

Electrochemical Degradation of Reactive Dyes in Textile Industrial Wastewater by Modified Electrodes

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Research Article

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Abstract

This research was formulated to introduce an electrochemical degradation for the degradation of reactive dyes of the textile industrial wastewater applying a full factorial experimental design. Electrochemical degradation is a green process which immensely reduces the chemical consumption of the wastewater leaving no impurities. Three factors with three-levels were used i.e. the NaCl electrolyte concentrations of 2, 4.5, 5.8 g/L, pH 4.2, 5.8, and 6.9, and reaction time 12.4, 15.5, and 20 min. The experiment was expected to generate 27 runs but due to the Design Expert 12, the number of experimental runs became 20. DC power supply of 14.6 V was used for the electrochemical degradation system whereas chemicals such as nitric acid (400 g/L), sulphuric acid (1.5 mg/L), and oxalic acid solution (100 g/L) were used for surface modification of the electrodes. The textile industrial wastewater was characterized based on the standard method of APHA. Dye, COD, BOD₅, and pH of the textile industrial effluent were found to be 0.35 ± 1.00 Abs., 1,711.55 ± 2.00 mg/L, 450.00 ± 3.00 mg/L, and pH of 6.63 ± 0.30, respectively. The maximum color removal was 94.89% at the optimum experimental condition after the results validated by design expert 12. These optimum conditions were the electrolyte concentration 5.1 g/L, pH 6.5, and reaction time 17 min, whereas the minimum color removal of 63.0% was recorded. The regression analysis of the color removal ($R^2 = 0.95$) depicts that electrolyte concentration was the dominant factor for the electrochemical degradation.

1 Introduction

The world-wide dye manufacturing industry amounts to nearly 700,000 to 800,000 tons per year (Hassaan and El Nembr 2017, Siddique, Rizwan et al. 2017). Textile manufacturing is one of the most water-consuming industries (Basha, Sendhil et al. 2012); 80 to 400 L of water is essential for producing 1 kg of textiles, and a great amount of highly polluted wastewater is generated (El-Sayed, Awad et al. 2014, Körbahti and Turan 2016, Bilińska 2017). It is estimated that around 2 to 50% of the applied textile dyes remain unfixed and are discharged into the surrounding water body (Chatzisyneon, Xekoukoulotakis et al. 2006).

Due to their special properties like good clothing application, color fastness, and the capacity of the reactive groups to bind on textile fibers by covalent bond formation, reactive dyes are the most frequently used in the textile industry compared to other textile dyes. They are successfully used in cellulose, wool and polyamide dyeing. Their usage is also well known in textile printing operations. The global production of reactive dyes is increasing every year (Bilinska, Gmurek et al. 2015) and their consumption reached 60,000 tons in 1988 and 178,000 tons in 2004 (Rezaee, Ghaneian et al. 2008, Ghaly, Ananthashankar et al. 2014).

Huge volumes of wastewater generation by textile industries is one of the consequences of uncontrolled demand for textile articles, dyeing and finishing (Koby, Demirbas et al. 2009), which leads to extreme water consumption (Bilińska 2017) and this in turn produces different potential pollutants like surfactants, detergents, and suspended solids (Najafpoor, Davoudi et al. 2017). The main pollution in the

textile wastewater came from dyeing and finishing processes. These processes require the input of a wide range of chemicals and dyestuffs, which are organic compounds of complex structure (Kariyajjanavar, Narayana et al. 2011, Stergiopoulos, Dermentzis et al. 2014).

The textile wastewater is characterized by high COD (Jovic, Stanković et al. 2013) and low BOD₅ value, which makes it non-biodegradable (Ledakowicz, Bilińska et al. 2012). It is also hard-to-treat due to its strong color (Chatzisyneon, Xekoukoulotakis et al. 2006), large amount of suspended solids, variable pH, salt content, and high temperature (Körbahti and Turan 2016). The wastewater generated in the reactive dyeing process is marked by the presence of high salinity and coloration, high pH value and surface active agents (Silva, Aquino Neto et al. 2011).

The treatment of textile dye effluent is difficult and ineffective with conventional biological processes because many synthetic dyes are very stable to light and temperature (Siddique, Rizwan et al. 2017). Reactive dyes are resistant to biodegradation under aerobic conditions, whereas anaerobic treatment is applied successfully. But, the anaerobic process, i.e. the breakdown of reactive dyes, leads to the formation of aromatic amines, which may be more toxic than the dye molecules (Bilińska 2017).

Most of traditional wastewater treatment methods containing dyes are becoming inadequate to treat the wastewater. However, in recent years, the use of electrochemical techniques attracting attention (Ganzenko, Huguenot et al. 2014) for the treatment of wastewater (Fadhil and Ghalib 2011). Large availability of electrochemical cells (Bersier, de León et al. 2008), versatility (Hmani, Samet et al. 2012), easy operation (Khezrianjoo and Revanasiddappa 2015), relatively lower cost (Kobyas, Demirbas et al. 2009), no/less production of sludge during the treatment (Sirés, Brillas et al. 2014), can operate at low temperature (Araújo, Oliveira et al. 2014) and total mineralization to carbon dioxide and water (Feng, Yang et al. 2016) are some of the major advantages of the electrochemical approach (Miled, Said et al. 2010, Silva, Aquino Neto et al. 2011). Therefore, this paper is aimed for the development of electrochemical degradation of reactive textile dyes of wastewater based on optimization approach that was studied by design expert 12. The experimental design of the three independent factors with three-levels were considered i.e. electrolyte concentration (2, 4.5, and 5.8 g/L), pH (4.2, 5.8, and 6.9), and reaction time (12.4, 15.5, and 20 min). The interaction effects of the three independent factors were clearly identified.

