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Original Article

Optimization of Dye Concentration and Energy Consumption in Electrochemical Treatment of Reactive Blue 19 Textile Effluent for Efficient Color and COD Removal

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Abstract *- The present study introduces a novel investigation into the electrochemical treatment of synthetic Reactive Blue 19 dye using aluminium electrodes in batch mode, with particular emphasis on optimizing operational parameters such as retention time, electrolysis time, and initial dye concentration to enhance process performance. Unlike conventional studies, this work highlights the comparative stability and performance at varying concentrations (50 and 100 mg/L), demonstrating maximum Color Removal Efficiencies (CRE) of 75.96% and 76.8%, respectively, while identifying improved operational stability at lower concentration and superior energy efficiency at higher concentration, thereby providing a balanced techno-economic perspective. Furthermore, the study establishes novelty by integrating kinetic modeling with process optimization, revealing that the removal mechanism follows first-order and pseudo-first-order kinetics, and systematically correlating energy and electrode consumption with treatment time, offering deeper insight into process control. The study confirms electrocoagulation as an efficient and economically viable treatment process. It provides a deeper understanding of concentration-dependent performance and reaction kinetics, supporting its broader application in textile dye wastewater treatment. RB19 removal at 50 mg/L exhibited pseudo-first-order kinetics ($R^2 = 0.985$).*

Keywords *- Electrocoagulation, Reactive Blue 19, Aluminum Electrode, Retention time, Current, Energy*.

1. Introduction

The Textile industry has a huge effect on the environment as it uses large volumes of water and chemicals in textile chemical processing. The huge consumption of water results in the generation of large amounts of effluent, which is required to be treated before being discharged into a natural water body. Reactive Blue 19 (RB19) is one of the most widely used dyes in the textile industry, especially for cotton, rayon, and cellulose-based fibers. Reactive dyes are a special class of dyes that form strong covalent bonds with fibers such as cotton, silk, and wool, giving them excellent durability. They produce bright, vibrant, and long-lasting colors that do not fade easily when exposed to sunlight or frequent washing. Because reactive dyes are water-soluble, they are easy to apply in common textile dyeing and printing processes. The textile industry uses them widely due to their superior color fastness, versatility, and wide range of shades. Moreover, they are cost-effective and suitable for large-scale production, making them ideal for coloring cellulose-based fabrics like cotton and rayon. Reactive Blue 19 is an anthraquinone-based vinyl sulphone dye known for its high resistance to degradation and excellent bonding with cellulose fibers. It forms stable covalent bonds, giving fabrics superior wash and light fastness. Reactive Blue 19 is very resistant to chemical oxidation due to its anthraquinone structure being stabilized by resonance [1].

Because of its persistence, it is widely used as a model pollutant in wastewater treatment studies involving adsorption and electrocoagulation processes [2]. Possible impacts of dye effluent on aquatic life when released into the aquatic ecosystem without appropriate treatment are: (1) Dye can block penetration of sunlight and hamper the growth of photoautotrophic organisms. (2) Suspended solids and oily substances of effluent interfere with the oxygen transfer mechanism of aquatic life. (3) Some inorganic chemicals used in the dyeing process are toxic to aquatic life. (4) Organic compounds undergo chemical and biological changes and deplete the oxygen level of the receiving stream. Removal of color from wastewater is a major environmental concern. A

multitude of research work has been reported in the literature on various color removal techniques, which can be categorized as physical or physicochemical, chemical, biological, and electrochemical [3,4,5]. The mechanism of color removal includes physical separation, which involves the breakdown of dyes and decolorization by adsorption and degradation [6]. Conventional physical treatments like adsorption, filtration, etc., are inefficient in treating dye wastewater due to the higher cost. Conventional biological treatments are inefficient in treating dye wastewater due to the chemical stability and low biodegradability of dyes.

Electrocoagulation (EC) technology offers an alternative technique for treating textile wastewater because of its flexibility and environmental sustainability. Furthermore, EC results in a decreased amount of precipitate or sludge, which sediments rapidly and holds less water. In the EC process, a coagulant is generated in situ through the sacrificial dissolution of the metal anode upon application of current. Simultaneous evolution of hydrogen at the cathode helps in removing oily wastewater and the flocculated particles by flotation. EC is a nonchemical, electrical means of removing suspended solids, dissolved solids, colloidal solids, and soluble salts from water & wastewater [7,8], distillery effluent [9], Paper mill effluent [10], and metal plating wastewater [11].

