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Effect of Operating Parameters on the Electrocoagulation of Reactive Orange 16 Using Aluminium Electrodes

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ABSTRACT. The discharge of coloured dye-containing wastewater from industries such as textiles, paper and plastics is an environmental concern due to its potential adverse effects on aquatic ecosystems and human health. Electrocoagulation (EC) has been widely studied as an alternative technique for dye removal from wastewater due to its simple operation and high removal efficiency. In this study, EC using aluminium electrodes was investigated for the removal of Reactive Orange 16 (RO16) from aqueous solution at an initial concentration of 150 mg L^{-1}. The effects of initial pH, current density and electrolysis time on colour removal efficiency were investigated and discussed. Initial pH substantially affected the colour removal performance. Near-neutral initial pH (measured at 7.73) achieved the highest observed colour removal efficiency of 96.24% after 160 min at a current density of 0.0075 A cm^{-2}. Although near-neutral pH gave the highest observed colour removal efficiency, an acidic initial pH of 3.57 also achieved a comparable colour removal efficiency of 95.91% and reached a removal plateau within a shorter treatment time of 140 min. The solution pH was observed to change during electrocoagulation and generally approached mildly alkaline conditions. Current density influenced both colour removal efficiency and the time required to reach a removal plateau. The highest current density investigated (0.0100 A cm^{-2}) achieved 97.88% colour removal within 110 min, whereas lower current densities required longer treatment periods. The removal of RO16 was attributed to the formation of aluminium hydroxide flocs, which promoted pollutant removal through charge neutralisation, adsorption and sweep flocculation. Overall, electrocoagulation using aluminium electrodes demonstrated high colour removal efficiency under the laboratory conditions investigated and showed potential for the treatment of dye-containing wastewater.

Keywords: Electrocoagulation, Reactive Orange 16, aluminium electrode, colour removal, wastewater treatment.

1. INTRODUCTION

The presence of dyes in water is undesirable because of their colour and potential toxicity. Large quantities of coloured wastewater are generated from industries such as textiles, paper, plastics and printing. Many synthetic dyes are resistant to biological degradation due to their complex molecular structures and may persist in the aquatic environment for a prolonged period. Furthermore, some dyes and their degradation products may exhibit toxic effects, posing potential risks to aquatic organisms and human health. Among the various classes of synthetic dyes, azo dyes represent the largest class and account for a substantial proportion of dyes used in industrial applications (Karagözoğlu & Malkoç, 2023; Saxena & Gupta, 2022).

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Reactive Orange 16 (RO16) is a sulphonated monoazo dye containing a vinyl sulfone reactive group and is widely used in textile dyeing processes (Ma et al., 2014). The discharge of RO16 into water bodies is of concern because reactive dyes are generally designed to be chemically stable and resistant to conventional treatment methods. As a result, considerable effort has been directed towards the development of efficient treatment technologies for dye-containing wastewater.

Various methods have been employed for the treatment of dye-containing wastewater, including adsorption, biological oxidation, chemical coagulation and membrane separation (Shabir et al., 2022). However, each treatment method has its own limitations, including incomplete removal, chemical or energy requirements, sludge generation, membrane fouling, or adsorbent regeneration requirements, depending on the treatment process. Activated carbon has been reported to be an effective adsorbent for dye removal, but its application is often limited by its high cost. Biological treatment, on the other hand, is frequently ineffective for the removal of recalcitrant dyes due to their low biodegradability (Mnif et al., 2026).

Electrocoagulation (EC) has attracted considerable attention as an alternative technique for wastewater treatment (Nigar & Kumar, 2026). In the EC process, coagulant species are generated in situ by the electrolytic dissolution of sacrificial electrodes, commonly aluminium or iron. The process offers potential advantages such as simple operation, reduced chemical addition, and high pollutant removal efficiency. When aluminium is used as the electrode material, Al^{3+} ions generated at the anode react with hydroxyl ions in solution to form aluminium hydroxide flocs, $Al(OH)_3$. These flocs can remove pollutants through charge neutralisation, adsorption, and sweep flocculation (Khandegar & Saroha, 2013).

Several studies have investigated the electrocoagulation of Reactive Orange 16 and other textile dyes using aluminium electrodes. Karagözoğlu and Malkoç (2017) studied RO16 removal from textile wastewater, while Hussain et al. (2023) and Zafar et al. (2024) evaluated the effects of electrode materials and operating conditions on dye removal. Despite these efforts, differences in wastewater characteristics and experimental conditions make direct comparisons difficult and highlight the need for further investigation of key operational parameters. Therefore, this study evaluates the effects of initial pH, current density, and electrolysis time on the electrocoagulation of Reactive Orange 16 using aluminium electrodes.

