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Treatment of real dye bath washing wastewater using different treatment processes

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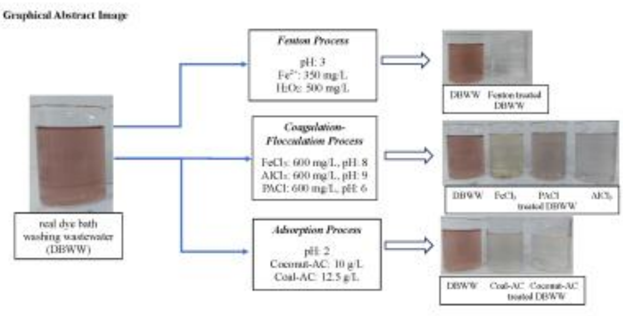
Graphical abstract



Abstract

In this study, the real dye bath washing wastewater (DBWW) treatment using coagulation-flocculation, Fenton, and adsorption processes was investigated. The suitable pH and coagulant dose were researched using $AlCl_3$, $FeCl_3$, and PACl for the coagulation-flocculation process.The Fenton process was used to estimate optimum pH, oxidation time, and Fe^{2+} and H_2O_2. The optimum pH and adsorbent dose for activated carbon derived from coal and coconuts throughout the adsorption process were researched. COD removal efficiency followed the order PACl > $AlCl_3$ > $FeCl_3$, while color removal efficiency followed the order $AlCl_3$ > PACl > $FeCl_3$ in the coagulation-flocculation process. COD and color removals of 60.9% and 79.2% were reached at pH 6 and 600 mg/L PACl dose, respectively. 64.0% COD and 98.8% color removal were found at pH 3, 350 and 500 mg/L Fe^{2+} and H_2O_2 for Fenton process. Higher removal efficiencies were achieved using activated carbon obtained from coconut compared to activated carbon obtained from coal in the adsorption process. 69.7% COD and 76.3% color removal were obtained at pH 2, 10 g/L activated carbon dose and 1 h adsorption time. As a result, even though high COD removal was established in dye bath washing wastewater treatment employing three treatment methods, Fenton process produced high color removal.

Keywords: Color, COD, Dye bath washing wastewater, Fenton, Treatment.

1. Introduction

The highest pollution load and wastewater production occurs at the dyeing process, rinsing and washing stages in the textile industry (Tanveer *et al.* 2021). The water is used both to heat the bath and to transfer color to the fiber in the textile industry and dye baths wastewater has high color intensity, organic compound load, and mineral salt concentration (Allegre *et al*. 2004; Patabandige *et al*. 2020). The dyeing process is complex due to the high inorganic salts and dyes, and the discharge of these wastewaters can be extremely adverse for the environment (Patabandige *et al*. 2020; Shu *et al.* 2024). The reuse of these high-volume wastewaters is crucial for sustainability (Shu *et al.* 2024). Commercial dyes are designed to be persistent under conditions of use and therefore exhibit high resistance to light and oxidation (Arslan 2001, Wang *et al*. 2022). Complex aromatic compounds, particularly azo dyes, can be resistant to biodegradation and toxic, with limited removal rates (Arslan and Akmehmet Balcioglu 2001). Components such as reactive dyes, surfactants, and salts contained in dye wastewaters can be both toxic and biologically persistent; therefore, biological processes do not often promote proper removal of color and organic matter (Wang *et al.* 2022).

Physicochemical and advanced oxidation methods are also used for dye bath wastewater treatment. Although coagulation-flocculation is a fast, simple, and economical pretreatment option for removing colloids and suspended solids, it may be insufficient on its own for organic matter removal (Patabandige *et al.* 2020; Shu *et al.* 2024). Dye molecular structures, chromophore groups, and charges significantly affected the treatment (Mcyotto *et al*. 2021). It has also been stated that in the coagulation-flocculation treatment of reactive/acidic dyes dyeing cotton/polyamide blends wastewater, it provides complete color removal and increases the biodegradability of the water (Golob *et al.* 2005). While high color removal achieved using the coagulation-flocculation process for real or synthetic dye bath effluents treatment, additional enhancement is required

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for organic matter removal (Rodrigues *et al.* 2014; Patabandige *et al.* 2020; Wang *et al.* 2022).

Advanced oxidation processes are effective breaking down soluble and resistant organic molecules via hydroxyl radicals and can provide high efficiencies in color and COD reduction, but they were costly (Patabandige *et al.* 2020; Ribeiro and Nunes, 2021; Wang *et al.* 2022). The Fenton process is regarded as a successful treatment way that increases biodegradability, achieves good color removal, and mineralizes organic contaminants in dye bath wastewater (Grisales *et al*. 2019; Tanveer *et al*. 2023). More than 80% of color removed for the real dye bath wastewater treatment using Fenton oxidation (Patabandige *et al.* 2020).