The electrocoagulation technique has been employed for the treatment of textile effluent containing various types of dyes. However, no study has reported on the use of EC to treat wastewater containing the commonly used dye Reactive Blue 19 at two different dye concentrations. This study is devoted to exploring the potential of EC for the treatment of a synthetic dye solution containing Reactive Blue 19 dye with 50mg/l and 100mg/l concentrations for comparison. The effect of various operational parameters on the efficiency of EC was investigated.

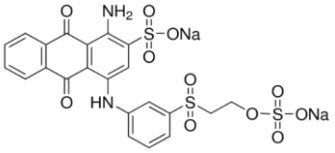
1.1. Data Abbreviations and Nomenclature

a – Cost of electricity/kWh = 8 Rs/kWh
b – Cost of electrode/kg electrode = 250 Rs/kg Al
COD – Chemical oxygen demand (mg/L)
Cf – Final concentrations of COD (mg/L)
C_0 – Initial concentrations of COD (mg/L)
EC – Electrocoagulation
ELC – Electrode consumption (kg of electrode/m³ of effluent)
ENC – Energy consumption (kWh/m³ of effluent)
F – Faraday's constant = 96,487 (C/mole)
I – Applied current (A)
M – Relative molar mass of the electrode = 26.98 (g/mole)
n – Number of electrons in oxidation/reduction reaction = 3
OP – Operating cost (Rs/m³ of effluent)
t – Electrolysis time (h or s)
U – Applied voltage (V)
V – Volume of treated effluent (m³)

2. Materials and Methods

Experiments were performed to investigate the effects of parameters such as dye concentration, electrolysis time, and retention time on the color and COD removal efficiencies of a synthetic Reactive Blue 19 dye solution. The characteristic of RB19 is shown in Table 1.

Table 1. Characteristics of Reactive Blue 19 Dye

Characteristics of Reactive Blue 19 Dye	
Parameter	**Value**
Dye	Reactive Blue 19
Trade Name	Remazol Brilliant Blue R
Appearance	Blue grain powder
Chemical class	Anthraquinones
Color	Dark Blue
Odor	None
Molecular Formula	$C_{22}H_{16}N_2O_{11}S_3Na_2$
Molecular Wt.(g/mol)	626 gm/mol
Molecular Structure	
λ_{max} (nm)	630 nm

The experiments were conducted in a batch mode of operation with a sample of 500ml. Solutions of 100 mg/l concentration and 50mg/l concentration were prepared by dissolving the dye in distilled water. An aluminum sheet of 50mm x 50mm x 5mm (length x width x thickness) was used as both positive and negative electrodes. The electrode was dipped 4 cm into the solution, and the submerged area of the electrode was 20 cm^2. The electrodes were connected to a DC power supply (PROZHAOXIN PS-305D), providing a range of 0-30 V and 0-10A. The contents of the beaker were agitated by a magnetic stirrer (BEXCO Magnetic stirrer 2 Ltr) to maintain uniform concentration in the beaker. After the electrolysis duration, the dye solution was allowed to settle for retention times ranging from 5 min to 120 min. After that retention time, the supernatant was filtered through filter paper (Lab World Test filter paper of 8–10-micron pores). The filtered liquid was measured to determine the CRE and COD removal efficiency. The schematic diagram of the experimental setup is shown in Figure 1. The conductivity of the Reactive Blue 19 dye solution was adjusted by adding NaCl to the solution. The dye concentration in the solution was determined from its absorbance characteristics using the standard method of photoelectric (APHA 1998) by a spectrophotometer (Manti Lab Digital spectrophotometer, wavelength 340- 960 nm, LED display). The maximum absorption wavelength λmax (nm) = 630 nm of Reactive Blue 19 was determined by measuring the absorbance at different wavelengths. The conditions for the experiments are shown in Table 2.

