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RESEARCH ARTICLE

OPTIMIZATION OF THE PERFORMANCE OF "FENTON" AND "ELECTRO-FENTON" PROCESSES FOR DYE REMOVAL IN SUSTAINABLE WASTEWATER MANAGEMENT

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Abstract

Technological advancements have led to the production and widespread use of numerous and diverse chemical substances in various industries. Among the produced and used substances, dyes hold one of the most significant shares. To mitigate the harmful effects and color problems caused by these substances, which are present in the wastewater of textile and dye manufacturing plants and can also be released into the environment, it is necessary to develop alternative technologies. For color removal, which is caused by dyes that are mostly toxic and resistant pollutants, the use of Fenton and Fenton-like processes, which are advanced oxidation methods, has been preferred over traditional treatment methods. In this study, the color removal performance of the Fenton and Electro-Fenton processes was optimized using Basic Blue 3 (BB3) dye. The study is three factors and three levels (Fe^{2+}: 5-10-20 mg/L, H_2O_2: 500-1000-2000 mg/L, Current Density: 20-30-40 mA/cm^2, and Dye Concentration C_0: 2.5-5-7.5 mg/L). In the experiments conducted in the laboratory, it was observed that in the Fenton (Fe + H_2O_2) process, the best color removal efficiency of 98.2% was achieved when the BB3 concentration was 7.5 mg/L, the iron (Fe^{2+}) concentration was 5 mg/L, and hydrogen peroxide (H_2O_2) was 500 mg/L. In the Electro-Fenton process, 100% color removal was observed when the hydrogen peroxide concentration was 500 mg/L, the dye concentration was 2.5 mg/L, and at all three current densities (20-30-40 mA/cm^2). In the Electro-Fenton process, higher removal efficiencies were achieved in a shorter time at lower dye concentrations, while energy consumption calculations revealed that the Fenton process is a more economical alternative.

Keywords

Basic Blue 3,
Electro-Fenton,
Fenton,
Color Removal

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1. INTRODUCTION

Water pollution is one of the world's most significant global and environmental issue. In recent years, the difficulty in accessing clean water and the increase in water pollution have made it crucial to reduce and reuse water. The wastewater from the textile industry is a major contributor to water pollution. Therefore, it is essential to treat dyed wastewater using effective and economical solutions. According to a study by [1] approximately 17-20% of industrial water pollution is caused by textile processing. Textile industry wastewater contains many complex chemical substances that affect aquatic organisms in receiving water environments. Dyed wastewater reduces light penetration in the receiving environment, which negatively impacts photosynthetic activity. The study by [1] also indicates that dyes are highly toxic and carcinogenic to aquatic life and humans. Dyes are colored compounds with complex chemical structures, containing many functional groups and high molecular weights. Basic dyes are particularly harmful, as they can cause eye burns that may lead to permanent damage in the eyes of humans and animals [2].

Treating textile industry wastewater is crucial to minimize the harmful effects of pollutants. Physical, chemical, and biological wastewater treatment processes typically cannot completely remove pollutants

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*Corresponding Author: ekacar@eskisehir.edu.tr from wastewater. Traditional chemical methods have some disadvantages, such as generating larger amounts of sludge and increasing the salinity of the wastewater. Advanced oxidation processes can convert complex chemicals into simpler compounds. The Fenton process is one of the most preferred advanced oxidation methods due to its low cost, ease of use, high degradation rate, and ability to achieve complete mineralization. The Fenton process relies on the formation of hydroxyl radicals, which have a high oxidation capacity to break down organic pollutants [1]. When H_2O_2 or Fe^{+2}, components of the Fenton reagents, are produced electrochemically, the process is known as Electro-Fenton (EF) [4]. The Electro-Fenton process is an important treatment method due to its low cost, high efficiency, and the non-toxic nature of the Fenton reagents, similar to the Fenton process.

The Fenton process was discovered approximately 100 years ago, but it began to be used as an oxidation process after the 1960s. The Fenton process is based on the formation of hydroxyl radicals resulting from the reaction of Fe^{2+} ions with hydrogen peroxide under acidic conditions [5]. Hydroxyl radicals ($OH\cdot$) rapidly mineralize most organic pollutants, converting them into less toxic or non-toxic products. The widely accepted mechanism of the Fenton process is shown in chemical reaction (1)-(3) [6].

$$Fe^{2+} + H_2\,O_2 \rightarrow Fe^{3+} + OH\bullet + OH^- \qquad (1)$$
$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2\bullet + H^+ \qquad (2)$$
$$Fe^{3+} + HO_2\bullet \rightarrow Fe^{2+} + H^+ + O_2 \qquad (3)$$

Electro-Fenton technology is a combination of electrochemical processes and Fenton oxidation. In the EF process, the primary mechanisms for pollutant degradation are the Fenton reaction in the solution (reaction (4)) and direct oxidation at the anode surface (reaction (7)). In the EF process, hydrogen peroxide (H_2O_2) is continuously produced in the solution during electrolysis by the reduction of oxygen at the cathode under acidic conditions (reaction (5)). The electrochemically generated H_2O_2 and the iron ions (Fe^{2+}) added to the solution produce hydroxyl radicals ($OH\cdot$) through the classical Fenton reaction (reaction (4)). Hydroxyl radicals have a high oxidation potential and react non-selectively with organic pollutants, leading to their complete mineralization. In this process, the regeneration of Fe^{2+} ions at the cathode through the electro-reduction of Fe^{3+} (reaction (6)) reduces the production of iron sludge [7].