2 Materials And Methods

2.1 Sample Collection and Characterization

Composite sampling techniques were applied to collect the wastewater samples three times a day for three consecutive days, and to get a representative sample, they were thoroughly mixed. The sample was collected from Bahir Dar Textile Share Company. The company's total water consumption and discharge/generation of wastewater from the textile process were 440m³/day and 380m³/day respectively. Polyethylene plastic box was used as a sample container after being thoroughly washed

with detergents and 10% HNO₃. The icebox was used to keep the sample cold for about 4°C in order to inhibit undesired hydrolysis during transportation to Addis Ababa Science and Technology University. Finally, the sample was preserved in a refrigerator at 4°C until the analysis was completed in the lab room. The analysis of each wastewater parameter and the corresponding testing method is indicated in Table 1.

2.2 Electrode Preparation

The platinum-iron anode electrode was found from Bahir Dar Textile Share Company. It was damped as a waste after it finished its functional working period, whereas the stainless steel cathode was prepared from a new knife. A similar size of both the anode and the cathode electrodes were prepared to conduct duplicated treatments at a time throughout the experimental work and the overall set up of the experimental design was indicated in Fig. 1. Accordingly, the dimensions of the electrodes were 60 mm in length, 15 mm in width, and 10 mm in depth. All the prepared platinum-iron electrodes' surfaces were successively polished using sandpaper on rough stone using water as a lubricant and cleaning agent. The alloy substrate surface was cleaned with sandpaper again and again and then treated with sulfuric acid (1.5 mg/L) to remove any oxides. Finally, the prepared electrodes were soaked in nitric acid (400 g/L) for 10 min and then, they were chemically treated by boiling (68°C) oxalic acid solution (100 g/L) for 5 min. For good results, it was dried at a temperature of 40°C. Electrolysis was carried out using the platinum-iron alloy electrode using a sodium chloride solution (2.0–5.8 mg/L) which was prepared from an analytical graded chemical in the laboratory. The electrochemical degradation of the textile industrial wastewater which contained a high concentration of color was performed in a 250 mL Pyrex glass beaker. In this treatment system, platinum-iron electrodes were used as working electrodes while stainless steel electrodes served as cathodes. The electrodes were connected to a DC power supply with a model FESTO (14.60 V), while the reading of the current was performed using a digital multimeter.

Table 1
Physicochemical parameters of textile industrial wastewater and their corresponding testing methods

S. No	Parameters	A specific method for each parameter
1	Dye	APHA 2120 D, Spectrophotometric – Multi-wavelength method
2	COD	APHA 5220 B, Open reflux method
3	pH	Hach HQD field case Model 58,258-00
4	BOD ₅	APHA 5210 B, 5-days BOD test
5	TSS	APHA 2540 D. Total suspended solids dried at 103–105°C
6	TS	APHA 2540 B, Total solid dried at 103–105°C
7	EC	Hach photometer HQD field case, Model 58,258-00

Table 2
The full factorial experimental design of electrochemical method with the three factors and three levels

Variables	Low factors	Middle factors	High factors
Reaction time (min) (A)	12.4	15.5	20
pH (B)	4.2	5.8	6.9
Electrolyte concentration (g/L) (C)	2	4.5	5.8

2.3 Experimental Design

The experiment was performed with the three selected experimental factors at the three levels as indicated in Table 2. The experimental design was formulated as a 3^3 which is expected to generate 27 runs, but the number of experimental runs was reduced to 20 runs due to Design Expert 12. The predicted dye removal was studied using the quadratic regression model. During the experiment period, the initial dye concentration was 0.3502 Abs. at room temperature and this concentration was used throughout the experiment. However, the dye removal values were expressed as an independent variable that was determined using electrochemical method performance in percentages (%). The level of each factor was designated as lower, middle, and higher factors respectively.

The color removal percentage was calculated using Eq. 1.

$$\%R = \left(\frac{Abs_i - Abs_f}{Abs_i} \right) * 100$$

.....(1)

where %R is the dye removal percentage, Abs_i is the initial dye concentration and Abs_f is the final dye concentration (Santos, Morão et al. 2008, Najafpoor, Davoudi et al. 2017).

The regression analysis was carried out using the quadratic model equation and the response surface methodology was also used to plot the relationship between the dependent and independent variables. In addition to experimental values, the interaction effects of the predicted values on the color removals were well studied. Compared to the linear, quadratic and cubic regression models, the quadratic regression model was well described based on the experimental data. A detailed explanation is given in Eq. 2.

$$Z_{dye} = a_0 + a_1A + a_2B + a_3C + a_{12}AB + a_{13}AC + a_{23}BC + a_{11}A^2 + a_{22}B^2 + a_{33}C^2$$

..... (2)

Where, Z_{dye} is the predicted dye removal, A, B, and C are the contact time, pH, and electrolyte concentration, respectively. And also, α_0 is the intercept, $\alpha_1, \alpha_2, \alpha_3$ are linear coefficients, $\alpha_{12}, \alpha_{13}, \alpha_{23}$ are interaction coefficients and $\alpha_{11}, \alpha_{22}, \alpha_{33}$ are squared coefficients. The electrochemical degradation of the dye concentration was tested using ANOVA analysis for the quadratic regression model. In this ANOVA test, the significance of the regression model was checked at a 97% confidence level.