2. METHODOLOGY

2.1. Materials and Chemicals

Reactive Orange 16 (RO16) dye (dye content ≥70%, molecular weight 617.54 g mol^{-1} and λmax = 493 nm) was obtained from Sigma-Aldrich, India. A stock dye solution was prepared using distilled water and diluted to the required concentration. Sodium chloride (NaCl) (HmbG Chemicals, Malaysia) was used as the supporting electrolyte at a concentration of 300 mg L^{-1}. Hydrochloric acid (0.1 M HCl) and sodium hydroxide (0.1 M NaOH) (Chemiz, Malaysia) were used for pH adjustment. All solutions were prepared using distilled water.

2.2. Experimental Setup

The electrocoagulation experiments were conducted in a batch reactor consisting of a 250 mL beaker containing 200 mL of dye solution. Two aluminium plates (allScience, Malaysia), each measuring 100 mm × 20 mm × 1.55 mm, were used as the electrodes. The effective submerged surface area of each electrode was maintained at 20 cm², and current density was calculated based on this effective electrode surface area. The distance between them was set at 2 cm. Both the electrode orientation and the immersed area were kept constant across all experimental conditions. The electrodes were connected to a DC power supply (GW Instek GPS30300, Taiwan) operating under constant-current mode. A magnetic stirrer (INTLLAB MS500, China) was used to agitate the solution at 200 rpm throughout the experiment to ensure uniform mixing and consistent treatment conditions. A pH meter (Peak Instrument S610L, China) was used for pH measurement, and a visible spectrophotometer (Spectrumlab 721s, China) was used for dye analysis.

A representative electrocoagulation experiment was conducted in duplicate to assess the reproducibility of the experimental procedure. The two runs differed by less than 5%. Subsequent experiments were single runs, representing individual observations rather than statistical replicates.

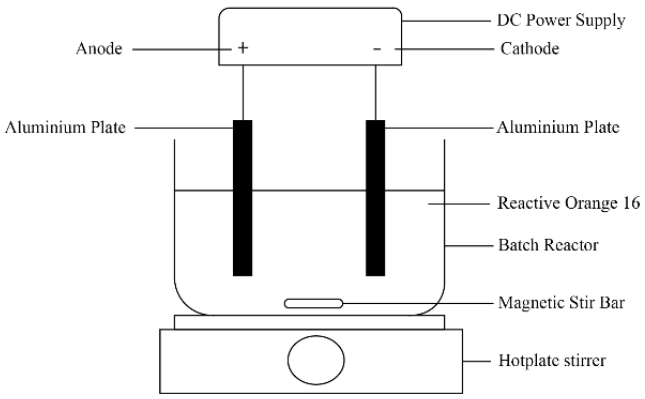

Figure 1. Schematic diagram of the batch electrocoagulation reactor setup.

2.3. Electrocoagulation Studies

At selected electrolysis times, 3 mL samples were withdrawn and filtered through a PTFE syringe filter (0.45 μm). Separate reactors were used for different sampling intervals, with a maximum of three samples per reactor (9 mL or 4.5% of the initial 200 mL volume). The residual dye concentration was determined using a visible spectrophotometer at the maximum absorbance wavelength of 493 nm. The colour removal efficiency (CRE) was calculated as follows:

$$\mathrm{CRE}(\%) = \frac{\mathrm{C_0} - \mathrm{C_t}}{\mathrm{C_0}} \times 100$$

where C_0 and C_t represent the initial dye concentration and dye concentration at time t, respectively.

The dye concentration was determined from the calibration equation:

$$y = 0.0243x + 0.0253$$

where y is the absorbance at 493 nm (dimensionless) and x is the RO16 concentration (mg L^{-1}), with a regression coefficient (R^2) of 0.9997.

2.4. Mechanism of Electrocoagulation

When an electric current is supplied to the EC reactor, aluminium dissolves at the anode, producing aluminium ions according to the following reaction:

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^-$$

At the cathode, water is reduced to produce hydrogen gas and hydroxyl ions:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$$

The Al^{3+} ions generated at the anode undergo a series of hydrolysis reactions in aqueous solution. Duan and Gregory (2003) and Mollah et al. (2001) note that the dominant aluminium species formed depend strongly on the solution pH and may be represented by the following reactions.