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + HO\bullet \qquad (4)$$
$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \qquad (5)$$
$$Fe^{3+} + e^- \rightarrow Fe^{2+} \qquad (6)$$
$$M + H_2O \rightarrow M(OH) + H^+ + e^- \qquad (7)$$

The Electro-Fenton process is notable for its high degradation efficiency for resistant organic pollutants, rapid pollutant removal rate, and environmental compatibility. The EF process has been applied as a suitable technology for the treatment of textile wastewater [7].

El-Desoky et al. used a network-shaped glassy carbon cathode and platinum gauze anode material in their electro-Fenton study to remove Levafix Blue CA and Levafix Red CA reactive azo dyes. The studies achieved 100% color removal, along with approximately 85-90% removal of Chemical Oxygen Demand (COD) [8].

Wang et al. investigated COD removal from real textile wastewater using an activated carbon fiber cloth cathode and platinum wire anode in their electro-Fenton studies. After 240 minutes of electrolysis, a COD removal rate of 75% was observed [8].

Atmaca et al. examined COD and color removal from aqueous solutions of commercial textile dyes Yellow 86 using the Electro-Fenton method. In their experimental studies, with electrolyte concentration (250-3000 mg/L), H_2O_2 concentration (250-3000 mg/L), initial dye concentration (50-500 mg/L), and anode-cathode distance (0.5-1.5 cm), they found maximum COD removal of 95.3% and color removal efficiencies of 99.5% under optimal conditions (NaCl: 1500 mg/L, H_2O_2: 1500 mg/L, initial dye concentration: 50 mg/L, anode-cathode distance: 1.5 cm). It was determined that H_2O_2 concentration and dye concentration had the highest impact on removal efficiencies [4].

Louhichi et al. investigated the effectiveness of methods such as electrocoagulation (EC), Electro-Fenton (EF), electrocoagulation with bubbling (ECSA), and Electro-Fenton with bubbling (EFSA) in the treatment of textile industry wastewater. Their study found that all electrochemical processes, including EC, EF, ECSA, and EFSA, achieved over 80% success in color removal and reduction of Chemical Oxygen Demand (COD) [9].

In this study, the aim was to investigate the removal of Basic Blue 3 dye at the laboratory scale using the Fenton and Electro-Fenton methods, and to examine the effects of various process parameters, such as pH value (set at 3), initial concentration, iron concentration, hydrogen peroxide amount, and current density, on the optimization process.

2. MATERIAL AND METHODS

2.1. Materials

Information on the chemicals and equipment used in the study has been provided in a Table 1 and Table 2.

Table 1. Chemicals used in the study

Chemical	Manufacturer	Purity (%)	CAS Number
Hydrogen Peroxide (H_2O_2)	ZAG Chemistry	50	7722-84-1
Basic Blue 3 Dystuff	Sigma-Aldrich	25	33203-82-6
Iron (II) Chloride Tetrahydrate	Carlo Erba	99	13478-10-9

Table 2. Equipments used in the study

Equipment	Brand	Specifications
Analytical balance	Ohaus	AX224
Ultrapure water system	Merck	Direct 16 Cat.744342
UV-Spectrophotometer	Shimadzu	UV -1700 Cat No:206-55401-34
Power supply	Statron	Type 3262

2.2. Methods

In the Fenton and Electro-Fenton studies, a calibration graph was first established (Figure 1). The calibration graph was prepared using Basic Blue 3 (BB3) dye at concentrations of 1, 2, 3, 4 and 5 mg/L in 50 mL flasks, and the relationship between concentration and absorbance values was analyzed using a UV-1700 Shimadzu Spectrophotometer set to a wavelength of 654 nm.

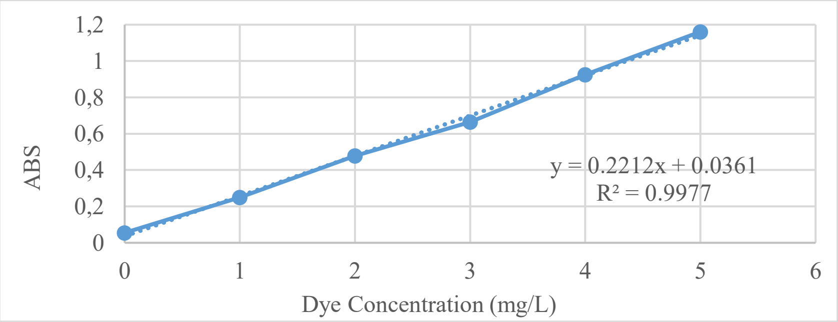

Figure 1. Calibration Graph

Throughout the study, Basic Blue 3 (BB3) dye was used. For the Fenton process, initial concentrations (C_0) of 2.5 mg/L, 5 mg/L, and 7.5 mg/L were selected. To operate the Fenton process (Fe^{2+} + H_2O_2), three different iron concentrations (Fe^{2+}) of 5 mg/L, 10 mg/L, and 20 mg/L were used, along with three different hydrogen peroxide (H_2O_2) concentrations of 500 mg/L, 1000 mg/L, and 2000 mg/L. The pH level was maintained at 3, and the solutions were prepared in 100 mL flasks. The mixtures were stirred for 30 minutes, and absorbance values were recorded every 10 minutes. The experimental design parameters used in the Fenton process are presented in Table 3.