3 Results And Discussion

3.1 Characteristics of Wastewater

The physicochemical properties of textile industrial wastewater test results were analyzed and they were higher than Ethiopia's discharging limit values as shown in Table 3. The total solid of $6,206.00 \pm 3.00$ mg/L is a high concentration and it has clearly shown that chemicals and other input materials are intensively used. The pH of the wastewater was within the tolerable range which can be discharged. The common pH range of Ethiopia's textile industrial wastewater was from 6.00 to 9.00 (Authority 2010). However, the concentration of the effluent like BOD_5 of 450.00 ± 3.00 mg/L was above the maximum permissible limit of Ethiopia's industrial effluent discharging limits of 50 mg/L. Therefore, the effluent has a significant effect on the environment and it should be treated before discharged using wastewater treatment technologies. Similarly, the concentration of the total suspended solids was $5,179.70 \pm 2.00$ mg/L. Discharging such a concentrated amount into the nearby water bodies prevents the penetration of sunlight and can also change the physicochemical characteristics of the water.

Table 3
Physicochemical characteristics of the wastewater sample taken from the equalization tank

Parameter	Units	Sample Average Value
Dye	Abs.	0.3502 ± 0.20
COD	mg/L	$1,711.55 \pm 2.00$
BOD_5	mg/L	450.00 ± 3.00
pH	-	6.63 ± 0.30
TSS	mg/L	$5,179.70 \pm 2.00$
TS	mg/L	$6,206.00 \pm 3.00$
EC	$\mu\text{S}/\text{cm}$	$1,352.00 \pm 3.0$

COD and BOD₅ are the critical indicators of the oxidation capacity of textile wastewater. The COD and BOD₅ concentration values were found to be $1,711.55 \pm 2.00$ mg/L, 450.00 ± 3.00 mg/L respectively, as shown in Table 3. These results clearly showed that the wastewater was highly loaded with organic matter. The biodegradability index (BI) of this study is 0.26, which is less than 0.3 and refers to non-degradability of the wastewater indicating biological treatment is ineffective, whereas the BI values between 0.3 and 0.6 can easily be degraded by conventional biological treatment methods. In general, COD and BOD₅ values were higher than the wastewater discharging limits of 150 mg/L and 50mg/L respectively, set by the Ethiopian Commission of Environment, Forest and Climate Change (Authority 2010). This wastewater can pose environmental pollution. For this to prevent, electrochemical degradation is the right decision.

3.2 Experimental Results Analysis

The results of the dye removal from the textile wastewater are shown in Table 4. The maximum dye removal of 94.0% was recorded at the optimum experimental results of the three independent factors, which are the reaction time of 15.5 min, pH 5.8, and NaCl electrolyte concentration of 4.5 g/L at the given experimental setup. Out of the sixty experimental runs (before average value taken) or twenty experimental runs (after average value taken), only five experiments had less than 80% dye removal performance. Similarly, seven experimental runs had more than 90% dye removal efficiencies. The dye removal was highly influenced by the three experimental factors at the three levels. However, the minimum dye removal of 63.0% was found on the fifth experimental run of the reaction time of 12.4 min, pH 4.2, and NaCl electrolyte concentration of 2.0 g/L. Interchanging the values of the three independent experimental factors resulted in increasing the degradation of dye by 31% from the lowest to the highest degradation efficiency. These high efficiencies were the outcome of interaction effects of the experimental variables. The maximum dye removal efficiency was very promising and higher than the maximum permissible discharging limits for textile industrial effluent.

Table 4

The levels of electrochemical experimental factors and their corresponding dye removal

Run	A:Reaction Time (minutes)	B:pH	C:Electrolyte Concentration (g/L)	Dye Removal (%)
1	15.5	5.8	2.0	85.0
2	12.4	6.9	2.0	84.1
3	20.0	4.2	5.8	90.2
4	20.0	4.2	4.5	90.7
5	12.4	4.2	2.0	63.0
6	12.4	4.2	5.8	72.7
7	15.5	5.8	2.0	78.6
8	15.5	5.8	4.5	93.4
9	15.5	5.8	4.5	85.4
10	20.0	4.2	2.0	63.9
11	20.0	5.8	4.5	92.7
12	15.5	6.9	5.8	90.3
13	12.4	5.8	5.8	77.4
14	20.0	6.9	5.8	89.7
15	20.0	5.8	4.5	91.1
16	15.5	5.8	4.5	94.0
17	15.5	4.2	4.5	85.2
18	12.4	6.9	4.5	83.0
19	15.5	4.2	4.5	84.9
20	20.0	6.9	2.0	80.0

3.3 Regression Analysis for Dye Removal

The regression model was used to check the impact of interactions on dye removal. But such interactions were irrelevant at a 95% confidence level. Hence, such expressions were excluded from Eq. 3 since they have no considerable impact on dye removal. Only the two-way interaction effects were evaluated for the wastewater treatment better performance. Important terms on dye removal were summarized in Eq. 2 and this equation can be used to make predictions about the response of the variables of each factor. The equation can also be useful for identifying the relative impact of the factors on dye degradation. The

ANOVA test is indicated in Table 5. The p -values for these factors were less than 0.05 at which the ANOVA test was performed (95% confidence level). All those terms were statistically significant. This showed good fitness of the model with the experimental data.

$$Z_{\text{dye}} = 91.14 + 4.41 A + 4.39 B + 5.19 C - 1.34 AB + 4.06 AC - 3.90 BC - 5.25 A^2 - 1.01 B^2 - 6.90 C^2$$

..... (3)

where Z_{dye} is the predicted dye removal (wastewater treatment performance in %), A, B and C are the coded values of the reaction time, pH and NaCl electrolyte concentration respectively, whereas the two-way interactions of AB , AC , and BC refer to the reaction time with pH, the reaction time with NaCl electrolyte concentration and the pH with NaCl electrolyte concentration, respectively.