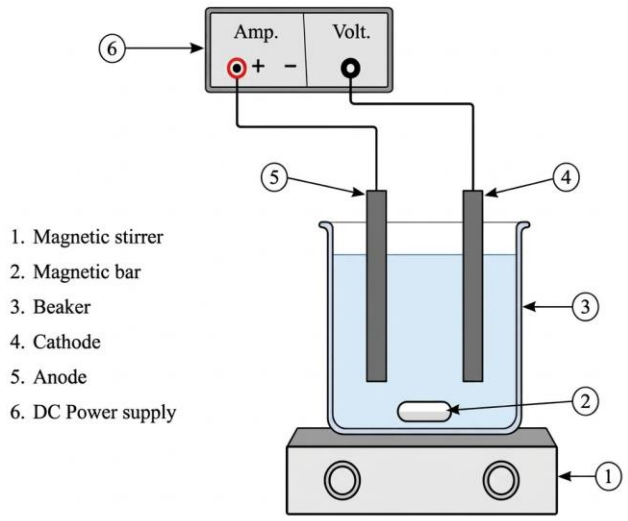


Fig. 1 Schematic Diagram of Electrocoagulation Set Up

Color Removal Efficiency (CRE) was calculated using the following equation

CRE (%) = (Ao – At)/Ao x 100

where CRE = Color Removal Efficiency (in %) Ao & At are the absorbance at 560 nm of the reaction solution at time t=0 & t=t, respectively.

Chemical Oxygen Demand (COD) of Reactive Blue 19 dye solution was measured by the standard method for examination of water (APHA 1998) at time t=0 & t=t, respectively, and COD removal efficiency was calculated.

Table 2. Values of Different Operating Parameters

Parameter	Value
Electrolysis time	10 min – 80 min
Current density	15 mA/cm2
Conductivity	1000 µS/cm
Retention time	10 min-100min
Dye Contraction	50mg/l and 100mg/l
Distance between electrodes	1.2 cm

3. Results and Discussion

Experiments were performed for the removal of color and COD from the synthetic dye solution containing Reactive Blue 19 as follows:

3.1. Effect of Electrolysis Time

Figure 2 illustrates the influence of electrolysis time on the percentage Color Removal Efficiency (%CRE) of Reactive Blue 19 at initial dye concentrations of 50 mg/L and 100 mg/L using the Electrocoagulation (EC) process. The %CRE increases progressively with increasing electrolysis time due to the continuous dissolution of the aluminium anode ($Al \rightarrow Al^{3+} + 3e^-$) and the in situ formation of gelatinous $Al(OH)_3$ flocs ($Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$), which effectively destabilizes and adsorbs dye molecules. The maximum %CRE of 79.47% was achieved at 50 min for the 50 mg/L solution, while the 100 mg/L solution attained a maximum %CRE of 76.8% at 40 min. Beyond the optimum electrolysis time, the %CRE of the 100 mg/L solution gradually decreased, which can be attributed to electrode passivation, excessive floc accumulation, and re-dispersion of adsorbed dye molecules, reducing the effective adsorption sites. In contrast, the 50 mg/L solution maintained consistently higher %CRE values (80.70–81.22%) at longer electrolysis times owing to the higher coagulant-to-pollutant ratio and improved floc–pollutant interactions.