Although the adsorption process is a flexible and practical method that can achieve high dye removal (Wang *et al.* 2022; Shu *et al.* 2024). Although activated carbon is expensive among various adsorbent materials, it possesses the most well-known adsorbent properties and can effectively remove many dyes (Wang *et al.* 2022). High color removal was also achieved in real or synthetic dye bath wastewater treatment by adsorption process at different adsorbents (Balci and Erkurt 2016; Kyzas *et al*. 2011).

Treatment performance can differ from that obtained with synthetically prepared dye bath wastewater and real dye bath because real (industrial) dye bath wastewater contains a complex matrix. Therefore, studies and process comparisons using real dye bath wastewater have become increasingly important.

This study aimed to determine the efficiency of three basic wastewater treatment processes coagulation-flocculation, Fenton, and adsorption in the treatment of real dye bath washing wastewater. The effectiveness of each method was evaluated based on key parameters that directly determine the yield. Three different coagulants, $FeCl_3$, $AlCl_3$, and PACl (polyaluminum chloride), were selected for the coagulation-flocculation process, and optimum conditions were determined by varying pH and coagulant dosages for each coagulant. The optimal conditions were established by varying Fe^{2+}, H_2O_2, pH, and oxidation times in the Fenton process. In the adsorption process, two different activated carbons obtained from coconut and coal were used, and optimum conditions were determined by varying pH and activated carbon dosage. The study in question, the effectiveness of these processes on wastewater streams with lower pollution loads but much higher flow was examined separately depending on different parameters. Thus, the aim is to contribute to studies on evaluating the possibilities of wastewater recovery by separately considering wastewater flows for production processes that consume a lot of water and generate wastewater with different characteristics from each unit, such as textile factories.

2. Materials and Methods

2.1. Characterization of real dye bath washing wastewater (DBWW)

Real dye bath washing wastewater (DBWW) was obtained from a textile dyeing factory in the Ergene basin. DBWW was the washing water of the dyeing machine after jet dyeing with reactive dyes. COD was 471±18 mg/L in the DBWW. The absorbance value of DBWW for the 254 nm wavelength was determined as 3.461, while the absorbance values for the 436, 525, and 620 nm wavelengths used for color were measured as 0.237, 0.177, and 0.104, respectively.

2.2. Coagulation-flocculation process

200 mL of real DBWW were applied in the experiments. After the addition of the coagulant to the wastewater, the pH meter was applied to regulate the pH level (using H_2SO_4/NaOH). Coagulation-flocculation was performed using rapid and slow mixing. Rapid mixing was achieved at 120 rpm for 1 min. Slow mixing was achieved at 45 rpm for 20 min. 0.5 mL of polyelectrolyte (0.05%, anionic) was added subsequent to the rapid mixing. The wastewater was settled for 30 min.

Three different coagulants were used: $FeCl_3$, $AlCl_3$, and PACl and the stock solutions (100 g/L) were prepared. First, the optimum pH value was determined with 6 different pH values (pH 4-9) at 200 mg/L coagulant dose. Subsequently, coagulation-flocculation was performed at the determined optimum pH (pH 8 for $FeCl_3$, pH 9 for $AlCl_3$ and pH 6 for PACl) at 12 different coagulant doses (50-1000 mg/L).

2.3. Fenton process

The Fenton process was performed at 45 rpm for 60 min. $FeSO_4.7H_2O$ (CAS: 7782-63-0) was used as the Fe^{2+} source. The pH of DBWW (200 mL) was brought down to 3 after $FeSO_4.7H_2O$ was added. Subsequently, 30% H_2O_2 (CAS: 7722-84-1) was added. The Fenton process continued for 60 min. Then, the pH was raised to approximately 8 and allowed to settle for 30 minutes. 6 N NaOH was used for pH adjustment.

The optimum H_2O_2 dose was identified between 250 and 1500 mg/L under constant conditions (pH: 3, Fe^{2+}: 500 mg/L). The optimum Fe^{2+} dose was determined between 50 and 500 mg/L under constant conditions (pH: 3, H_2O_2: 500 mg/L). The optimum pH was determined between 2.0 and 4.0 under constant conditions (Fe^{2+}: 350 mg/L, H_2O_2: 500 mg/L). Finally, the most suitable oxidation time was determined by applying reaction times varying between 10 and 60 minutes under optimum conditions.

2.4. Adsorption process

Two different types of activated carbon were used: commercially available activated carbon obtained from coconut (AC-1) and activated carbon obtained from coal (AC-2).

Adsorption was performed by shaking at 150 rpm, and a Biosan PSU-20i was used as the shaker. Activated carbon was employed to real DBWW. The pH meter was applied to regulate the pH level (using H_2SO_4/NaOH). The wastewater was shaken in the shaker for 1 hour. Then, it was centrifuged (Speed: 4000 rpm, time: 5 min) to separate the activated carbon. Experiments were performed on the treated wastewater.

Adsorption was first performed at 5 different pH (2-9) under constant conditions (AC: 10 g/L, adsorption time: 1 hour). Subsequently, experiments were conducted with 7 different activated carbon doses (2.5-20 g/L) under constant conditions (pH: 2, adsorption time: 1 hour).