The fit of the model is best described by the coefficient of determination R^2 , which was found to be 0.9193, indicating that 91.93% of the variability is explained by the model. The high value of adjusted R^2 (0.8467) indicated that the model fit well with the experimental data. This showed a high correlation between the observed and the predicted values, which means the regression model provides an excellent explanation of the connection between the independent variables and the responses. The level of accuracy or significance of the models for dye removal was tested by p -values (p -value less than 0.05 best fit and p -value more than 0.1 is not significant). The p -value for the dye removal was 0.0008, showing good fitness for the regression model as shown in Table 5. The Adequate Precision (11.9013), which is more than 4.0, is desirable to navigate the design space.

Table 5
ANOVA result response for quadratic model for the dye removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1416.40	9	157.38	12.66	0.0002	significant
A-Reaction time	216.85	1	216.85	17.45	0.0019	
B-pH	212.86	1	212.86	17.13	0.0020	
C-Electrolyte concentration	282.90	1	282.90	22.76	0.0008	
AB	15.93	1	15.93	1.28	0.2840	
AC	126.98	1	126.98	10.22	0.0096	
BC	121.70	1	121.70	9.79	0.0107	
A ²	97.63	1	97.63	7.86	0.0187	
B ²	2.71	1	2.71	0.2178	0.6508	
C ²	188.22	1	188.22	15.14	0.0030	
Residual	124.29	10	12.43			

$R^2 = 0.9193$; Predicted $R^2 = 0.6477$; Adjusted $R^2 = 0.8467$; Adequate Precision = 11.9013.

The comparison of the predicted and actual values is described in Fig. 2. The plot of the predicted value against the actual value showed that there is a favorable relationship between the two results. The predicted value in the plot describes its degree of accuracy to the actual value. The plot clearly implies a noble correlation between the two values. This means that the irregularity in prediction by the model is practically insignificant. External residuals of the experimental operation were used to check whether a run is consistent, assuming the chosen model holds.

3.4 The Effect of Each Factor on the Dye Removal

The removal efficiency of the dye was improved with increasing reaction time, as is indicated in Fig. 3. The removal efficiency of the dye has effective degradation (92.06%) up to 17.6 minutes. But, when reaction time increased beyond 18 min, the dye removal had the tendency to decrease, which was indicated after equilibrium was reached. Therefore, reaction time is one of the most important factors that influence the degradation of the textile dye in the wastewater treatment performance.

It is also possible to examine the effect of pH on the dye removal efficiencies as demonstrated in Fig. 3. In electrochemical degradation, recorded values indicate that pH is not affected significantly during the experiments and showed that it just moves to higher values (basic direction). This shows that the

production of OH⁻ ions is greater than H⁺ ions, resulting in a shift of pH to the basic region. The pH increases because of hydrolysis, ionization, and HOCl/OCl⁻ consumption reactions, and the production of hydroxyl ions and oxygen evolution reactions. The maximum rate of degradation or faster dye removal was achieved at a relatively low acidity close to neutral due to the presence of ClO⁻ is higher than Cl₂ and HClO. In some cases, pH effect interpretation is a difficult task due to the pH interaction with many components of the wastewater in the degradation system.

Increasing NaCl electrolyte concentration has increased the removal efficiency of the dye as indicated in Fig. 2. More than 92% decolorization was achieved between 4.3 g/L and 5.1 g/L NaCl electrolyte concentration. Increasing NaCl concentration increases the decolorization efficiency by generating HOCl/OCl⁻ redox reagents up to the optimum level (5.1 g/L) for dye removal. No decolorization was found in the absence of an electrolyte NaCl solution.

3.5 The Interactive Effects of the Factors on Dye Removal

Examination of the interactive effects of the three independent factors (reaction time, pH and NaCl electrolyte concentration) is very important for the optimization of the wastewater treatment process. The response surface plots and their corresponding contour plots of dye removal were generated with one independent factor kept constant, and by varying the other two within the given experimental ranges.

3.5.1 Interactive Effects of Reaction Time and pH

The interaction effect of the reaction time and pH on the degradation of the textile dye was studied and the results are demonstrated in Fig. 4. The values of the two independent factors were varied within the experimental ranges. In this regard, NaCl electrolyte concentration was kept constant. The interaction pattern was in an increasing fashion to some extent, and gradually it started to reduce. The prediction areas were green, yellow, and red. Adjusting the reaction time to 17.18 and pH to 6.90 has reached the dye removal efficiency of 94.96% by keeping the NaCl electrolyte concentration constant at 4.00 g/L. The predicted value of the minimum dye degradation efficiency was 63.00% at a minimum reaction time of 13 min and pH 4.8. The maximum predicted and experimental values were a good fit.