Table 3. Experimental Design Parameters Used in the Fenton Process

Level	**Fe^{+2} (mg/L)**	**H_2O_2 (mg/L)**	**C_0 (mg/L)**
-1	5	500	2.5
0	10	1000	5
1	20	2000	7.5

In the second step of the study, Electro-Fenton experiments were conducted using the concentrations determined in the Fenton process. This Electro-Fenton process was carried out in a batch system using an iron plate and three different current densities in order to observe its effect on color removal. The reactor volume is 500 mL. The Electro-Fenton operation was monitored by supplying current for 10 minutes, and samples were taken every 2 minutes to read the results on the spectrophotometer. The experimental design parameters used in the Fenton process are presented in Table 4 and the experimental setup used for the Electro-Fenton process is illustrated in Figure 2.

Table 4. Experimental Design Parameters Used in the Electro-Fenton Process

Level	**Current Density (mA/cm^2)**	**H_2O_2 (mg/L)**	**C_0(mg/L)**
-1	20	500	2.5
0	30	1000	5
1	40	2000	7.5

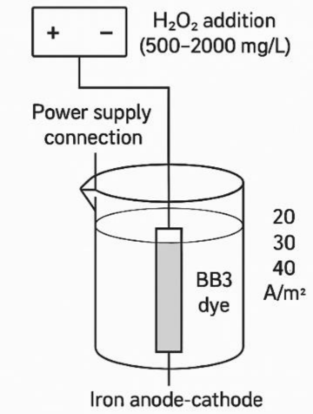

Figure 2. Batch Experimental Setup used in Electro-Fenton Experiment

3. RESULTS AND DISCUSSION

3.1. Fenton Process Studies and Investigation of Its Effect on Color Removal

After the calibration graph was created, the Fenton process studies commenced, and color removals were examined at the specified dye concentrations, hydrogen peroxide concentrations, and iron concentrations. It was carried out using the Taguchi design model in the Minitab software. A total of 27 experiments were performed in a L27 orthogonal array, covering all combinations of the selected factors at three levels each. The response variable was the color removal efficiency (%). The experimental data and ANOVA analysis are presented in the tables below (Table 5 and Table 6).

Table 5. Experimental design using Minitab

pH	**Fe^{+2}(mg/L)**	**H_2O_2 (mg/L)**	**C_0 (mg/L)**	**Removal (%)**
3.2	5	500	2.5	94.8
3.17	5	1000	2.5	94.9
3.15	5	2000	2.5	94.5
3.2	10	500	2.5	91.1
3.22	10	1000	2.5	89.6
3.23	10	2000	2.5	91.2
3.12	20	500	2.5	81.9
3.06	20	1000	2.5	81
3.03	20	2000	2.5	81
3.15	5	500	5	97.2
3.08	5	1000	5	96.7
3.06	5	2000	5	96.8
3.08	10	500	5	94.3
2.94	10	1000	5	93.8
2.93	10	2000	5	93.8
3.13	20	500	5	87.3
3.08	20	1000	5	87.3
3.02	20	2000	5	86.9
3.1	5	500	7.5	98.2
3.07	5	1000	7.5	97.9
3.14	5	2000	7.5	98.1
3.13	10	500	7.5	94.9
3.08	10	1000	7.5	96
3.1	10	2000	7.5	96.4
2.92	20	500	7.5	91.8
2.95	20	1000	7.5	91.2
3	20	2000	7.5	91.6

In the Fenton studies, 27 different experiments were conducted, and it was determined that the best color removal (98,2%) was achieved with 5 mg/L Fe^{2+}, 500 mg/L H_2O_2, and a dye concentration of 7.5 mg/L.

At the end of the 10 minutes, a significant color removal was observed, as the solution changed from blue to a clear color. Among the 27 different experiments, the best color removal occurred at low dye concentrations. The analyses indicated that the factors providing the best color removal were 500 mg/L hydrogen peroxide, 2.5 mg/L dye concentration, and a current density of 40 mA/cm^2, resulting in 100% color removal.

When comparing three Fenton experiments where hydrogen peroxide concentrations and dye concentrations were kept constant while only varying the iron concentrations, it was observed that at an iron concentration of 5 mg/L, a color removal rate of 94.8% was achieved. However, when the iron concentration was increased to 20 mg/L, the color removal decreased to 81.9%. Higher dye concentrations (C_0) showed better performance, possibly due to more available target molecules for hydroxyl radical attack. As Fe^{2+} increased from 5 to 20 mg/L, the average removal efficiency decreased, likely due to iron-induced radical scavenging or sludge formation [10]. Higher dye concentrations (C_0) showed better performance, possibly due to more available target molecules for hydroxyl radical attack.At high Fe^{2+} concentrations, the ions can react with hydroxyl radicals (•OH), reducing their availability for dye degradation and thus lowering color removal efficiency [11,12]. High concentrations of iron can cause turbidity in the reaction medium, leading to interference in UV-vis spectrophotometric measurements and potentially underestimating color removal [13].