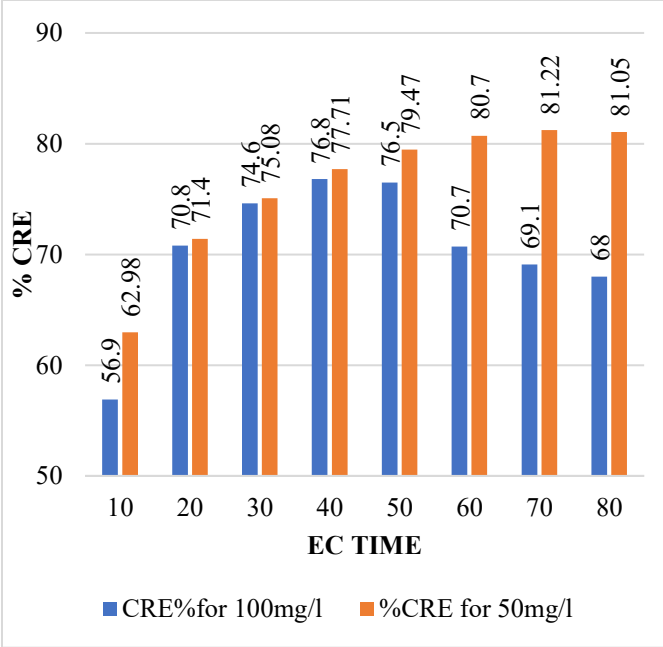


Fig. 2 Effect of Electrolysis Time on the %CRE

This behaviour is consistent with Faraday's law (m=ItM/zF), which states that the amount of coagulant generated is directly proportional to electrolysis time, thereby enhancing color removal until an optimum treatment duration is reached. The results demonstrate that electrolysis time is a critical operational parameter governing the generation of aluminium hydroxide coagulants and the subsequent adsorption of dye molecules. An optimum electrolysis time of 50 min was identified for the 50 mg/L solution, beyond which no significant improvement in %CRE was observed, indicating the attainment of equilibrium between coagulant generation and dye removal.

3.2. Effect of Retention Time on CRE

The effect of retention time, defined as the duration for which the treated effluent was allowed to remain undisturbed after Electrocoagulation (EC) before filtration, was studied for

two different initial dye concentrations of Reactive Blue 19, i.e., 100 mg/L and 50 mg/L. The purpose of this analysis was to understand the influence of post-treatment sedimentation on the Color Removal Efficiency (CRE) of EC-treated samples. The results are shown in Figure 3.

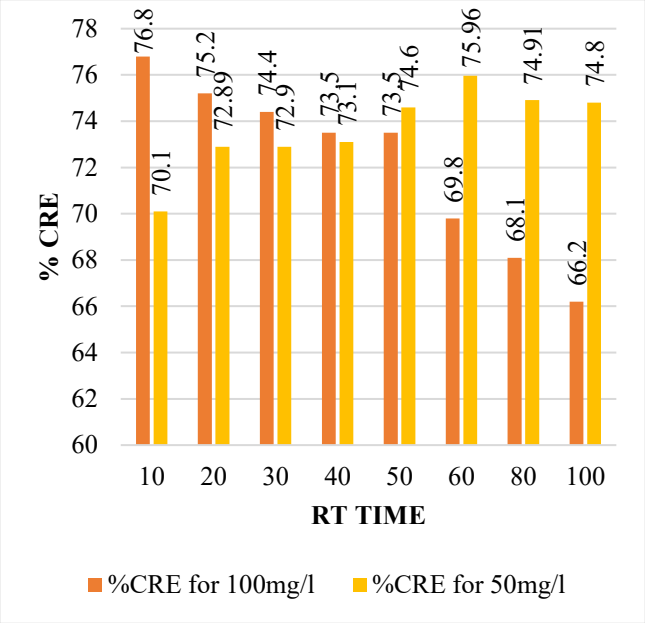


Fig. 3 Effect of Retention Time on CRE

For the 100 mg/L solution, CRE was observed to be 76.8 % at 10 min, which gradually decreased with increasing retention time, reaching 66.2 % at 100 min. This downward trend suggests that prolonged standing after electrolysis leads to the re-dispersion or partial dissolution of previously coagulated dye particles back into the solution. Possible causes include floc compaction and breakdown, release of entrapped color species, and minor re-oxidation or desorption processes during extended quiescent periods. The optimum retention time for higher dye concentration was thus found to be relatively short (≈ 10–20 min), beyond which no additional improvement occurred.

In contrast, for the 50 mg/L dye concentration, the CRE increased from 70.1 % at 10 min to a maximum of 75.96 % at 60 min, and then stabilized (~ 74–75 %) up to 100 min. The improvement at lower concentration indicates that settling promotes effective separation of fine flocs and enhances clarification, as the lighter particle load allows better gravitational settling and less risk of re-suspension. The gradual rise in CRE with time shows that adequate settling (≈ 50–60 min) is beneficial for complete floc sedimentation in dilute systems.