3.5.2 Interactive Effects of Reaction Time and Electrolyte Concentration

The interactive effects of the reaction time and the NaCl electrolyte concentration on the degradation of the textile dye were examined in Fig. 5. Increasing both factors (the reaction time and the NaCl electrolyte concentration) was effective to a certain extent in the degradation of the dye, as shown in the curved prediction area of the 3D surface. Increasing both the reaction time and electrolyte concentration up to 18.53 min and 5.14 g/L respectively, enhanced the dye removal efficiency to 94.01% while pH was kept at 5.50, as shown in the darkest red section of the graph. Increasing both of these factors has efficiently increased the dye degradation. This prompt response of the factors was clearly experienced by both the

surface and contour plots. Increasing or decreasing both the reaction time and the NaCl electrolyte concentration resulted in a quick change in the dye removal efficiencies as compared to other interactive effects. After certain changes, the interactive effects on dye removal have reached a steady state and the percentage variation of dye degradation has been reduced.

3.5.3 Interactive Effects of pH and Electrolyte Concentration

The interactive effects of the pH and electrolyte concentration on the dye degradation were studied and the interaction patterns are described in Fig. 6. Increasing the pH and the NaCl electrolyte concentration increased the degradation of the dye. The maximum dye removal of 94.53% was attained at pH 6.90 and the electrolyte concentration of 4.33 g/L at keeping the reaction time of 16 min. These interactive effects certainly improved the degradation performance of the dye to a certain extent. The electrolyte concentration change looks more sensitive than the pH because the pH has the role of interaction with different components in the wastewater.

The individual interactions had less influence on the dye degradation than interactive effects. This amounts to interactive effects of 1.2–2.1% of the dye degradation and individual interactions of 1.4% of the dye removal.

3.6 Optimization and Verification

Dye removal efficiencies are optimized by considering three independent factors. Optimization of the dye removal efficiencies was improved by harmonizing the efficient utilization of the three independent factors at one time. After prediction was done, the optimized and desired (desirability = 0.97) results were run again for better degradation efficiency. Hence, it was found to have 94.89% dye removal efficiency. Due to optimization, an additional 0.89% degradation efficiency was recorded.

4 Conclusions

The emerging textile industries have a substantial contribution to the economic growth of the world, but the untreated discharge from the wastewater plant is persistently affecting the surface and ground water and public health in various places. In this regard, the characterized textile industrial wastewater specified in the dye concentration was far beyond the maximum permissible discharging limits. Therefore, textile industrial wastewater treatment must be operated well and advanced oxidation technologies in line with other biological treatments must be applied to protect the environmental pollution loads and their effects. The electrochemical degradation method was applied for dye removal and its performance was 94.89% at the optimum experimental conditions of reaction time of 17.0 min, pH 6.9, and NaCl electrolyte concentration of 5.1 g/L. The predicted dye removal values were approximately closer to the experimental values, which indicate that the model was reasonably describing the experimental reality. Generally,

electrochemical degradation systems with platinum-iron modified electrodes are promising methods to reduce/eliminate the pollution load from textile industrial wastewater.

5 Declarations

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Figures

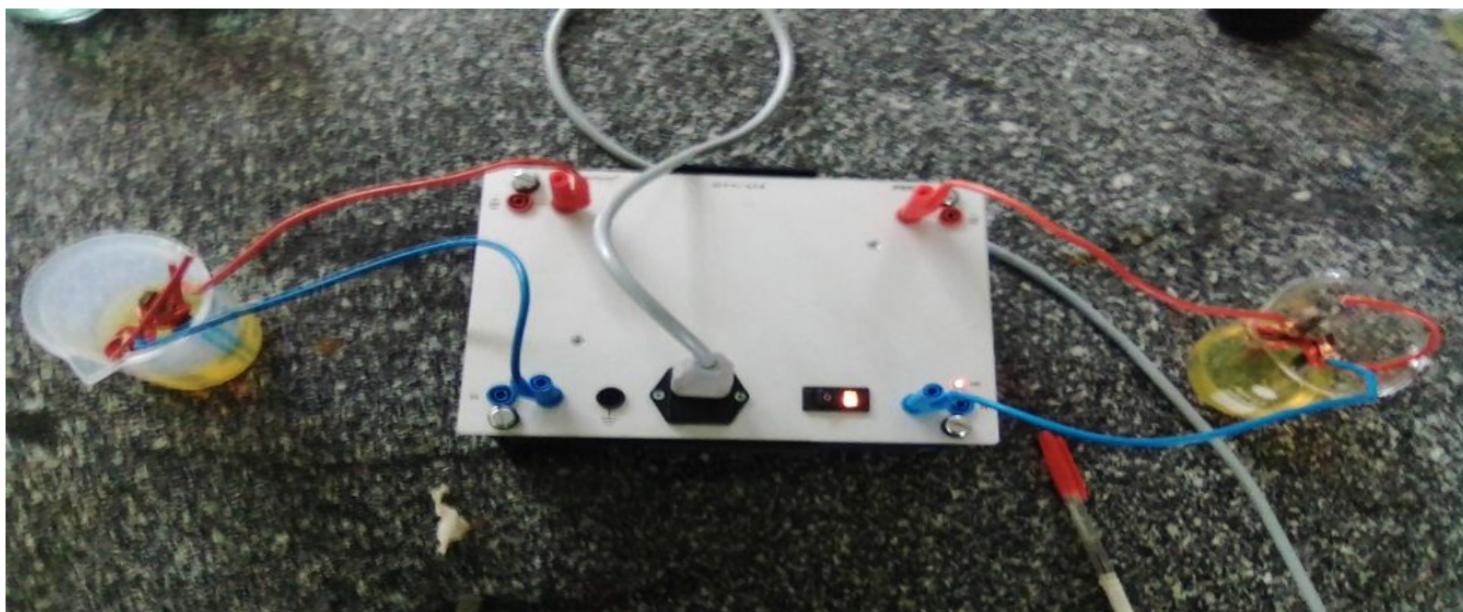


Figure 1

Electrochemical degradation of reactive textile dye in the wastewater

Color removal

Color points by value of
Color removal:

