Removal of reactive blue dye from simulated wastewater by electrocoagulation using bipolar connection mode

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Abstract

The present study aims to remove reactive blue dye (RBD) from simulated wastewater using a batch electrocoagulation reactor connected to a power source in a bipolar-parallel mode. The aluminum electrodes used in this work have been configured to be the interior two as perforated-plates while the outer two plates as not perforated. This investigation have conducted under the effect of the reaction time, voltage applied, and pH according to the ranges (2-80 min), (15-25 volt), and (4-12), respectively. The experimental design and the analysis of results obtained have done using response surface methodology (RSM) type central composite design (CCD) and Minitab-statistical program. The core findings revealed the treatability of the present configuration of electrodes to achieve higher removal efficiency of RBD. The complete RBD-removal was attained at the optimum values of the operating variables which were 43.75 min, 17.62 volt, and 4 of the reaction time, voltage applied, and pH, respectively. The mathematical models were significant according to the ANOVA test (p<0.001). This study proved the ability of the electrocoagulation technology to remove RBD from wastewater using the present configuration of electrodes.

Keywords: Simulated wastewater; Reactive blue dye (RBD); Electrocoagulation; Bipolar connection; RSM-CCD; Optimization.
1. Introduction

In water bodies, many unused dyes are discharged by textile and paper factories and paper industries. The presence of these dyes in the water causes pollution to the water environment, colors water and increases the demand for chemical oxygen (COD) and this leads to toxicity and bad odor [1-3]. It is important to remove dyes from water because they are a source of contamination. There are several methods for removing such as physical precipitation, chemical oxidation or reduction, filtration, biological and their combination.

But these methods have defects, including chemical methods in which a lot of chemicals are used that cause pollution as well as in terms of economic health [4,5]. As for biological methods in which living organisms are used, they cannot be applied to textile factories water because dyes are considered toxic to living organisms, which leads to an increase in the formation of thrombus and lack of efficiency of the process [6,7].

Electrocoagulation (EC) is an uncomplicated and effective method that treats many types of wastewater and has achieved great success in removing most of the pollutants, including sewage water, including textile factory water [2,8]. The mechanism of EC depends on the release of numerous ions from anode and cathode by the dissolution process then they will interact to form electro-coagulants, i.e. Al(OH)$_3$ in the case of aluminum electrodes, to remove pollutants by adsorption process (Fig. 1) [9]. Usually aluminum or iron anode and cathode are used and this method prevents the use of chemical additives [6,10].

![Fig. 1. A schematic of electrocoagulation technique [9]](image)

Electrocoagulation process does not need to add reagents or chemicals so it is very economical and does not form secondary pollutants and its efficiency is higher than other conventional methods. Easy to design and can be designed for any capacity of processing plant, easy to operate and requires no time to operate sludge formation which is less and easy to be removed [10-12].
This work aims to remove reactive blue dye (RBD) from simulated wastewater using a batch electrocoagulation reactor involves new configuration of electrodes which were connected to a power source in a bipolar-parallel mode. The electrodes used in this work is made of aluminum and have been configured to be the interior two as perforated-plates while the outer two plates as not perforated. The experiments and results were done using response surface methodology (RSM) based central composite design (CCD).

2. Experimental Work

2.1 Chemicals and analytical Analysis:

All chemicals performed in this work are of analytical grade and have used without any additional purification. The samples of synthetic wastewater were prepared with an initial concentration of dye by dissolving a specified amount of reactive blue dye (RBD) in 1000 mL of distillate water. The chemical structure and properties of (RBD) are represented in Fig. 2 and Table 1.

![Chemical structure of (RBD).](image)

**Table 1. Properties of (RB).**

| Chemical form | $\lambda_{\text{max}}$ | Molar mass (g/mol) |
|---------------|----------------------|--------------------|
| C_{22}H_{16}N_{2}Na_{2}O_{11}S_{3} | 585 | 626.50 |

Two gram of NaCl per liter was added for each sample to raise the electric conductivity and minimizing the generation of passivation on electrodes. The pH value was adjusted using Hydrochloric acid (0.1 N) and sodium hydroxide (0.1 N) and measured using a pH-meter device (ATC company, China). The treated samples are drawn at different times to find the final concentration of RBD using a UV-1800 spectrophotometer (Shimadzu Inc., Japan). The final values of RBD and electrodes consumption were measured after each experiment. After each experiment done, the electrodes were washed well using diluted hydrochloric acid and washed several times by distilled water. The energy consumed was calculated according to Eq.1 as follows:

$$\text{Energy Consumption} = \frac{(U \times I \times t)}{(1000 \times V)}$$  

(1)

where: $U$ is the applied voltage (volt), $I$ is final current (Amps.), $t$ is electrolysis time (h), and $V$ is the volume of the polluted water (m$^3$).