2.5. Analysis methods

COD analysis was performed according to APHA 5220C. Analysis was performed on DBW and treated DBW using a UV spectrophotometer (Shimadzu UV-1800) and ABS-254 and color (436 nm, 525 nm, 620 nm) removals were calculated.

3. Results and Discussion

3.1. Real DBWW treatment by coagulation-flocculation process

3.1.1. Coagulation-flocculation using $FeCl_3$

In coagulation-flocculation using $FeCl_3$, COD removal of DBWW enhanced from 14.9% to 30.7%, and color removal enhanced from 35.1% to 62.2% as pH increased from 4 to 8 (**Figure 1a**). COD and color removal reduced to 15.8% and 48.3% at pH 9, respectively. ABS-254 removal was 37.2%, 30.2%, and 36.3% at pH 4, 7, and 8, respectively. In the coagulation-flocculation process using $FeCl_3$, Fe^{3+} ions interact with water, transforming into various hydrolysis products according to pH (Nguyen *et al.* 2022). These hydrolysis products provided destabilization by neutralizing the charges of colloidal particles in the wastewater and facilitated particle accumulation through surface adsorption and scavenging flocculation mechanisms of amorphous $Fe(OH)_3$ precipitate (Duan and Gregory, 2003; Rajabi *et al.*, 2025). Therefore, floc size and density can be changed according to pH (Nguyen *et al.*, 2022).

The ideal pH for different wastewaters employing the coagulation-flocculation using $FeCl_3$ was frequent close neutral values (pH 6-8) (Sakhi *et al.*, 2020; Nguyen *et al.* 2022, Rajabi *et al.*, 2025).

Coagulant dosage is the essential parameters affecting process performance (Rajabi *et al.*, 2025). $FeCl_3$ (cationic coagulant) neutralize or reduce the surface charges of particles in wastewater, which generally have negative surface charges, weakening the electrostatic repulsive forces between particles (Duan and Gregory, 2013; Rajabi *et al.*, 2025). Van der Waals attraction forces become dominant, and help colloidal and fine suspended solids aggregate into form flocs with the reduction of electrostatic repulsion (Rajabi *et al.*, 2025).

COD, ABS-254, and color removal efficiencies gradually improved when the $FeCl_3$ dose enhanced from 50 to 600 mg/L, and reached their maximum values at 600 mg/L. Further increases in $FeCl_3$ (700-1000 mg/L) did not lead to any notable enhancements in COD, ABS-254, or color removal (**Figure 1b**). COD, ABS-254 and color removal reached 43.4%, 43.5%, and 77.4%, at the 600 mg/L $FeCl_3$, respectively. 54% COD and 97% color removal reached using $FeSO_4$, and 66% COD and 30% color removal were attained using $FeCl_3$ for simulated dye bath wastewater treatment (Arslan 2001; Kabdaslı *et al.* 2007).

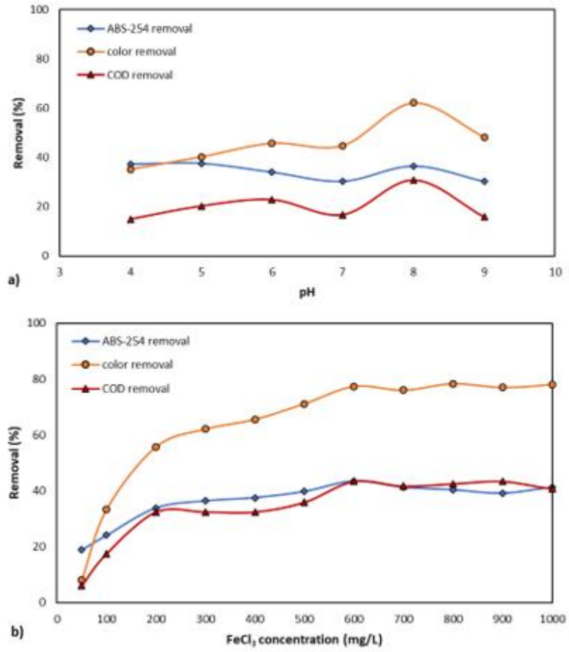

Figure 1. Treatment of DBWW by coagulation-flocculation process using $FeCl_3$ a) different pH value (FeCl3: 200 mg/L), b) different FeCl3 (pH: 8).

3.1.2. Coagulation-flocculation using $AlCl_3$

Although color and ABS-254 removals reduced as pH increased from 4 to 5, the highest color (72.6%) and ABS-254 (41.8%) removals were achieved at pH 9 (**Figure 2a**). Highest COD (38.8%) removal also reached at pH 9. Al^{3+} ions are rapidly hydrolyzed in wastewater and converted into different types of aluminum hydroxide hydrolysis products depending on pH (Duan and Gregory, 2003). The resulting aluminum hydrolysis products interact with colloidal and fine suspended solid particles in the wastewater, acting as key factors in determining the effectiveness of coagulation mechanisms such as surface adsorption, charge neutralization, and sweep flocculation (Duan and Gregory, 2003; Shu *et al*., 2024). Amorphous $Al(OH)_3$ precipitates are formed at high pH, and these precipitates physically retain pollutants through a flocculation mechanism, increasing floc formation and removal efficiency (Duan and Gregory, 2003).