62.98  94.04

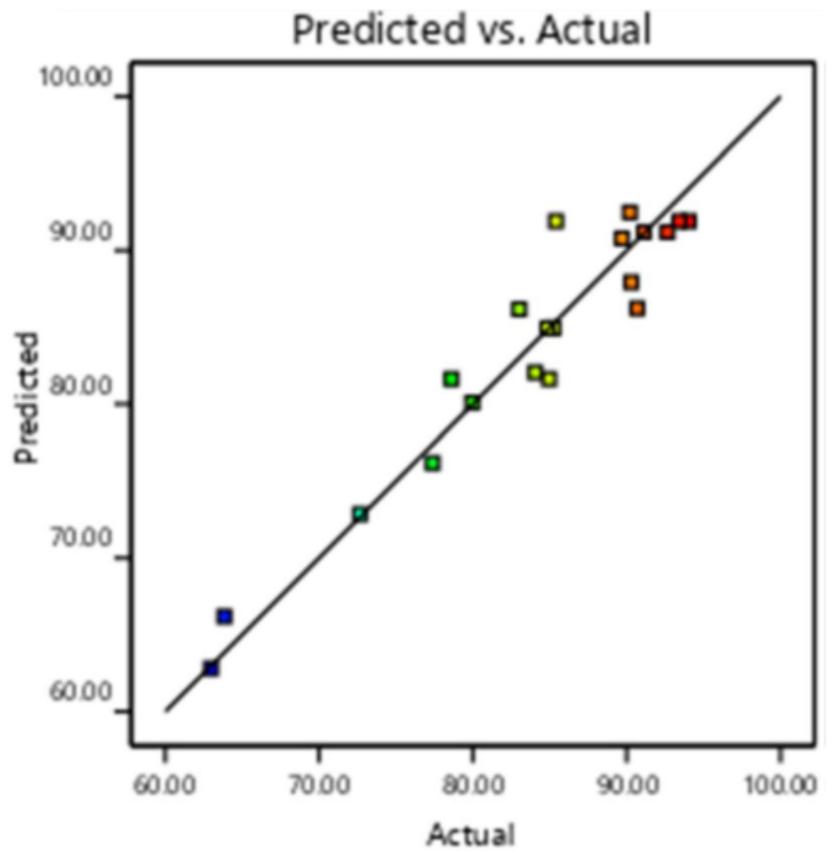


Figure 2

The predicted value against the actual value of the dye degradation

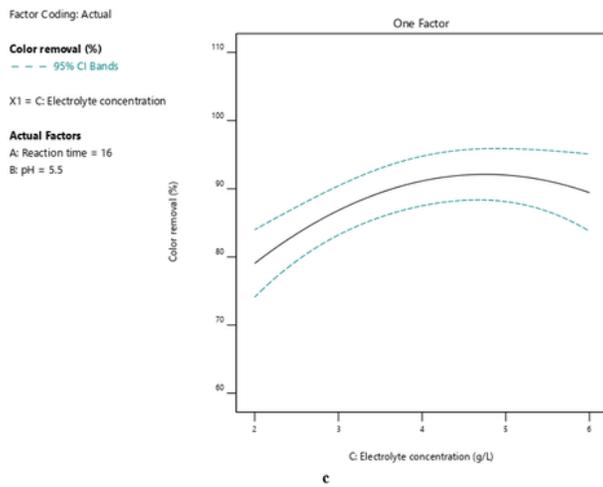
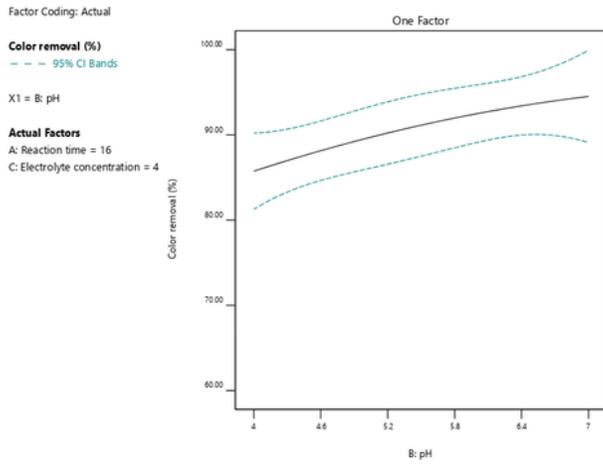
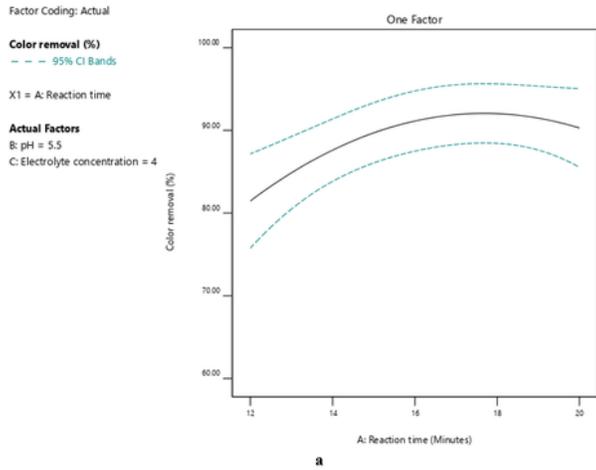