Anodic Dissolution:

$$\mathrm{Al^{3+}_{(aq)} + H_2O_{(l)} \rightleftharpoons Al(OH)^{2+}_{(aq)} + H^+_{(aq)}}$$

Cathodic Reduction:

$$\mathrm{Al(OH)^{2+}_{(aq)} + H_2O_{(l)} \rightleftharpoons Al(OH)^{+}_{2(aq)} + H^+_{(aq)}}$$

Hydrolysis Reactions:

$$\mathrm{Al(OH)^{+}_{2(aq)} + H_2O_{(l)} \rightleftharpoons Al(OH)_{3(s)} + H^+_{(aq)}}$$

The overall floc formation reaction may be represented as:

$$\mathrm{Al^{3+}_{(aq)} + 3OH^-_{(aq)} \rightarrow Al(OH)_{3(s)}}$$

This behaviour may be related to enhanced anodic aluminium dissolution and the formation of positively charged hydrolysed aluminium species that can promote dye destabilisation. The distribution of these aluminium species is highly dependent on solution pH, with near-neutral conditions favouring the formation of amorphous $Al(OH)_3$ flocs that enhance pollutant removal efficiency (Duan & Gregory, 2003; Mollah et al., 2001). The formed $Al(OH)_3$ flocs act as coagulating species and remove dye molecules through charge neutralisation, adsorption, and sweep flocculation (Das et al., 2022).

3. RESULTS AND DISCUSSION

3.1. Effect of Initial pH

The effect of initial pH on the colour removal efficiency of RO16 was investigated at a current density of 0.0075 A cm^{-2} and an initial dye concentration of 150 mg L^{-1}. The experiments were conducted at nominal initial pH values of 3, 5, 7, and 9. The corresponding measured pH values were 3.57, 5.14, 7.73, and 9.59, respectively. As shown in Figure 2, colour removal efficiency increased with increasing electrolysis time for all pH conditions studied. However, the colour removal efficiency varied with the initial solution pH.

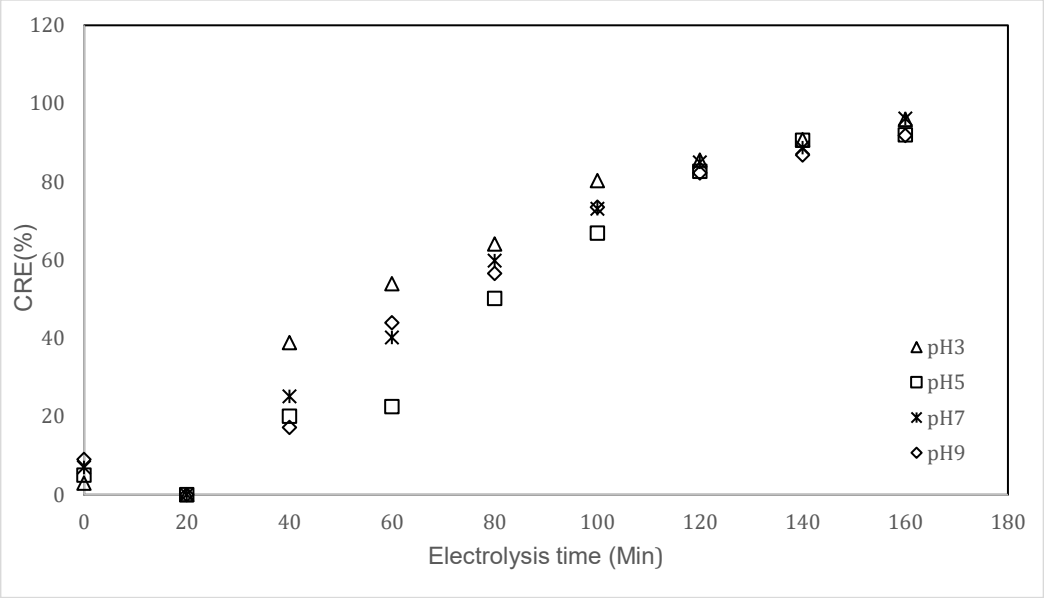

Figure 2. Colour removal efficiency as a function of electrolysis time for RO16 electrocoagulation at different initial pH values (conditions: C_0 = 150 mg L^{-1}, current density = 0.0075 A cm^{-2}, [NaCl] = 300 mg L^{-1}, 200 rpm).