The ideal pH was found to be 9.23 for natural stone processing wastewater treatment using $AlCl_3$ (Ehteshami *et al.* 2016). The highest wastewater treatment was achieved at pH 9 for real dye bath wastewater using alum (Patabandige *et al.* 2020).

COD, ABS-254, and color removal gradually improved and reached maximum values as the $AlCl_3$ improved up to 600 mg/L. COD and ABS-254, were 54.5% and 46.3%, while color removal was 87.3% at 600 mg/L $AlCl_3$, respectively. In contrast, increasing the $AlCl_3$ dose to the 700-1000 mg/L range did not produce any noticeable improvement in COD, ABS-254, and color removal (**Figure 2b**). COD and color removal were attained as %54,2 and %28,0 at 1500 mg/L alum in the simulated reactive dye bath wastewater treatment (Kabdaslı *et al.*, 2007).

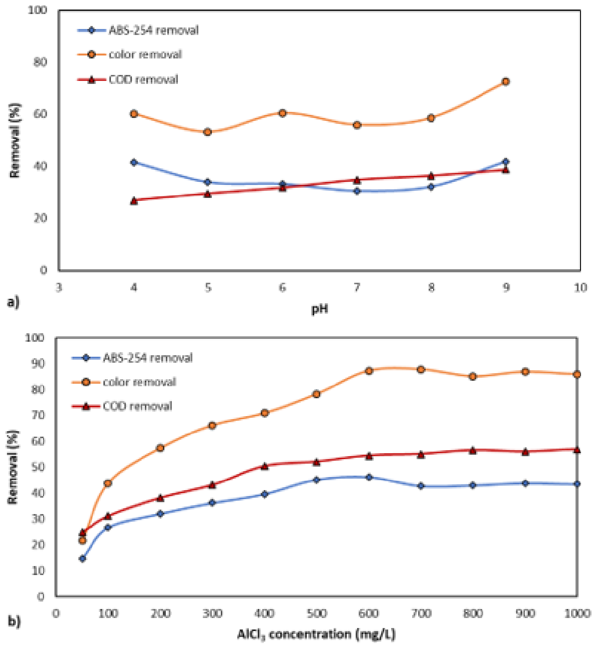

Figure 2. Treatment of DBWW by coagulation-flocculation process using AlCl3 a) different pH value ($AlCl_3$: 200 mg/L), b) different $AlCl_3$ (pH: 9).

3.1.3. Coagulation-flocculation using PACl

Color and COD removal rose from pH 4 to pH 6, there was a tendency for removal efficiency to decline above pH 6 (**Figure 3a**). 61.2% color and 49.1% COD removal were achieved at pH 6. ABS-254 removal was 38.2% at pH 5 and it was reduced to 36.6% at pH 6. This indicates that polymeric aluminum species and amorphous $Al(OH)_3$ precipitates by PACl hydrolysis are in their most effective form for coagulation in this pH range. Coagulation was mainly limited to the charge neutralization mechanism due to the dominance of monomeric and low-grade polymeric Al species at lower pH values, which particularly limits the removal of high molecular weight organic substances. In contrast, amorphous $Al(OH)_3$ precipitates formed around pH 6 enable higher color and COD removal by physically trapping colloidal and dissolved organic substances through a scavenging flocculation mechanism. The optimum pH value was 6 for chemical wastewater treatment using PACl (Zhang *et al.* 2023).

COD, ABS-254, and color removal gradually enhanced as the PACl rose from 50 to 600 mg/L. Further increases in PACl (700-1000 mg/L) did not result in a notable enhancement in COD, ABS-254, or color removal (**Figure 3b**). COD, ABS-254, and color removal were 60.9%, 44.8%, and 79.2% at 600 mg/L PACl, respectively. Increasing the PACl dose from 50 to 600 mg/L resulted in a gradual improvement for COD, ABS-254, and color removal, indicating the formation of more polymeric aluminum species and $Al(OH)_3$ precipitate phase in the medium due to the increasing amount of coagulant (**Figure 3b**). Flocculation and charge neutralization mechanisms worked well to increase surface area and floc volume, raising the probability of pollutant retention. In contrast, increasing the PACl dose to the 700-1000 mg/L range did not produce any noticeable improvement in COD, ABS-254, and color removal.