In a similar investigation of the effect of hydrogen peroxide on removal while keeping the iron concentrations and dye concentrations constant, it was found that at a dye concentration of 2.5 mg/L and an iron concentration of 5 mg/L, a hydrogen peroxide concentration of 500 mg/L achieved 94.8% color removal. When the hydrogen peroxide concentration was increased to 2000 mg/L, the color removal slightly decreased to 94.5%. A moderate dose of H_2O_2 (1000 mg/L) gave higher removal in many cases, while 2000 mg/L led to a slight decline, attributed to excess peroxide acting as •OH scavenger [14] In Fenton experiments, the observed decrease in color removal efficiency at elevated H_2O_2 concentrations is attributed to the quenching of hydroxyl radicals by excess H_2O_2 beyond the optimal level, which promotes the predominance of side reactions (such as formation of hydroperoxyl radicals) and thus leads to a reduction in overall process efficiency. Martínez et al. reported that in their study on the Fenton treatment of Direct Blue 71 dye, increasing the H_2O_2 dosage up to 125 mg/L enhanced color removal efficiency to as high as 94%. However, beyond this concentration, the efficiency began to decline. This decrease was attributed to the scavenging of hydroxyl radicals (•OH) by excess H_2O_2, leading to the formation of less reactive hydroperoxyl radicals (HO_2•), which negatively affect the system performance [15].

In Fenton processes, the optimal initial pH is generally around pH 3, where the synergy between Fe^{2+} speciation and H_2O_2 stability maximizes hydroxyl radical production, leading to superior color and COD removal efficiencies [16,17,18]. At pH values below 3, excessive protonation results in formation of slower-reacting iron complexes and possible radical scavenging by H^+, thus reducing performance. According to Ertugay and Acar, the highest color and COD removal efficiencies were observed at pH 3, with diminishing performance at both lower and higher pH values [16]. Recent studies confirm that pH ≈ 3 represents the optimal initial pH for Fenton oxidation, where the generation of hydroxyl radicals and iron reactivity are maximized. For example, Daneshvar et al. reported over 97% color removal efficiency at pH 3 in textile wastewater treatment using the Fenton process [17].

Table 6. ANOVA Results for the Effects of Fe^{2+} Concentration, H_2O_2 Concentration, and Initial Dye Concentration (C_0) on Color Removal Efficiency

Source	**Sum of Squares (SS)**	**Degrees of Freedom (df)**	**Mean Square (MS)**	**F-value**	**P-value**
Fe^{2+} Concentration	1327.89	2	663.94	470.15	<0.001
H_2O_2 Concentration	12.45	2	6.23	4.40	0.049
Initial Dye Concentration (C_0)	362.78	2	181.39	128.44	<0.001
Fe × H_2O_2 Interaction	8.32	4	2.08	1.47	0.26
Fe × C_0 Interaction	1.17	4	0.29	0.21	0.93
H_2O_2 × C_0 Interaction	9.65	4	2.41	1.71	0.21
Fe × H_2O_2 × C_0 Interaction	2.54	8	0.32	0.28	0.97
Residual (Error)	25.37	9	2.82		

The ANOVA results presented in Table 4 indicate that Fe^{2+} concentration and initial dye concentration (C_0) have a significant effect on color removal efficiency ($p<0.001$), while the effect of H_2O_2 concentration is statistically significant but less pronounced ($p=0.049$). Interactions between factors were not statistically significant ($p > 0.05$).

3.2. Electro-Fenton Studies and Investigation of Its Effect on Color Removal

Upon reviewing all Electro-Fenton studies, it was found that 100% color removal was achieved at low dye concentrations, while color removal exceeded 75% at high dye concentrations. It was determined that increasing the current density from 20 mA/cm² to 40 mA/cm² played an effective role in enhancing color removal. It was carried out using the Taguchi design model in the Minitab software. The experimental datas and ANOVA analysis are presented in the tables below (Table 7 and Table 8).

Table 7. Experimental Design Using Minitab

H_2O_2 (mg/L)	C_0 (mg/L)	Current Density (mA/cm^2)	Removal (%)
500	2.5	20	100
500	2.5	30	100
500	2.5	40	100
1000	2.5	20	99.9
1000	2.5	30	100
1000	2.5	40	99.3
2000	2.5	20	97.8
2000	2.5	30	95.4
2000	2.5	40	76.2
500	5	20	100
500	5	30	99.5
500	5	40	99.5
1000	5	20	97.3
1000	5	30	99.4
1000	5	40	99.9
2000	5	20	72.2
2000	5	30	74
2000	5	40	90.1
500	7.5	20	99.6
500	7.5	30	98.4
500	7.5	40	99.9
1000	7.5	20	96.3
1000	7.5	30	97.6
1000	7.5	40	95.7
2000	7.5	20	74.9
2000	7.5	30	95.2
2000	7.5	40	85.4

In the Electro-Fenton studies, when the current densities and dye concentrations were kept constant to examine the effect of hydrogen peroxide on removal, it was found that at a dye concentration of 2.5 mg/L and a current density of 20 mA/cm², a hydrogen peroxide concentration of 500 mg/L achieved 100% color removal. However, when the hydrogen peroxide concentration was increased to 2000 mg/L, the color removal decreased to 97.8%.