Overall, the results indicate that retention time significantly affects post-EC clarification efficiency, and its effect varies with initial dye concentration. For concentrated solutions (100 mg/L), shorter settling durations are preferred to avoid secondary color release, while for dilute effluents (50 mg/L), longer retention up to 60 min ensures maximum clarification. Prolonged settling can either improve or reduce apparent removal efficiency depending on suspension stability and floc characteristics. [2].

3.3. Effect of COD Removal for different Dye Concentrations

As shown in the data, the COD removal was 50% for the 100 mg/L solution and 59% for the 50 mg/L solution of Reactive Blue 19 dye. The higher COD removal at lower dye concentration (50 mg/L) can be attributed to the greater availability of electrogenerated coagulant species (Al^{3+} and $Al(OH)_3$) relative to the organic load, which enhances pollutant adsorption and oxidation. In contrast, at higher concentration (100 mg/L), the limited amount of active coagulant per dye molecule leads to incomplete oxidation and slower organic matter removal, resulting in a lower COD reduction.

Furthermore, increased dye concentration tends to raise the solution's viscosity and color intensity, reducing current efficiency and mass transfer during the electrochemical process. Hence, the results clearly indicate that lower initial dye concentrations favor better COD and color removal performance due to improved electrocoagulation kinetics and charge neutralization efficiency.

3.4. Effect of Dye concentration on Energy consumption using the performance of EC

Also, Energy consumption (ENC) (kWh/m3), Electrode consumption (ELC) (kg/m3), and operating cost (OP) were observed throughout the experiments. The following equations were adopted from the literature, and resultant ENC, ELC, and OP are tabulated in Table 3.

Table 3. ENC, ELC, OS for 50mg/l dye concentration

FOR 50 MG/L DYE CONCENTRATION	
Parameter	**Value**
Energy consumption (ENC)	8.34 kWh/m³
Electrode consumption (ELC)	0.234 kg Al/m³
Energy cost	₹66.72/m³=$0.73/m³
Electrode cost	₹58.5/m³=$0.64/m³
Total operating cost (OP)	₹125.22/m³=$1.36/m³

Removal efficiency (COD) (%) = ((Co-Cf)/Co) x100

Energy consumption (ENC) (kWh/m3) = UIt/V

Electrode consumption (ELC) (kg/m3) = ItM/nFV

Operating cost (OP) = (a x ENC) + (b x ELC)

The operating cost obtained for the treatment of 50 mg/L RB19 dye solution was ₹125.22 m^{-3} (US$1.36 m^{-3}), comprising energy cost of ₹66.72 m^{-3} (US$0.73 m^{-3}) and electrode cost of ₹58.50 m^{-3} (US$0.64 m^{-3}). The energy consumption of 8.34 kWh m^{-3} is comparable with the range

reported for aluminium electrocoagulation systems treating textile wastewater, where operating costs generally vary between US$0.8 and US$3.0 m^{-3}, depending on current density, treatment time, wastewater characteristics, and electrode configuration. Studies by Kobya, Mollah, and Emamjomeh [13,14,15] have similarly reported that electricity consumption and electrode dissolution are the dominant contributors to the operating cost of electrocoagulation processes. The relatively low operating cost achieved in the present study indicates that the aluminium electrode provides efficient dye removal while maintaining an economically acceptable energy requirement. Therefore, the proposed electrocoagulation process demonstrates good potential for practical application in textile wastewater treatment.

A comparison of the results of the present study with the studies reported in the literature is shown in Table 4.

When compared with previous electrocoagulation studies on Reactive Blue 19, the present investigation provides a comprehensive techno-economic evaluation by quantifying electrical energy consumption (4.48–8.34 kWh/m^3), aluminium electrode consumption (0.134–0.234 kg Al/m^3), and operating cost (0.75–1.36 USD/m^3) under optimized operating conditions. While earlier studies primarily emphasized dye removal efficiency or reported only qualitative cost reductions, the present work establishes practical operational benchmarks for energy and electrode utilization. The relatively low energy and aluminium consumption, achieved under optimized current density and conductivity, indicate efficient in-situ generation and utilization of $Al(OH)_3$ coagulant species with minimal electrical losses, thereby enhancing pollutant removal while reducing operating expenses and demonstrating the technical feasibility of the proposed electrocoagulation process for large-scale textile wastewater treatment.

