١١,١١ ملي أمبير/سم²، ورقم هيدروجيني ابتدائي قدره ٦، وزمن تفاعل قدره ١,٥ ساعة، وتركيز ابتدائي للاحتياج الكيميائي للأكسجين قدره ٢٥١٠ ملغم/لتر، وقد استُهلك في ذلك ما مقداره ٨,٨٩ واط. ساعة/كغم COD فقط من الطاقة الكهربائية المطبقة. تم أيضاً تتبع العديد من متغيرات الاستجابة في هذه الدراسة لبيان التفاعل المعقد بين المتغيرات التشغيلية وخصائص المحلول النهائي وصفاته. وشملت الخصائص التي جرى فحص تغيراتها: درجة الحرارة النهائية، والموصلية الكهربائية، وجهد المحلول، إضافة إلى الاستهلاك النظري للأنود والاستهلاك النوعي للطاقة. وقد سُجِّل تأثير تآزري معقد أثناء تتبع خصائص المحلول، ويمكن أن يُعزى ذلك إلى تأثير الشحنات السالبة والموجبة للصبغتين، الأمر الذي يعكس سلوكاً غير اعتيادي مقارنةً بإزالة الصبغات المفردة أو خلطات الصبغات من النوع نفسه.

الكلمات الدالة: مياه الصرف الاصطناعية، التخثير الكهربائي، إزالة الاحتياج الكيميائي للأكسجين، نوع الصبغة، التصميم المركب المركزي، تحسين العمليات، منهجية سطح الاستجابة.