Figure 3

The effect of reaction time (a), pH (b), and NaCl electrolyte concentration (c) on dye removal from textile wastewater

Factor Coding: Actual

3D Surface

Color removal (%)

Design Points:

● Above Surface

○ Below Surface

62.9831  94.0415

X1 = A: Reaction time

X2 = B: pH

Actual Factor

C: Electrolyte concentration = 4

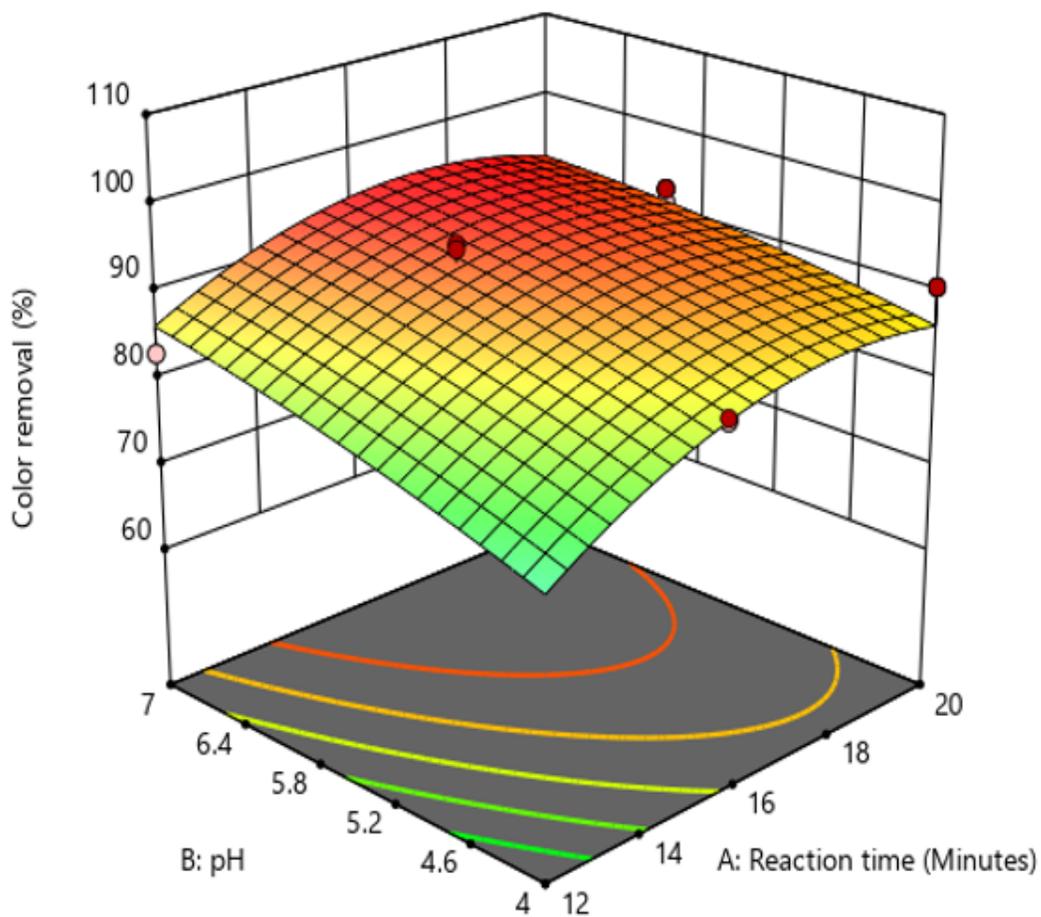


Figure 4

The interactive effect of reaction time and pH on dye removal

Factor Coding: Actual

3D Surface

Color removal (%)