3.5. Kinetic Study for Dye Removal

Kinetic analysis provides quantitative insight into the rate and mechanism of dye removal during electrocoagulation.

In reactive dye wastewater treatment, dye molecules are removed primarily through adsorption and coagulation by in-situ generated metal hydroxide flocs.

Table 4. Comparison of results of the present study with the studies reported in the literature

No.	Pollutant	Operating Conditions	Electrode Material	Electrical Energy Consumption	Electrode Consumption	Operating Cost	Reference
1	Reactive Blue 19 (synthetic solution)	EC-Flotation with rotating bipolar multiple disc electrodes; 50 mg/L dye; short electrolysis times	Novel bipolar EC-F electrodes (rotating & static)	Reduced vs static EC (not reported)	-	Lower than conventional EC (qualitative)	Keyikoglu & Can (2021) [16]
2	Reactive Blue 19 (textile effluent mixture)	Electrocoagulation at pH 7–10; lab-scale reactor; 1% shade dye	Aluminium / Aluminium	-	-	Moderate (electricity + Al dissolution)	Fatima & Shaikh (2024) [17]
3	Reactive Blue 19 (comparative EC study)	Batch EC; current density ~4.17 A/m^2	Aluminium (monopolar)	-	-	≈ 6.72 USD/kg dye removed	Keyikoglu (2021) [12]
4	Reactive Blue 19 (ultrasound-assisted hybrid EC)	Ultrasound + EC; 50 A/m^2; 100 mg/L dye	Fe–Fe and Al–Al	Lower than conventional EC	-	Reduced due to shorter EC time	Chemosphere (2023) [18]
5	Reactive Blue 19 (Present study)	Batch EC; current density 15 mA/cm^2; Conductivity 1000 µS/cm	Al–Al	4.48–8.34 kWh/m^3	0.134–0.234 kg Al/m^3	$0.75–$1.36/m^3)	Present study

Estimation of the corresponding rate constants allows determination of the reaction kinetics and efficiency of the electrocoagulation process.

The model that best fits the experimental data indicates the dominant mechanism controlling dye removal, whether it is surface adsorption, charge neutralization, or mass transfer, as reported in studies on Reactive Blue 19 (RB19) [16].

The kinetic study was carried out for the removal of RB19 dye from its synthetic solutions of different initial concentrations of dye: 50 and 100 mg/l. The following equations were used to carry out the kinetic study:

3.5.1. First-Order Kinetic Model

Assumes the dye removal rate is directly proportional to the dye concentration.

$$-\frac{dC}{dt} = k_1 C$$

Integrated form:

$$\ln\left(\frac{C_0}{C_t}\right) = k_1 t$$

Where:
C_0 = initial dye concentration (ppm)
C_t = dye concentration at time t (ppm)
k_1 = first-order rate constant (min^{-1})

3.5.2. Second-Order Kinetic Model

Assumes the removal rate is proportional to the square of the dye concentration.

$$-\frac{dC}{dt} = k_2 C^2$$

Integrated form:

$$\frac{1}{C_t} - \frac{1}{C_0} = k_2 t$$

Where k2 is the second-order rate constant ($ppm^{-1}\cdot min^{-1}$).

3.5.3. Pseudo-First-Order Kinetic Model

Assumes the removal rate depends on the difference between the dye concentration and its equilibrium value.

$$-\frac{dC}{dt} = k_{app}(C - C_e)$$

$$-\frac{dC}{dt} = k_{app}(C - C_e)$$

Integrated form:

$$\ln\left(\frac{C_t - C_e}{C_0 - C_e}\right) = -k_{app} t$$

Where:
Ce = equilibrium dye concentration (ppm)
k_{app} = apparent rate constant (min^{-1})

Table 5. Parameters of the kinetics study of RB19 dye from the synthetic solution

Initial Dye Conc. (mg/L)	k_1 (min^{-1})	k_2 ($ppm^{-1}\cdot min^{-1}$)	kapp (min^{-1})	R^2 (Best Fit)
100	0.025	0.00018	0.030	0.982
50	0.028	0.00020	0.033	0.985