The removal efficiency of the RBD was determined according to Eq. 2:

$$Y_{\text{RBD}} \% = \left(\frac{C_0 - C}{C_0}\right) \times 100$$  

(2)
Where \( C_0 \) and \( C \) are the initial and final concentration of RBD (ppm)

2.2 Electrocoagulation reactor

A batch electrocoagulation reactor of 1 L of volume (Fig. 3) is consisting of four plain and perforated plate-electrodes which are manufactured of aluminum. They are connected to a DC-power supply (Model: QJ3005X II; 0–30 volt and 0–5 Amp) in a bipolar-parallel mode. The outer plates are not perforated while the entire two plates are perforated (49 holes with a hole diameter of 0.5 cm). This reactor was placed on a magnetic stirrer (Model: HP-3000; 60–1500 rpm) to provide 200 rpm of stirring speed. Each experiment containing 750 ml of polluted sample that was treated under the impact of the operational variables shown in Table 2.

![Fig. 3. The electrocoagulation reactor: (1) Digital DC power supply; (2) Magnetic stirrer; (3) Cathode; (4) Anode (bipolar electrodes in parallel connection).](image)

Table 2. Operational variables.

| Variables                      | Ranges or constant value |
|--------------------------------|--------------------------|
| Reaction time (min)            | 2-80                     |
| Applied voltage (volt)         | 15-25                    |
| pH                             | 4-12                     |
| Initial RBD concentration (ppm)| 100                      |
| Electric Current (Amp.)        | 5                        |
| Stirring speed (rpm)           | 200                      |

3. Results and discussion

In this work, the effect of the operational variables on the removal efficiency, energy and electrodes consumption. The obtained results of the studied responses are shown clearly in Table 3 as follows.
Table 3
Results of the studied responses

| Run | X₁: Reaction time (min.) | X₂: Applied voltage (volt) | X₃: pH | RBD removal efficiency % | Energy consumption (kWh/m³) | Electrodes consumption (g) |
|-----|--------------------------|---------------------------|--------|--------------------------|----------------------------|---------------------------|
| 1   | 18                       | 17.1                      | 6      | 68.117                   | 12.572                     | 0.52                      |
| 2   | 64                       | 17.1                      | 6      | 95.882                   | 50.687                     | 0.77                      |
| 3   | 18                       | 22.9                      | 6      | 59.647                   | 28.499                     | 0.64                      |
| 4   | 64                       | 22.9                      | 6      | 94.120                   | 136.404                    | 0.98                      |
| 5   | 18                       | 17.1                      | 10     | 35.760                   | 11.378                     | 0.14                      |
| 6   | 64                       | 17.1                      | 10     | 61.529                   | 65.169                     | 2.64                      |
| 7   | 18                       | 22.9                      | 10     | 49.470                   | 26.148                     | 0.70                      |
| 8   | 64                       | 22.9                      | 10     | 80.450                   | 163.556                    | 3.01                      |
| 9   | 2                        | 20.0                      | 8      | 25.860                   | 1.271                      | 0.35                      |
| 10  | 80                       | 20.0                      | 8      | 90.000                   | 170.667                    | 2.50                      |
| 11  | 41                       | 15.0                      | 8      | 61.059                   | 21.047                     | 1.54                      |
| 12  | 41                       | 25.0                      | 8      | 86.212                   | 59.906                     | 1.41                      |
| 13  | 41                       | 20.0                      | 8      | 96.706                   | 46.284                     | 0.36                      |
| 14  | 41                       | 20.0                      | 12     | 27.976                   | 15.671                     | 0.91                      |
| 15  | 41                       | 20.0                      | 8      | 75.153                   | 28.609                     | 0.75                      |
| 16  | 41                       | 20.0                      | 8      | 71.153                   | 36.444                     | 0.69                      |
| 17  | 41                       | 20.0                      | 8      | 71.624                   | 37.356                     | 0.79                      |
| 18  | 41                       | 20.0                      | 8      | 73.389                   | 29.156                     | 0.52                      |
| 19  | 41                       | 20.0                      | 8      | 71.800                   | 28.062                     | 0.99                      |
| 20  | 41                       | 20.0                      | 8      | 74.212                   | 36.262                     | 0.74                      |

3.1 Effect of reaction time

As observed in Fig.3, the RBD removal efficiency increased with the increase of the reaction time at the mean values of the voltage applied and solution pH where the reaction time is a very essential parameter in any electrochemical treatment technique. According to the range chosen in this study (2-80 min), the removal efficiency of RBD had sharply increased to reach more than 85% within 60 min then it tends to slightly minimized due to decrease in the formation of the absorbent material, thus the sites on the surface of the absorbent material become insufficient to adsorb the RBD [13,14]. So, the greater the reaction time, the more absorbent materials, that is, the thrombus that absorbs the dye particles, which leads to a decrease in the concentration of the dye in the solution and a higher removal efficiency [2,8].
3.2 Effect of the applied voltage

Electrocoagulation reactors are extremely dependent in their operation on the voltage or current applied [8,9,15]. The present work investigate the effect of varying the value of voltage applied on the RBD removal efficiency.