When comparing Electro-Fenton experiments where current densities and hydrogen peroxide concentrations were kept constant and dye concentrations varied at 2.5, 5, and 7.5 mg/L, it was observed that at a dye concentration of 7.5 mg/L, color removal was 98.4%, while at a dye concentration of 2.5 mg/L, the color removal was 100%. At high concentrations, hydrogen peroxide can act as a scavenger of hydroxyl radicals (·OH), reducing their availability for dye degradation and thus decreasing the overall color removal efficiency [19]. Excess hydrogen peroxide may promote the formation of by-products that inhibit the reaction or compete for hydroxyl radicals, resulting in decreased dye removal efficiency[20]. Recent studies confirm that in Electro-Fenton processes under constant current density and H_2O_2 concentration, increasing the initial dye concentration leads to a slight reduction in color removal efficiency. For example, in a 2021 study by Eskandari et al., the initial concentration of DB80 dye was identified as a significant factor negatively affecting removal efficiency in a Heterogeneous Electro-Fenton system [21].

In the comparison of studies where dye concentrations and hydrogen peroxide concentrations were kept constant while varying current densities at 20, 30, and 40 mA/cm², it was noted that at a current density of 20 mA/cm², color removal was 72.2%. When the current density was increased to 40 mA/cm², color removal improved to 90.1%. In electro-Fenton processes, increasing the current density positively affects color removal efficiency. This is because higher current densities enhance the production of hydrogen peroxide (H_2O_2) and hydroxyl radicals ($\cdot OH$), accelerating the oxidation of organic dyes. For example, Atashgahi et al. reported that increasing the current density from 20 mA/cm² to 40 mA/cm² improved color removal efficiency from around 70% to 90%. This improvement is attributed to enhanced electrochemical reaction kinetics, resulting in greater radical generation and thus higher treatment efficiency [22]. Additionally, a study by Rodríguez-Chueca et al. also demonstrated that increasing current density in electro-Fenton treatment significantly enhances the degradation rate of textile dyes, confirming the positive correlation between current density and color removal efficiency [23].

In the electro-Fenton experiments, pH 3 was also selected, aiming to enable a better comparison between the Fenton and electro-Fenton processes under identical acidic conditions. According to Merouani et al., pH plays a crucial role in the efficiency of the electro-Fenton process, with pH 3 being reported as the optimum value for maximizing hydroxyl radical generation and pollutant degradation efficiency [24].

Tablo 8. Three-Way ANOVA Results for Color Removal Efficiency (%)

Source	**DF**	**Sum of Squares (SS)**	**Mean Square(MS)**	**F-value**	**P-value**
Hydrogen Peroxide (H_2O_2)	2	1586.4	793.2	82.4	<0.0001
Initial Concentration (C_0)	2	1107.5	553.7	57.5	<0.0001
Current Density	2	289.3	144.6	15.0	<0.0001
$H_2O_2 \times C_0$ Interaction	4	48.6	12.15	1.26	0.29
H_2O_2 × Current Density Interaction	4	275.7	68.9	7.15	0.002
C_0 × Current Density Interaction	4	44.8	11.2	1.16	0.33
$H_2O_2 \times C_0$ × Current Density Interaction	8	28.5	3.56	0.37	0.91
Error	9	86.6	9.62		
Total	35	3467.4			

A three-way ANOVA was conducted to evaluate the effects of hydrogen peroxide concentration (H_2O_2), initial dye concentration (C_0), and current density on color removal efficiency (%). The results indicated that all three factors had statistically significant main effects on removal efficiency ($p < 0.0001$). Among the interactions, only the interaction between hydrogen peroxide concentration and current density was statistically significant ($p = 0.002$), suggesting that the effect of hydrogen peroxide on removal efficiency depends on the applied current density. Other interaction effects were not significant. These findings highlight the importance of optimizing both H_2O_2 dosage and current density to maximize removal efficiency in the Electro-Fenton process.

3.3. Comparing The Results of the Fenton and Electro-Fenton Experiments

Laboratory analysis of the results from the Fenton experiments conducted with Basic Blue 3 dye, which were mixed for 30 minutes using a stirrer, indicated that as the iron (Fe^{2+}) concentration increased, the removal efficiency decreased. It was observed that hydrogen peroxide concentrations of 500 and 1000 mg/L yielded better removal efficiencies compared to 2000 mg/L. Additionally, higher dye concentrations resulted in better color removal than lower concentrations.

In the Electro-Fenton experiments, conducted using a power supply at 9 volts and 20, 30, and 40 mA/cm^2 for 10 minutes in a batch setup, a noticeable clarity was achieved. Out of the 27 experiments conducted, five achieved 100% color removal, while 22 experiments demonstrated color removal rates exceeding 90%. The results indicated that better outcomes were achieved at lower hydrogen peroxide concentrations and dye concentrations, while higher current densities resulted in improved color removal efficiency.