The kinetic study revealed that the electrocoagulation process for the 50 mg/L RB19 solution was well described by the pseudo-first-order kinetic model, as evidenced by the high coefficient of determination (R^2 = 0.985). The first-order rate constant (k_1 = 0.028 min^{-1}) and the apparent rate constant (kapp = 0.033 min^{-1}) were slightly higher than those obtained for the 100 mg/L solution, indicating a faster removal rate at the lower initial dye concentration. This behavior can be attributed to the higher availability of electrochemically generated Al $(OH)_3$ flocs and active adsorption sites relative to the number of dye molecules. At lower dye concentrations, the coagulant species are sufficient to effectively destabilize and adsorb dye molecules, resulting in enhanced mass transfer and rapid pollutant removal. In contrast, increasing the initial dye concentration increases the competition among dye molecules for the limited adsorption and coagulation sites, thereby reducing the apparent reaction rate. The excellent agreement between the experimental and predicted data confirms that the pseudo-first-order kinetic model satisfactorily describes the electrocoagulation mechanism for RB19 removal under the investigated conditions.

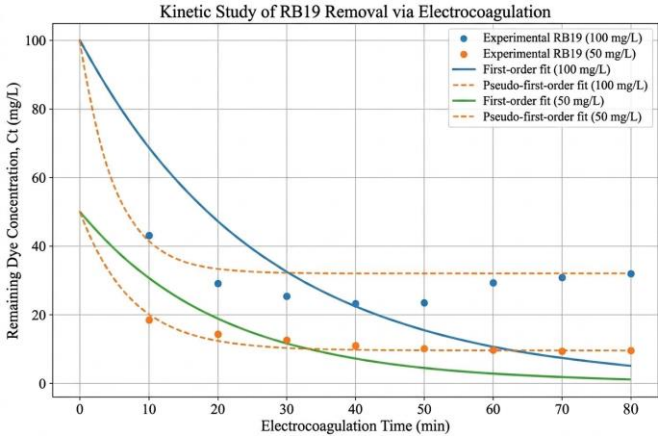


Fig. 4 Kinetic study of Reactive Blue 19 removal via electrocoagulation at initial dye concentrations of 50 and 100 mg/L, showing experimental data and first-order and pseudo-first-order kinetic model fits

Figure 4 illustrates the kinetic behavior of Reactive Blue 19 (RB19) removal during electrocoagulation at initial dye concentrations of 50 and 100 mg/L. Experimental concentration–time data were fitted using first-order and pseudo-first-order kinetic models. A faster decrease in dye concentration was observed at a lower initial concentration (50 mg/L), indicating enhanced mass transfer and adsorption onto

in situ generated metal hydroxide flocs. The pseudo-first-order model provided a better representation of the experimental data, suggesting that adsorption-controlled mechanisms dominate the RB19 removal process.

3.6. Statistical Analysis of Color Removal Efficiency Using ANOVA

Single-factor Analysis of Variance (ANOVA) was employed to evaluate the effect of Electrocoagulation (EC) time and dye concentration on Color Removal Efficiency (CRE). The results, as tabulated in Table 7, show a statistically significant difference among the studied groups, as the calculated F value (9.71) exceeded the critical F value (3.47) at the 95% confidence level, with a p-value of 0.00103.

This confirms that variations in EC operating conditions and dye concentration significantly influence CRE. The mean CRE increased from 70.43% at 100 mg/L to 76.20% at 50 mg/L, as shown in Table 6, indicating improved treatment efficiency at lower dye concentrations. The relatively low variance observed for CRE at both concentrations compared to EC time suggests stable removal performance under optimized conditions.

Table 6. Mean and Variance Analysis of EC Contact Time and CRE (%) at Varying Dye Concentrations (n=8)

Parameter	No. of observations (n)	Total	Mean	Variance
EC time (min)	8	360.00	45.00	600.00
CRE (%) at 100mg/L	8	563.40	70.43	40.82
CRE (%) at 50 mg/L	8	609.61	76.20	40.14

These findings demonstrate that dye concentration is a critical factor governing electrocoagulation efficiency and support the selection of lower influent concentrations for enhanced color removal with reduced process variability.