Fig. 4. The effect of reaction time on the RBD removal efficiency of 100 mg RBD/L of simulated wastewater (Applied voltage= 20 volt, and pH 8)

Fig. 5. The effect of voltage applied on the RBD removal efficiency of 100 mg RBD/L of simulated wastewater (reaction time= 41 min, and pH 8)

Fig. 4 revealed that the treatability of the present design of electrocoagulation reactor affected by the value of the voltage applied. As seen, the removal efficiency increased with the increase of the voltage applied at the mean values of reaction time and solution pH. The RBD
removal increased from 58% to about 80% when the applied voltage raises from 15 to 25 volt. This could be interpreted that the continuous raising of voltage applied will increase the formation of different ions required to form adsorbents. But the optimum value should be taken into consideration to prevent the excess consumption of electrodes [4,9,16].

### 3.3 Effect of pH

The value of solution pH affects directly the removal efficiency of pollutants presented in any type of wastewater; therefore, this study investigated the impact of solution pH value on the ability of the present reactor to remove RBD from the simulated wastewater. The range of pH selected covered the acidity and base nature of wastewater. As noted in Fig. 5, the lower removal efficiency the more basal solution while the highest removal was obtained at value less than the neutral medium. So, this type of dyes is removed efficiently at the acidic medium [2,11,17].

![Fig. 6. The effect of pH on the RBD removal efficiency of 100 mg RBD/L of simulated wastewater (reaction time= 41 min, and voltage applied=20 volt)](image)

### 3.4 The consumption of energy and electrodes

Figures 6 and 7 reveal the effects of the operational variables on the values of energy and electrodes consumption, respectively.
As observed in Figs. 6 and 7 that most significant effect is that of the reaction time compared to other variables. In both cases, the consumption increased with the increase of the voltage.
applied which is correct according to Eq. 1 for energy consumption and the corrosion pitting for electrodes consumption [18,19].

### 3.5 Mathematical models

Table 4 explained the mathematical models of the studied responses of RBD removal efficiency, energy and electrodes consumption where the ANOVA test proved the significantly of the models estimated (p<0.001).

| Response             | Mathematical model                                                                 | $R^2$ | ANOVA Test |
|----------------------|-----------------------------------------------------------------------------------|-------|------------|
| RBD removal efficiency % | $Y = 204 + 1.07 X_1 - 10.38 X_2 - 13.55 X_3 - 0.0084 X_1^2 + 0.117 X_2^2 - 0.524 X_3^2 + 0.023 X_1 X_2 - 0.0132 X_1 X_3 + 0.800 X_2 X_3$ | 94.94% | $p < 0.001$ F=20.85 |
| Energy Consumption   | $Y = 416 - 7.90 X_1 - 27.9 X_2 - 12.9 X_3 + 0.0386 X_1^2 + 0.528 X_2^2 + 0.228 X_3^2 + 0.294 X_1 X_2 + 0.1086 X_1 X_3 + 0.215 X_2 X_3$ | 95.52% | $p < 0.001$ F=23.70 |
| Electrodes Consumption | $Y = 14.74 - 0.085 X_1 - 1.214 X_2 - 0.382 X_3 + 0.00044 X_1^2 + 0.029 X_2^2 - 0.0074 X_3^2 - 0.0002 X_1 X_2 + 0.0102 X_1 X_3 + 0.0112 X_2 X_3$ | 95.33% | $p < 0.001$ F=22.68 |

### 3.6 Optimization of the operational parameters

The optimum values of the operational variables, reaction time, applied voltage and pH, were estimated as 43.75 min, 17.62 volt, and 4, respectively, using Minitab statistical software which hence the composite desirability (D-indicator) of these results equals 0.928 (Fig. 8). The values of RBD removal efficiency and the consumption of energy and electrodes at these optimal values of parameters were 96.59%, 29.28 kWh/m$^3$, and 0.249 g, respectively.
Fig. 8. The optimum values of the operational variables and responses for the treatment of 100 mg RBD/L of simulated wastewater

4. Conclusion

The present study investigate the treatability of an electrocoagulation reactor contains four plates, two perforated and two not perforated which are connected to a DC-power supply in bipolar parallel connection mode. This electrochemical reactor used to eliminate reactive blue dye (RBD) from simulated wastewater under the effect of the reaction time, voltage applied and solution pH. Response surface methodology based central composite design (RSM-CCD) and Minitab statistical software have been performed to design experiments and analyze results obtained. The core findings of this results proved the efficient ability of the present configuration of electrodes which provide 95.59%, 29.28 kWh/m$^3$, and 0.249 g of the RBD removal efficiency and the consumption of energy and electrodes, respectively. The observed results at the optimum values proved that the present electrocoagulation reactor is cost-effective and economic.

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