It was found that the nominal pH 7 condition (measured initial pH = 7.73) achieved the highest observed colour removal efficiency (96.24%) after 160 min. The higher removal observed at near-neutral pH may be attributed to the formation of amorphous $Al(OH)_3$ flocs, which can promote dye removal through adsorption and sweep flocculation (Al-Marri et al., 2023; Chen, 2004). Although the highest observed removal was obtained at pH 7.73, the acidic condition (pH 3.57) also achieved a comparable removal efficiency of 95.91% and reached a removal plateau within a shorter treatment time of 140 min. This behaviour may be related to enhanced anodic aluminium dissolution and the formation of positively charged hydrolysed aluminium species that can promote dye destabilisation. In contrast, pH 9 resulted in lower colour removal efficiency (91.95%), which may be associated with the formation of soluble aluminate species that reduce the availability of aluminium species for effective coagulation (Duan & Gregory, 2003).

Notably, the solution pH shifted throughout the electrocoagulation process for all initial conditions, generally converging toward a mildly alkaline state. Initial pH values of 3.57, 5.14, 7.73, and 9.59 shifted to final values of 8.76, 6.90, 8.56, and 9.05, respectively. The increase in pH under the acidic and neutral conditions may be associated with the generation of hydroxyl ions at the cathode during water reduction (Mollah et al., 2001). While the final pH

was higher than the initial pH under the acidic and near-neutral conditions, the pH of the nominal pH 9 solution decreased considerably to 8.23 before rising to 9.05. This behaviour may be associated with the hydrolysis of aluminium species and subsequent formation of aluminium hydroxide flocs during treatment (Mansouri et al., 2011; Weiss et al., 2021).

3.2. Effect of Current Density

The effect of current density on RO16 removal was investigated using the unadjusted initial pH of the dye solution (pH 6.80–7.65), which was near-neutral and close to the best-performing initial pH condition tested (nominal pH 7; measured pH 7.73). As presented in Figure 3, the colour removal efficiency increased with both increasing current density and electrolysis time.

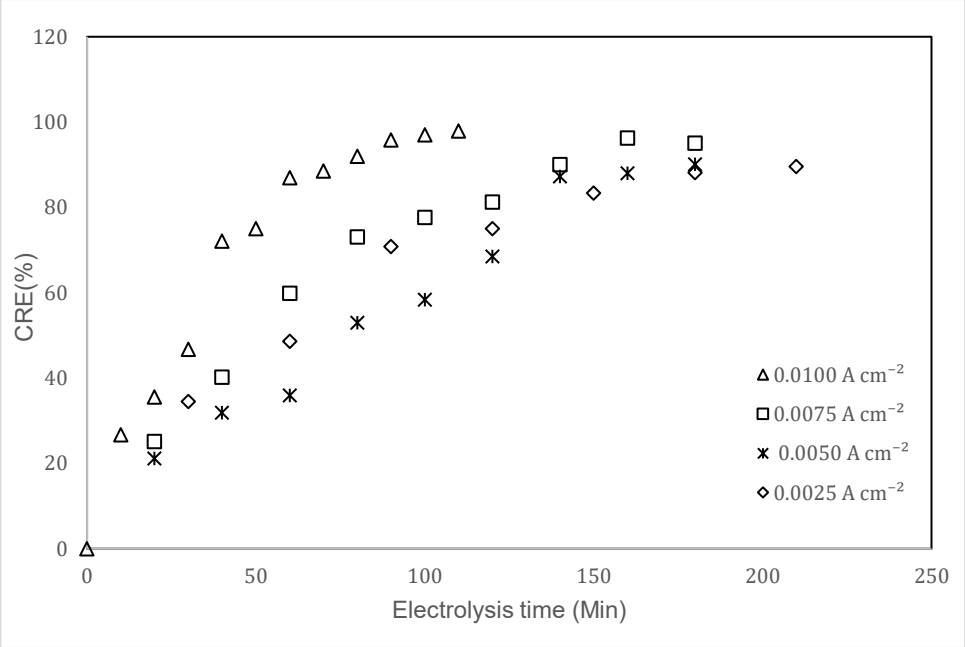

Figure 3. Colour removal efficiency as a function of electrolysis time at different current densities for RO16 electrocoagulation (conditions: original pH 6.80-7.65, C_0 = 150 mg L^{-1}, [NaCl] = 300 mg L^{-1}, 200 rpm).

It was found that the highest current density (0.0100 A cm^{-2}) achieved 97.88% colour removal efficiency within 110 min, whereas the lowest current density (0.0025 A cm^{-2}) achieved 88.17% removal after 180 min. The improved performance at higher current density may be attributed to accelerated aluminium dissolution and increased generation of coagulant species, which promote the formation of $Al(OH)_3$ flocs responsible for dye removal (Holt et al., 2005; Yazıcı Karabulut, 2025). Thus, higher current densities substantially reduced the time required to reach a removal plateau, with the 0.0100 A cm^{-2} condition reaching the plateau earlier than the 0.0025 A cm^{-2} condition. This suggests that increased coagulant generation contributed to faster colour removal.