Table 7. Statistical Significance Analysis of Process Parameters using Single-Factor ANOVA

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F Value	p-value	F Critical
Between Groups	4408.84	2	2204.42	9.71	0.00103	3.47
Within Groups	4766.76	21	226.99	—	—	—
Total	9175.6	23	—	—	—	—

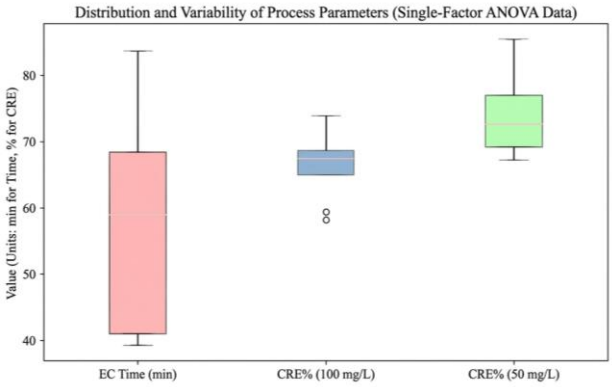


Fig. 5 Distribution, means, and variability of EC time, CRE%(100mg/l) and CRE%(50mg/l)

Figure 5 shows the distribution, means, and variability in three different boxes marked in red, blue, and green.

- EC Time (Red Box): This group shows the widest distribution. The high variance (600.00) is reflected in the height of the box and the length of the whiskers, indicating that the time intervals were broadly spread out relative to the performance results.
- CRE% at 100 mg/L (Blue Box): The mean is significantly higher than the EC time (70.43%), and the box is much more compact due to the lower variance (40.82). This indicates more consistent removal performance at this concentration.
- CRE% at 50 mg/L (Green Box): This represents the most efficient group with the highest mean (76.20%). The compact nature of this box (variance of 40.14) shows that the removal efficiency was stable and consistently outperformed the 100 mg/L group.

4. Conclusion

1. Electrocoagulation using Al–Al electrodes effectively treated synthetic Reactive Blue 19 wastewater, achieving maximum color removal efficiencies of 75.96% and 76.80% for initial dye concentrations of 50 and 100 mg/L, respectively. The experimental results followed pseudo-first-order kinetics, enabling the prediction of color and COD removal behavior under varying operating conditions.
2. Although both dye concentrations exhibited comparable color removal efficiencies, the 50 mg/L solution demonstrated superior overall treatment performance by achieving higher COD removal (59% versus 50%), indicating more efficient utilization of electrogenerated Al $(OH)_3$ flocs, enhanced charge neutralization, and improved sweep coagulation due to a favorable coagulant-to-pollutant ratio.

3. A comprehensive techno-economic assessment revealed electrical energy consumption of 4.48–8.34 kWh/m³, aluminum electrode consumption of 0.134–0.234 kg/m³, and operating costs of 0.75–1.36 USD/m³. The higher operating cost observed for the 50 mg/L solution was primarily attributed to the longer electrolysis time required to achieve optimum treatment efficiency rather than the initial dye concentration itself.
4. Compared with previously reported electrocoagulation studies on Reactive Blue 19, the present work provides quantitative benchmarks for energy consumption, electrode dissolution, and operating cost in addition to treatment performance, thereby demonstrating the technical feasibility and practical applicability of the proposed electrocoagulation process for textile wastewater treatment.
5. The kinetic analysis confirmed that RB19 removal at 50 mg/L followed pseudo-first-order kinetics ($R^2 = 0.985$), with faster removal due to the higher availability of Al $(OH)_3$ flocs.
6. The investigated dye concentrations (50 and 100 mg/L) represent the initial operating conditions evaluated in this study and should not be considered universal optimum concentrations. Future work should investigate a broader range of dye concentrations together with optimization of current density, electrode configuration, inter-electrode spacing, electrolyte concentration, and reactor design, followed by pilot-scale validation and integrated cost–energy analysis to facilitate industrial implementation.

Conflicts of Interest

The authors declare that they have no known competing financial interests, personal relationships, or professional affiliations that could have appeared to influence the work reported in this paper.

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Ethical Consideration

Ethical approval was not required for this study as it did not involve human participants, animals, or personal data. The research was conducted using laboratory-prepared synthetic dye solutions following standard experimental procedures.

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