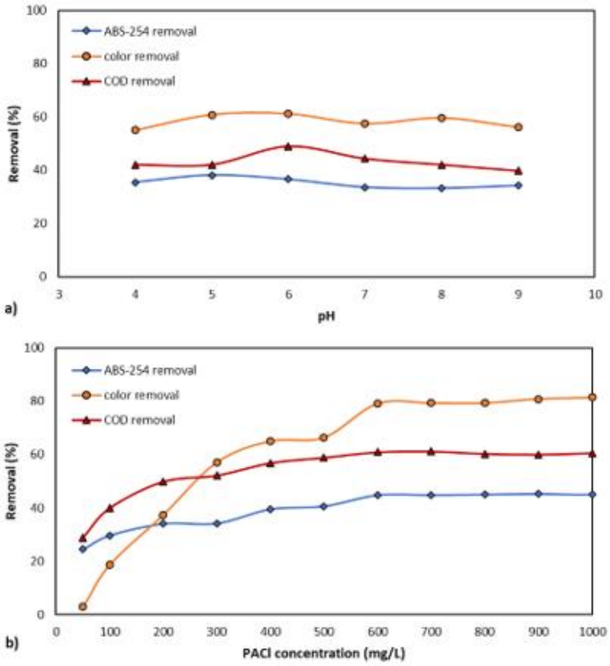

Figure 3. Treatment of DBWW by coagulation-flocculation process using PACl a) different pH value (PACl: 200 mg/L), b) different PACl (pH: 6).

In this study, the treatment of dye bath washing wastewater using $FeCl_3$, $AlCl_3$, and PACl coagulants was investigated, and the results obtained under optimum conditions are summarized in **Table 1**. When examining treatment studies using coagulation processes with dye bath wastewater, it is observed that the results obtained in this study are similar.

3.2. Real DBWW treatment by Fenton process

COD, ABS-254, and color removal efficiencies obtained in the real DBWW treatment using the Fenton process are presented in **Figure 4**. COD removal enhanced from 52.6% to 59.6%, and ABS-254 removal enhanced from 75.5% to 92.0% when the H_2O_2 rose from 125 to 500 mg/L (**Figure 4a**). This improvement is due to H_2O_2 reacting with Fe^{2+} to produce more •OH radicals, thus leading to more efficient oxidation of organic molecules (Eq. 1) (Machado *et al.*, 2023).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^{-} \qquad (1)$$

Color removal exceeded 90% at all H_2O_2 concentrations and reached 97.5% at 500 mg/L H_2O_2. A slight reduction in COD and ABS-254 removal was noted at above 500 mg/L H_2O_2. The DBWW treatment redused due to the scavenging effect resulting from excessive H_2O_2 (Eq. 2) (Machado *et al.* 2023).

$$H_2O_2 + {}^{\bullet}OH \rightarrow {}^{\bullet}HO_2 + H_2O \qquad (2)$$

This reaction reduces •OH radicals, producing $•HO_2$ radicals which have less oxidizing capacity, and this negatively affects DBWW treatment (Machado *et al.* 2023, Ilhan *et al.* 2019).

COD, ABS-254 and color removals improved from 36.8% to 63.6%, from 77.5% to 90.6%, and from 88.0% to 98.1% as the Fe^{2+} rose from 50 to 350 mg/L (**Figure 4b**). Since Fe^{2+} catalyzes the breakdown of H_2O_2, producing more hydroxyl radicals, DBWW treatment improves with increasing Fe^{2+} (Eq. 1). No significant enhancement in DBWW removal efficiency was observed beyond 350 mg/L Fe^{2+}. Fe^{2+} higher than 350 mg/L increased the amount of Fenton sludge produced after oxidation, resulting in higher wastewater treatment costs (Ribeiro and Nunes 2021).

Table 1. Comparison of coagulation of dye bath wastewater treatment

Wastewater	Conditions	Treatment efficiency	References
Real dye bath washing wastewater	pH: 8, $FeCl_3$: 600 mg/L	COD: 43.4%, Color: 77.4%,	In this study
	pH: 9, $AlCl_3$: 600 mg/L	COD: 54.5%, Color: 87.3%	
	pH: 6, PACl: 600 mg/L	COD: 60.9%, Color: 79.2%	
acrylic yarn dye-house wastewater	pH: 8.5-9.0, $FeSO_4$: 1100 mg/L	COD: 29.7%, Color: 87.9	Ilhan *et al.* (2019)
	pH: 6.5-7.0, $Al_2(SO_4)_3$: 1100 mg/L	COD: 33.4%, Color: 75.6	
simulated disperse dye-bath	pH: 11, $FeSO_47H_2O$: 5000 mg/L	COD: 54%, Color: 97%	Arslan (2001)
Synthetic dye (RB 59) wastewater	pH: 9, $FeCl_3$: 2.23 mM	Color: 63.6%	Patel *et al.* (2025)
	pH: 7, PACl: 340 mg/L	Color: 91.9%	
Real dye bath	pH: 9, PACl: 400 mg/L	COD: 84%, Color: 80%	Patabandige *et al.* (2020)
	pH: 9, Alum: 400 mg/L	COD: 66%, Color: 80%	
	pH: 9, $FeSO_4$: 400 mg/L	COD: 75%, Color: 80%	
Simulated reactive dyebath effluent	pH: -, $FeSO_4$: 1000 mg/L	COD: 56.6%, Color: ~70%	Kabdaşlı *et al.* (2007)
	pH: -, $FeCl_3$: 1250 mg/L	COD: 66.4%, Color: ~17%	
	pH: -, Alum: 1250 mg/L	COD: 54.2%, Color: ~17%	