Comparing the results of the Fenton and Electro-Fenton experiments at the zero and tenth minutes revealed that in the Fenton experiments, the iron and hydrogen peroxide reacted quickly at the beginning, leading to rapid removal, but the removal rate slowed down over the subsequent half hour. In contrast, in the Electro-Fenton experiments, the iron plate and hydrogen peroxide did not react at the zero minute mark, but over time, they reacted with hydrogen peroxide, demonstrating high removal performance.

In the Fenton and Electro-Fenton experiments conducted with a dye concentration of 7.5 mg/L and a hydrogen peroxide concentration of 500 mg/L, the Fenton process achieved a high removal efficiency of 96.5% at the zero minute mark, while the Electro-Fenton experiment showed a low reaction with the iron plate at first, resulting in a 21.8% color removal. However, by the tenth minute, both experimental setups demonstrated high removal efficiencies. The graph showing the removal efficiencies for both processes is presented in Figure 3.

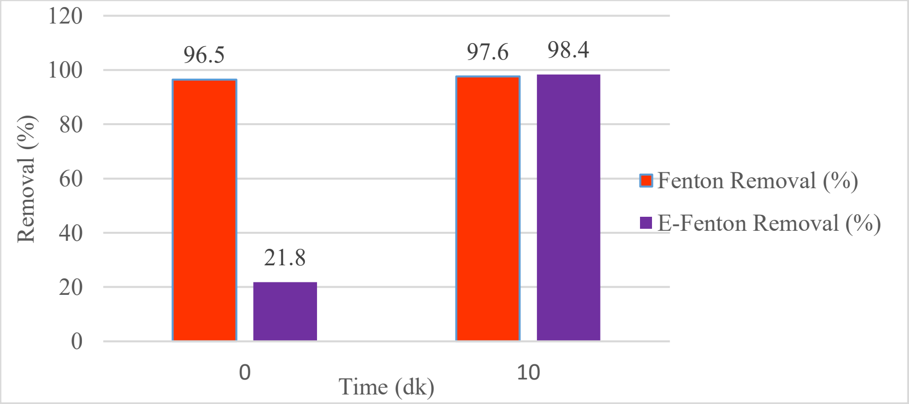

Figure 3. Comparison of the Removal Efficiencies of Fenton and Electro-Fenton Experiments Over Time

In the classical Fenton process, Fe^{2+} ions and H_2O_2 react rapidly at the beginning, producing hydroxyl radicals (·OH) that degrade dyes quickly. However, the Fe^{2+} ions get consumed over time, and side reactions reduce the generation rate of OH radicals, leading to a slowdown in pollutant removal efficiency [25]. This explains the rapid initial color removal followed by a decrease in the reaction rate. In contrast, the Electro-Fenton process continuously generates Fe^{2+} ions via anodic dissolution of an iron electrode and produces H_2O_2 electrochemically at the cathode. This continuous supply maintains the generation of hydroxyl radicals over time, resulting in sustained and even enhanced color removal efficiency during the reaction [26, 27]. Thus, although the initial reaction may be slower due to the absence of Fe^{2+} ions at time zero, the prolonged generation of reactive species leads to higher overall degradation.

3.4. Energy Cost Calculation

For the iron electrode experiments, the energy consumption and costs were calculated at different current intensities while keeping the voltage constant at 9 volts.

At a current of 2 amperes and a reaction time of 10 minutes (600 seconds), the power consumption wascalculated as:
P = I × V = 2 A × 9 V = 18 W = 0.018 kW.

This power was applied to 500 mL of water. The energy consumption per 500 mL was calculated by multiplying the power by the operation time and converting to kilowatt-hours: 0.018 kW × 600 seconds / 3600 seconds/hour = 0.003 kWh per 500 mL.

Scaling this up to one cubic meter (2000 times 500 mL), the energy consumption was: 0.003 kWh × 2000 = 6 kWh per cubic meter.

With an energy price of 4.6176 TL per kWh, the energy cost was determined as:
0.003 kWh × 4.6176 TL = 0.01385 TL per 500 mL, and equivalently,
6 kWh × 4.6176 TL = 27.7056 TL per cubic meter.

At 3 amperes current and the same voltage and duration, the power consumption increased to:
P = 3 A × 9 V = 27 W = 0.027 kW.

Accordingly, the energy consumption per 500 mL was:
0.027 kW × 600 seconds / 3600 seconds/hour = 0.0045 kWh, and for one cubic meter:
0.0045 kWh × 2000 = 9 kWh.

This resulted in an energy cost of:
0.0045 kWh × 4.6176 TL = 0.02078 TL per 500 mL, and 9 kWh × 4.6176 TL = 41.5584 TL per cubic meter.

Finally, at 4 amperes, the power consumption reached:
P = 4 A × 9 V = 36 W = 0.036 kW.

The energy consumption per 500 mL was calculated as: 0.036 kW × 600 seconds / 3600 seconds/hour = 0.006 kWh, and scaled up to one cubic meter: 0.006 kWh × 2000 = 12 kWh.
Thus, the energy cost was:
0.006 kWh × 4.6176 TL = 0.0277 TL per 500 mL and 12 kWh × 4.6176 TL = 55.4112 TL per cubic meter.

The summary of energy costs per cubic meter at different currents is given in Table 9.