Consistent with the observations in the initial pH study, the solution pH across all tested current densities shifted to a final mildly alkaline range (7.90 to 8.32). Specifically, initial pH values of 6.93, 7.05, 7.62, and 7.65 shifted to final values of 8.20, 8.32, 8.13, and 7.90, respectively. This suggests that the cathodic hydroxyl generation naturally

maintains a favourable environment for the persistence of active $Al(OH)_3$ flocs, regardless of the specific current applied (Duan & Gregory, 2003; Mollah et al., 2001). Interestingly, at the two highest current densities (0.0075 and 0.0100 A cm^{-2}), the pH unexpectedly peaked at 8.20 and 8.49, respectively, before decreasing slightly towards the end of the treatment. This behaviour is attributed to the ongoing hydrolysis of aluminium species and the subsequent formation of flocs during the later stages of electrocoagulation (Mansouri et al., 2011; Weiss et al., 2021). Although the highest current density achieved the highest colour removal efficiency within the shortest treatment time, increasing current density would also be expected to increase electrical energy consumption and electrode dissolution. Therefore, the highest removal efficiency does not necessarily represent the most energy-efficient operating condition.

3.3. Effect of Electrolysis Time

It was found that colour removal efficiency increased rapidly during the initial stages of electrocoagulation before gradually approaching a plateau with prolonged electrolysis (Figures 2 and 3). This rapid initial decolorization is consistent with the generation of coagulant species immediately following current application, which is a characteristic feature of electrocoagulation processes (Mollah et al., 2001). The time required for the removal efficiency to stabilize was observed to be notably influenced by both initial pH and current density. At a current density of 0.0100 A cm^{-2}, the maximum colour removal efficiency of 97.88% was reached within 110 min, whereas lower current densities required longer treatment periods to achieve peak removal. Similarly, it was observed that acidic conditions shortened the time required to reach a steady state compared with neutral and alkaline conditions.

The faster decolorization observed at higher current densities is attributed to enhanced aluminium dissolution and the increased production of aluminium hydroxide flocs. These flocs have been widely reported in the literature to facilitate RO16 removal via adsorption and sweep flocculation mechanisms (Hussain et al., 2023). The importance of current density in accelerating treatment performance has also been highlighted in recent reviews (Phu et al., 2025). In summary, these findings indicate that increasing current density accelerated the electrocoagulation process and increased the observed colour removal efficiency within the investigated range.

4. CONCLUSION

This study demonstrated that electrocoagulation using aluminium electrodes is an effective method for the removal of Reactive Orange 16 (RO16) from aqueous solution. Colour removal was influenced by initial pH, current density, and electrolysis time. Near-neutral conditions (initial pH 7.73) achieved the highest colour removal efficiency among the pH conditions investigated (96.24%), while the highest current density evaluated (0.0100 A cm^{-2}) produced the maximum colour removal efficiency (97.88%) and the shortest treatment time. The solution pH changed during electrocoagulation and generally approached mildly alkaline conditions. Near-neutral pH was found to favour RO16 removal, primarily due to the formation of aluminium hydroxide flocs that facilitate charge neutralisation, adsorption, and sweep flocculation. Colour removal occurred rapidly during the initial stage of treatment and gradually approached a plateau with increasing electrolysis time. Overall, electrocoagulation using aluminium electrodes showed potential for the treatment of dye-containing wastewater because of its high colour

removal efficiency and simple operation. A limitation of the present study is that the experiments were conducted using synthetic Reactive Orange 16 solutions under laboratory conditions. Therefore, future studies should evaluate the performance of electrocoagulation using actual textile wastewater containing multiple contaminants and more complex water matrices.

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AUTHOR CONTRIBUTIONS

Nur Izzatul Hada Azrin conducted the experiments and wrote the initial draft of the manuscript. Shariff Ibrahim reviewed the data and refined the overall direction of the manuscript. Sabiha Hanim Saleh analyzed the data and provided insightful comments on the text, while Megat Ahmad Kamal Megat Hanafiah provided critical feedback and finalised the manuscript.

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DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

Generative AI tools were used solely to improve language clarity, grammar, and readability of the manuscript. The authors reviewed, edited, and approved the final version of the manuscript and take full responsibility for its content.

DATA AVAILABILITY

The data are available from the corresponding author upon reasonable request.

COMPETING INTERESTS

The authors declare that there are no competing interests.

COMPLIANCE OF ETHICAL STANDARDS

Not applicable.

SUPPLEMENTARY MATERIAL

Not applicable.

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