● Design Points

62.9831  94.0415

X1 = C: Electrolyte concentration

X2 = A: Reaction time

Actual Factor

B: pH = 5.5

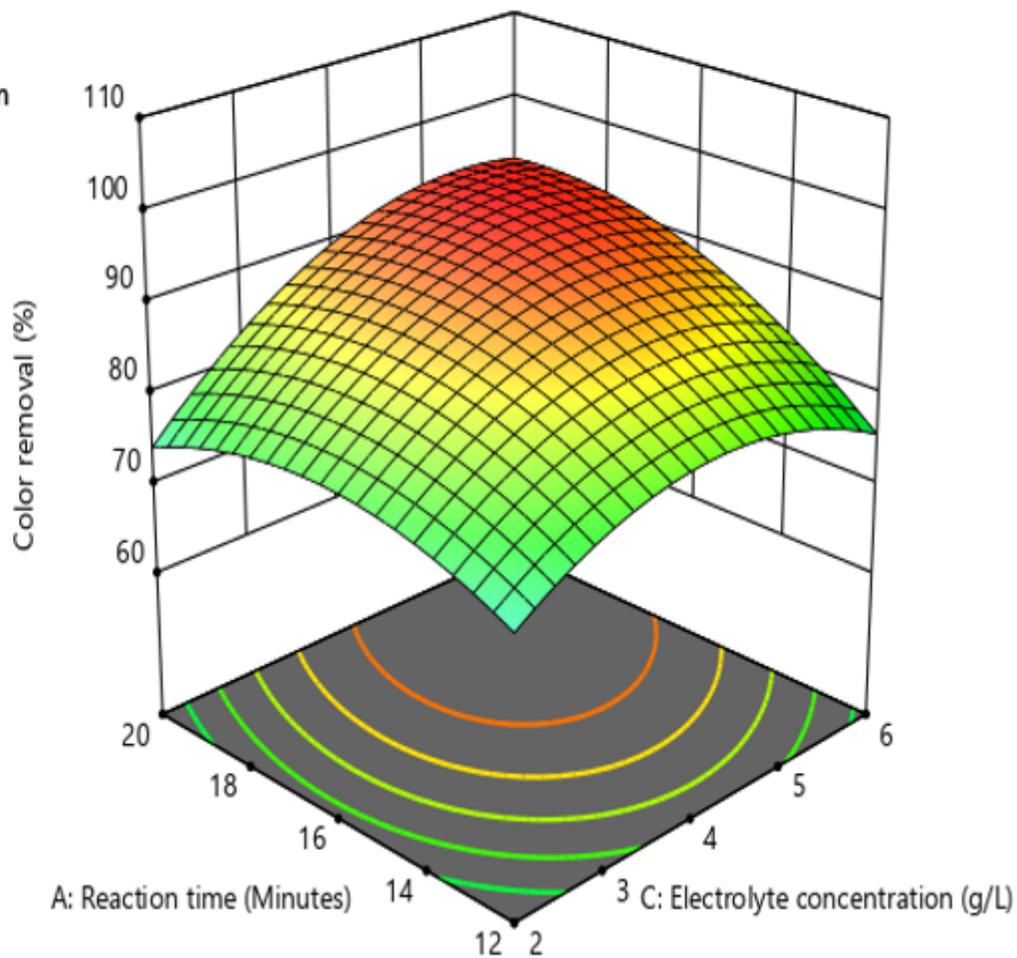


Figure 5

Interactive effects of the reaction time and electrolyte concentration on dye degradation

Factor Coding: Actual

3D Surface

Color removal (%)

● Design Points
62.9831  94.0415

X1 = B: pH

X2 = C: Electrolyte concentration

Actual Factor

A: Reaction time = 16

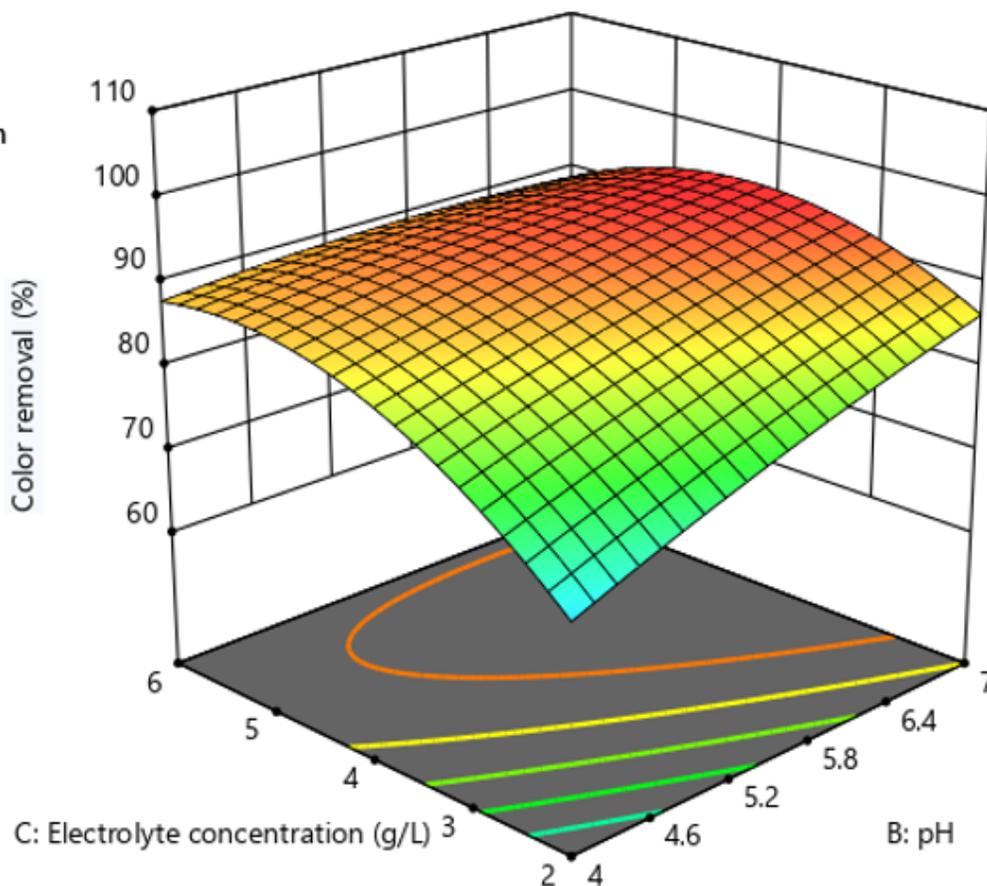


Figure 6

Interactive effects of pH and electrolyte concentration on dye degradation