Table 9. Energy Cost Calculation

Current (A)	Energy Cost (TL/m³)
2	27.7056
3	41.5584
4	55.41120

The energy consumption and associated costs calculated in this study for the Fenton process are generally consistent with values reported in the literature. For instance, the energy consumption values ranging from 6 to 12 kWh/m³ (corresponding to current intensities of 2 to 4 A) and energy costs between approximately 27.7 to 55.4 TL/m³ fall within similar ranges reported in previous studies.

Popescu et al. reported energy consumptions in Fenton processes for dye degradation typically between 5 and 15 kWh/m³, depending on operational parameters such as catalyst concentration and reaction time[1]. Similarly, Nidheesh and Gandhimathi observed that energy consumption is strongly influenced by reagent dosages and process optimization, with costs varying proportionally to applied electrical energy [28,29]

Furthermore, Brillas et al. highlighted that although the Fenton process can achieve high removal efficiencies at relatively low energy inputs, excessive reagent or current use can increase costs without proportional improvements in performance[3]. This observation aligns with the increased energy costs at higher current intensities seen in the present calculations [30]

In summary, the energy cost results obtained in this study are well-supported by literature data, confirming that careful optimization of current density and reagent concentrations is crucial to balance treatment efficiency and operational costs in Fenton-based wastewater treatment.

4. CONCLUSION

As a result of the studies conducted using Fenton and Electro-Fenton processes, high color removal efficiencies were achieved. The effect of both processes on removal efficiency is discussed in detail in Section 3. A total of 27 experiments were conducted with the Fenton process, achieving the highest color removal of 98.2% with a concentration of 5 mg/L Fe^{2+}, 500 mg/L hydrogen peroxide, and 5 mg/L dye concentration; the lowest color removal was 81% with a concentration of 20 mg/L Fe^{2+}, 2000 mg/L hydrogen peroxide, and 2.5 mg/L dye concentration. It was observed that the blue dye which was stirred for 30 minutes turned yellowish during this process.

In the Electro-Fenton experiments, 100% color removal was achieved at a dye concentration of 2.5 mg/L, resulting in the basic blue 3 dye becoming colorless and clear by the tenth minute. In the Electro-Fenton studies, 100% color removal was achieved at low dye concentrations across three current densities, while color removal approached 100% at current densities of 30-40 mA/cm² for dye concentrations of 5 and 7.5 mg/L. At high dye concentrations and low current densities, color removal decreased and fell to 74%.

According to the energy cost calculations, as the current increased, the energy cost per cubic meter also rose, being 27.7 TL at 2 Amperes, 41.5 TL at 3 Amperes, and 55.41 TL at 4 Amperes. In the Fenton experiment, the highest removal efficiency was achieved at an energy cost of 7.686 TL per cubic meter.

In conclusion, regarding the optimization studies between the two processes for textile wastewater, both processes are suitable for color removal. While the Electro-Fenton process can achieve better removal in a shorter time, it may be advantageous at high currents and low dye concentrations. However, this is considered a disadvantage due to being a costly treatment method. On the other hand, the Fenton process is more advantageous as a treatment process since it has low costs but high iron costs and can achieve higher removals at low dye concentrations, and low hydrogen peroxide concentrations.

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CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

CRediT AUTHOR STATEMENT

Esra Fındık: Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing,
Eda Nur Dağcı: Resources , Writing – Original Draft, Formal analysis.

REFERENCES

[1] Bulca Ö, Palas B, Atalay S, Ersöz G. Post-treatment of real textile wastewater by using a hybrid system comprising of electrocoagulation and Fenton-like oxidation in the presence of perovskite/activated carbon composite catalyst. Gazi Univ J Sci Part C Des Technol. 2023;11(3):631-642.

[2] Bulut E. Removal of CI Basic Blue 3 dye from textile wastewater by electrochemical application. Sakarya Univ J Sci. 2016;20(3).

[3] Gümüş D. Treatment of mixed dyed wastewater by peroxy-coagulation method using stainless steel and graphite electrodes. Gümüşhane Univ J Sci. 2023;13(2):491-499.

[4] Atmaca K, Beyazıt N. Colour and COD removal from aqueous solutions of direct yellow 86 textile dyestuff by electro-Fenton method. Int J Glob Warm. 2020;20(4):324-340.

[5] Aldığ SA, Sönmez G. Investigation of treatability of automotive industry wastewaters by coagulation-flocculation, Fenton and UV/H_2O_2. Niğde Ömer Halisdemir Univ J Eng Sci. 2024;13(2):490-499.

[6] Kuleyin A, Gök A, Akbal F. Treatment of textile industry wastewater by electro-Fenton process using graphite electrodes in batch and continuous mode. J Environ Chem Eng. 2021;9(1):104782.

[7] El-Desoky HS, Ghoneim MM, El-Sheikh R, Zidan NM. Oxidation of Levafix CA reactive azo-dyes in industrial wastewater of textile dyeing by electro-generated Fenton's reagent. J Hazard Mater. 2010;175(1-3):858-865.

[8] Wang CT, Chou WL, Chung MH, Kuo YM. COD removal from real dyeing wastewater by electro-Fenton technology using an activated carbon fiber cathode. Desalination. 2010;253(1-3):129-134.

[9] Louhichi B, Gaied F, Mansouri K, Jeday MR. Treatment of textile industry effluents by electro-coagulation and electro-Fenton processes using solar energy: A comparative study. Chem Eng J. 2022;427:131735.