Table *2.* Comparison of Fenton process of dye bath wastewater treatment

Wastewater	Conditions	Treatment efficiency	References
Real dye bath washing wastewater	pH:3, Fe^{2+}:350 mg/L, H_2O_2:500 mg/L	COD: 64.0%, Color: 98%	In this study
acrylic yarn dye-house wastewater	pH: 3.2, Fe^{2+}: 1093 mg/L, H_2O_2: 1600 mg/L	COD: 84.6%, Color: 98.6%	Ilhan *et al.* (2019)
Simulated reactive dyebath effluent	pH: 3, Fe^{2+}:5 mM, H_2O_2:20 mM	COD: 62%, Color: ~81%	Kabdaşlı *et al.* (2007)
Real dye bath	pH: 3, Fe^{2+}: 0.1 mM, H_2O_2: 0.5 mM	Color: 91%	Patabandige *et al.* (2020)
Synthetic dye (dispersed dyes) wastewater	pH: 3, Fe^{2+}: 250 mg/L, H_2O_2: 300 mg/L	COD: 85%, Color: 100%	Szpyrkowicz *et al.* (2001)

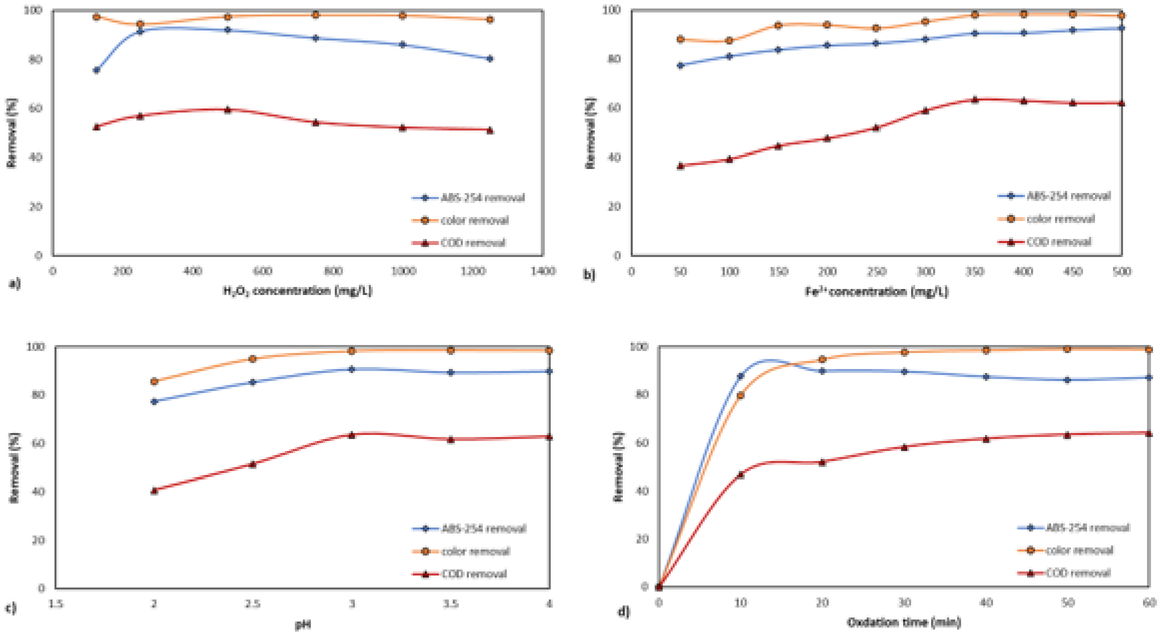

Figure 4. Treatment of DBWW by Fenton process a) different H_2O_2 (pH:3, Fe^{2+}:500 mg/L, t:1h), b) different Fe^{2+} (pH:3, H_2O_2:500 mg/L, t:1h), c) different pH (Fe^{2+}:350 mg/L, H_2O_2:500 mg/L, t:1h), d) different oxidation time (pH:3, Fe^{2+}:350 mg/L, H_2O_2:500 mg/L).

The Fe^{2+}/H_2O_2 (molar) ratio was determined to be 0.43 for DBWW treatment. Fe^{2+}/H_2O_2 (molar) ratio was founded as 0.33 for synthetic acid dye bath effluent treatment (Arslan Alaton and Teksoy 2007). 56.2% COD removal was achieved at 0.29 Fe^{2+}/H_2O_2 (weight) ratio for dye bath effluents treatment (Tanveer *et al.* 2022). 90% COD and 98% color removal were achieved for textile dye bath wastewater (containing RB 5) at 0.1 Fe^{2+}/H_2O_2 molar ratio (Patabandige *et al.* 2020).

COD, ABS-254, and color removal rates were obtained as 40.7%, 77.2%, and 85.5% at pH 2, respectively (**Figure 4c**). A gradual increase in COD, ABS-254, and color removal was observed at pH 2.5 and pH 3.0. COD, ABS-254, and color removal rates reached 63.6%, 90.6%, and 98.1% at pH 3, respectively. The reason for the low COD and color removal at pH 2.0 and 2.5 was attributed to the slow reaction of H_2O_2 with $[Fe(H_2O)_6]^{2+}$ and the excess H^+ ions leading to $H_3O_2^+$ (Ribeiro and Nunes, 2021; Machado *et al.*, 2023). No significant changes in COD, ABS-254, or color removal were observed at pH 3.5 and 4.0.

ABS-254 removal increased to 87.6% within 10 min. and remained unchanged thereafter (**Figure 4d**). Color removal increased during the first 30 min., reaching 97.7%. COD removal gradually increased throughout the 60 min. oxidation period. 46.7% COD removal was achieved in the first 10 min., followed by 51.9%, 61.6%, and 64.0% after 20, 40, and 60 min., respectively. There was no apparent variation between 50 and 60 minutes of oxidation. The high color removal achieved in the first 10 minutes is generally due to the fact that hydroxyl radical production reaches its maximum at the beginning of the reaction. Since hydroxyl radicals initially exhibit high reactivity, the removal of easily oxidizable organic structures occurs rapidly. The gradual enhance in COD removal over time was due to the fact that the oxidation of more difficult to decompose organic fractions requires longer radical interaction times.

The removal efficiencies obtained for dye bath wastewater treatment using Fenton process are summarized in **Table 2**. 85% COD and complete color removal were achieved at pH 3, 250 and 300 mg/L Fe^{2+} and H_2O_2 for synthetic dye (dispersed dyes) wastewater treatment (Szpyrkowicz *et al.* 2001). 84.6% COD and 98.6% color removal were reported at pH: 3.2, 1093 and 1600 mg/L Fe^{2+} and H_2O_2 for acrylic yarn dye effluent treatment (Ilhan *et al.* 2019). In another study investigating the treatment of chemical industry wastewater by the Fenton process, 81.6% COD, 80.6% TOC and 77.3% organic peroxide removal were stated under operation conditions where pH, Fe^{2+} and H_2O_2 concentrations were 3,2 g/L and 17,5 g/L, respectively (Dinçer *et al.* 2025).

3.3. Real DBWW treatment by adsorption process

3.3.1. Adsorption using activated carbon from coconut (AC-1)

The optimal pH was 2 for the highest removal efficiencies, and increasing pH led to a decrease in COD, ABS-254, and color removal (**Figure 5a**). COD, ABS-254, and color removals reached 69.7%, 75.8%, and 76.3% at pH 2, respectively.

pH plays an essential factor in color removal as it influences the adsorbent surface charge and the adsorbate ionization degree. An acidic environment was needed for reactive, direct, and acidic dyes, while an alkaline environment was required for basic dyes to improve color removal (Foo and Hameed 20210; Kheddo *et al.* 2020). This is because, for anionic reactive dyes, the activated carbon surface becomes positively charged in an acidic environment due to the presence of H^+ ions, causing protonation and electrostatic attraction (Foo and Hameed 20210, Kheddo *et al.* 2020). Conversely, the negatively charged activated carbon surface causes deprotonation of surface groups, and electrostatic repulsion occurs in a basic environment (Kheddo *et al.* 2020). The highest color removal in the adsorption of synthetic dye wastewater containing reactive dyes using activated carbon produced from rice husk was obtained at pH 2 (Kheddo *et al.* 2020).

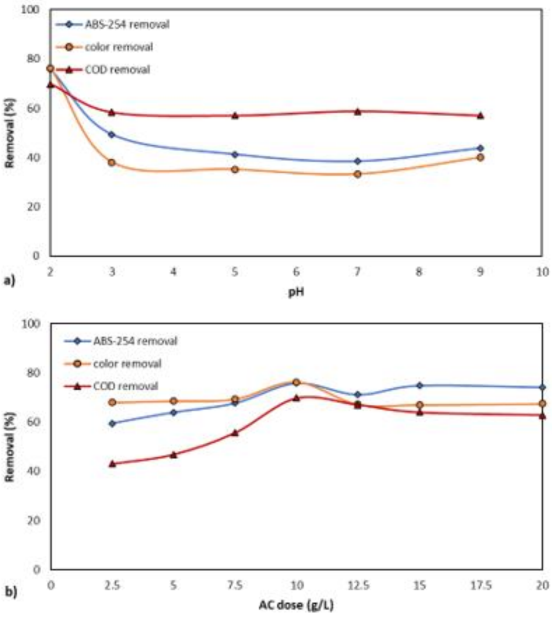

Figure 5. Treatment of DBWW by adsorption process using AC-1 a) different pH (AC dose: 10 g/L, t:1h), b) different AC dose (pH:2, t:1h).