[10] Merouani S, Hamdaoui O, Chiha M, et al. Electro-Fenton process for the degradation of persistent organic pollutants: kinetics, mechanism, and performance optimization. RSC Adv. 2022;12(5):2630-2640. doi:10.1039/D2VA00011C

[11] Popescu AL, Minescu A, Prundeanu M, Neamtu M. The Fenton-like degradation of dyes: influence of reaction parameters. J Hazard Mater. 2010;179(1-3):188-194. doi:10.1016/j.jhazmat.2009.09.137

[12] Brillas E, Sirés I, Oturan MA. Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. Chem Rev. 2009;109(12):6570-6631. doi:10.1021/cr900136g

[13] Zhang Y, Wang H, Song Y, et al. Insight into hydroxyl radical scavenging in the Fenton process at high ferrous ion concentrations. Environ Sci Pollut Res Int. 2021;28(33):45644–45655. doi:10.1007/s11356-021-13914-9

[14] Zhou Y, Li X, Wang J, et al. Optimization of Fenton process conditions for dye wastewater using Taguchi method. Environ Res. 2023;224:115415. doi:10.1016/j.envres.2023.115415

[15] Martínez F, Melero JA, Bautista LF, Morales G, Iglesias J. Fenton oxidation of Direct Blue 71 in aqueous solution: kinetic study and mineralization. Arabian Journal of Chemistry. 2011;4(3):343-349. doi:10.1016/j.arabjc.2010.06.030

[16] Ertugay N, Acar FN. Removal of COD and color from Direct Blue 71 azo dye wastewater by Fenton's oxidation: Kinetic study. J Environ Health Sci Eng. 2014;12(1):118. doi:10.1186/s40201-014-0118-8.

[17] Daneshvar N, Hosseini M, Yaghmaeian K, et al. Comparison of kinetics and costs of Fenton and Photo-Fenton processes used for the treatment of a textile industry wastewater. J Environ Manag. 2021;288:112425. doi:10.1016/j.jenvman.2021.112425

[18] Gamaralalage JGP, et al. Municipal Leachate Treatment by Fenton Process: Effect of Some Variable and Kinetics. Water Sci Technol. 2020;85(7):2225–2234. doi:10.2166/wst.2020.025

[19] Malakootian M, Karami A, Kord Mostafapour F, et al. Effect of operating parameters on Fenton and photo-Fenton processes for textile wastewater treatment. J Environ Health Sci Eng. 2017;15(1):17. doi:10.1186/s40201-017-0277-7

[20] Sobczak J. Application of electro-Fenton process for removal of organic pollutants from wastewater: a review. Chem Eng J. 2024;450:138275. doi:10.1016/j.cej.2023.138275

[21] Eskandari P, Farhadian M, Nazar ARS, Goshadrou A. Investigation and optimization of the performance of sono-photo-electro-Fenton process for removal of Acid Black 172 and Disperse Blue 56 from polluted water: comparison of the degradation activity with electro-Fenton-based processes. Int J Environ Sci Technol. 2021;18(2):297–316. doi:10.1007/s13762-021-03296-0.

[22] Atashgahi S, Shams M, Mousavi SM, et al. Optimization of electro-Fenton process for dye removal from wastewater: influence of operational parameters. J Environ Chem Eng. 2019;7(5):103343. doi:10.1016/j.jece.2019.103343

[23] Rodríguez-Chueca J, Fernández-Álvarez E, Saez C, et al. Influence of current density on the electro-Fenton oxidation of azo dyes in aqueous solutions. Chemosphere. 2020;247:125860. doi:10.1016/j.chemosphere.2019.125860

[24] Merouani S, Hamdaoui O, Saoudi F, Chiha M. Sonochemical oxidation process for the degradation of rhodamine B in aqueous phase: Effect of parameters and degradation pathway. Ultrason Sonochem. 2022;90:106205. doi:10.1016/j.ultsonch.2022.106205.

[25] Pérez-Estrada L, Valenzuela M, Miranda-García O, et al. Degradation of azo dyes by Fenton and photo-Fenton processes: a kinetic study. J Hazard Mater. 2015;283:17-23. doi:10.1016/j.jhazmat.2014.08.036

[26] Brillas E, Sirés I, Oturan MA. Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. Chem Rev. 2009;109(12):6570-6631. doi:10.1021/cr900136g

[27] Martínez-Huitle CA, Brillas E. Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review. Appl Catal B Environ. 2009;87(3-4):105-145. doi:10.1016/j.apcatb.2008.09.017

[28] Popescu M, Boari G, Teodosiu C, Oller I, Maldonado MI, Malato S. Decolorization of dye wastewater by advanced oxidation processes: Fenton and solar photo-Fenton. J Hazard Mater. 2010;180(1-3):295-301. doi:10.1016/j.jhazmat.2010.04.068

[29] Nidheesh PV, Gandhimathi R. Trends in electro-Fenton process for water and wastewater treatment: An overview. Desalination. 2015;299:1-15. doi:10.1016/j.desal.2012.10.023

[30] Brillas E, Sirés I, Oturan MA. Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. Chem Rev. 2009;109(12):6570-6631. doi:10.1021/cr9002929