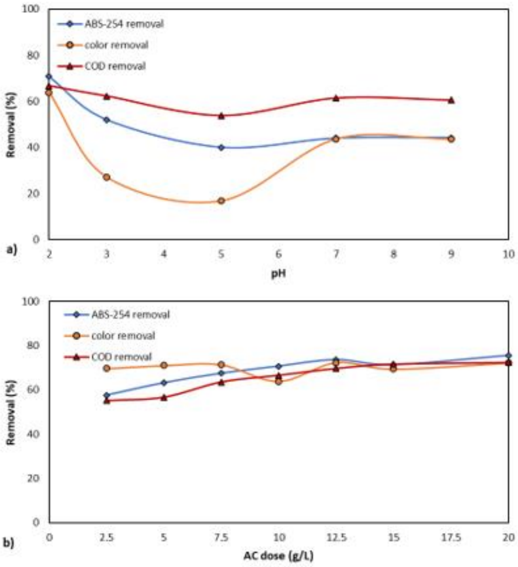

Figure 6. Treatment of DBWW by adsorption process using AC-2 a) different pH (AC dose:10 g/L, t:1h), b) different AC dose (pH:2, t:1h).

In adsorption studies conducted at pH 2, increases in COD, ABS-254, and color removal were observed with increasing AC doses up to 10 g/L (**Figure 5b**). A slight decrease was observed due to the remaining activated carbon particles in the wastewater after the 10 g/L AC dose. As the adsorbent dose increases, pollutant removal increases owing to the formation of more active sites on the activated carbon surface. However, removal becomes limited at high adsorbent doses because adsorption sites do not reach saturation, the total surface area decreases due to agglomeration, and the diffusion path becomes longer (Foo and Hameed 2010). COD removal was 43.0%, 46.8%, 55.6%, and 69.7% at 2.5, 5.0, 7.5, and 10 g/L AC doses, while ABS-254 removal was 59.4%, 63.9%, 67.6%, and 75.8%, respectively. Color removal similarly increased up to 76.3% at a 10 g/L AC dose.

3.3.2. Adsorption using activated carbon from coal (AC-2)

The optimal pH was 2 for the highest removal efficiencies, with efficiencies of 66.7% of COD, 70.8% of ABS-254, and 63.9% of color, and all removal efficiencies decreased as pH increased (**Figure 6a**). COD and ABS-254 removals increased to 69.8% and 73.7% at 12.5 g/L AC at pH 2 and did not produce any noticeable improvement at higher doses **(Figure 6b)**. Color removal also rose from 71.0% at 5 g/L to 72.4% at 12.5 g/L AC.

In the adsorption using activated carbons, pH 2 was found to be suitable with both types of activated carbon for efficient COD and color removal. Higher removal of COD and color were observed with coconut-based activated carbon at lower activated carbon amounts when the two activated carbon were compared.

3.4. Real DBWW treatment cost analysis

Chemical and electricity costs were calculated under optimum conditions for DBWW wastewater treatment using coagulation-flocculation, Fenton, and adsorption processes (**Table 3**). It is assumed that the cost of coagulants in the coagulation-flocculation process is \$0.35/kg, and the cost of activated carbon in the adsorption process is \$0.45/kg (Mukherjee *et al.*, 2022; Güneş *et al.*, 2024). In the Fenton process, the costs of $FeSO_4$ and H_2O_2 are assumed to be \$0.47/kg and \$0.64/kg, respectively (Sayın *et al.*, 2022). According to the current dollar/TL exchange rate, the cost of electricity in Türkiye is \$102/MWh. When the treatment costs of DBWW wastewater were examined, the increase in cost was determined as follows: Coagulation-flocculation < Fenton < Adsorption process. Therefore, the Fenton process is considered more suitable in terms of both DBWW treatment performance and cost.

Table 3. Cost of DBWW wastewater treatment with different processes

Treatment Process	COD removal (%)	Color removal (%)	Total cost ($\$/m^3$)
Coagulation ($FeCl_3$)	43.4	77.4	1.8
Coagulation ($AlCl_3$)	54.5	87.3	1.8
Coagulation (PACl)	60.9	79.2	1.8
Fenton	64.0	98.8	3.4
Adsorption (AC-1)	69.7	76.3	5.5
Adsorption (AC-2)	69.8	72.4	6.6

4. Conclusion

This study investigated real dye bath washing wastewater treatment using different wastewater treatment methods. For this purpose, coagulation-flocculation, Fenton, and adsorption processes were used. DBWW was treated with $FeCl_3$, $AlCl_3$, and PACl coagulants at different pHs and coagulant doses. PACl for COD removal and $AlCl_3$ for color removal provided the best DBWW treatment.In the treatment of DBWW using Fenton process, 64.0% COD and 98.8% color removal were achieved. Both activated carbons produced the greatest COD and color removal at pH 2 in the adsorption process. 69.7% COD and 76.3% color removal was observed at 10 g/L AC using activated carbon from coconut and 69.8% COD and 72.4% color removal was achieved at 12.5 AC using activated carbon from coal. Activated carbon from coconut provided higher COD and color removal at a lower adsorbent dosage.

In conclusion, the DBWW treatment showed varying efficiencies for different pollutant parameters of the treatment processes; in particular, Fenton process was identified as an effective alternative for color removal, and adsorption as a viable alternative for organic matter removal. This situation is important in terms of determining the treatment efficiencies of these processes in the treatment of high-flow but less polluted wastewaters originating from different production processes in factories, and revealing the recovery potential of these wastewaters as separate streams.

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