

Color and COD Removal from Textile Effluent by Advanced Oxidation Processes (Ozonation)

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Received Dec.25, 2025

Revised Feb.12, 2026

Accepted Feb.14, 2026

Online Jun.1, 2026

ABSTRACT

This study investigates the ozone treatment to remove MB dye. The main goals were to indicate the ozone treatment worked to break down methylene blue dyes, lower COD, and clear up the water, and to find the best contact time for the best results. The results indicated that ozonation significantly improved the elimination of turbidity, color, and COD with time. Ozonation 1 (10%) exhibited the lowest effectiveness in COD removal, achieving around 30% removal at 180 minutes, while Ozonation 2 (20%) and Ozonation 5 (50%) attained reductions of 55% and 60%, respectively. Ozonation 1 eliminated 50% of the turbidity, while ozonation 2 and ozonation 5 had the highest efficacy with 75% and 78% reduction at 180 minutes, respectively. Ozonation 1 eliminated around 50% of the color; ozonation 5 achieved a 70% reduction within the same reaction duration, resulting in a significant increase in color removal. After 180 minutes, ozonation 4 (40%) showed moderate efficacy, achieving COD, turbidity, and color removal rates of 70%, 70%, and 75%, respectively. The highest removal efficiency is recognized at ozonation 5, which reached 85% for turbidity removal, 74% for COD removal, and 75% for color removal. This study demonstrates that extended reaction durations greatly enhance the removal efficiencies of COD, color, and turbidity. For ozonation 5, the specially designed ozone reactor worked well to improve ozone settings, leading to the best results in getting rid of methylene blue dyes, COD, turbidity, and color.

Keywords: Advanced oxidation process, COD, Color removal, Ozone, Wastewater treatment.

1. Introduction

Large quantities of chemical dyes, surfactants, salts, and organic compounds are released into effluent streams during dyeing and finishing operations. Strong colors, high chemical oxygen demand (COD), limited biodegradability, and fluctuating pH define these streams, which render traditional biological treatment techniques useless for completely treating them [1]. The most often used synthetic dyes in the sector, azo dyes have complicated aromatic compounds with nitrogen-nitrogen double bonds. These dyes are meant to resist fading under exposure to light, heat, and microbial degradation, which renders them durable in aquatic environments [2]. Dye chemicals can provide vast amounts of visible color in water even at concentrations as low as 1 mg/L, therefore compromising aquatic photosynthesis and creating long-term ecological concerns [3]. With color removal and organic matter degradation as its main goals, COD in textile effluents typically falls between 1000 and 3000 mg/L [4]. Advanced oxidation processes (AOPs) have arisen as strong alternatives in reaction to these difficulties since they can produce reactive oxygen species (ROS), especially hydroxyl radicals ($\cdot\text{OH}$), which non-selectively oxidize a broad spectrum of organic pollutants [5]. Among AOPs, ozonation is a promising technology that creates little sludge and does not call for extra chemicals. A triatomic molecule, ozone (O_3), interacts directly with unsaturated bonds and aromatic rings to decompose complicated colored compounds. Ozone also breaks down in alkaline conditions to produce hydroxyl radicals, thereby increasing

oxidation [6]. The current work looks at how well ozonation removes color and COD from textile wastewater and finds the best operating conditions to provide outstanding treatment performance.

2. Literature review

2.1. Characteristics of textile wastewater

Synthetic dyes, surfactants, detergents, and metal salts in textile effluent cause its high toxicity and low biodegradability. Robinson et al. [1] characterized textile effluent as one of the most difficult industrial wastewaters to manage because of the stability of dye molecules and their resilience to microbial assault. Typically, textile effluent exhibits high color intensity and high COD values, with some samples displaying COD levels exceeding 4000 mg/L [4].

Azo dyes, reactive dyes, and anthraquinone-based dyes are common in textile production. Their molecular structures are designed to bind strongly with fabrics and resist chemical breakdown. As a result, they persist in aquatic environments and inhibit light penetration and oxygen transfer in surface water bodies [2, 3].

2.2. Mechanism of ozonation

Ozone can act as both a direct and indirect oxidizing agent. In direct oxidation, ozone attacks electron-rich functional groups in dye molecules such as $-NH_2$, $-OH$, and azo groups ($-N=N-$). In indirect oxidation, especially under alkaline conditions, ozone decomposes to form hydroxyl radicals ($\bullet OH$), which are more reactive and non-selective [5, 6].

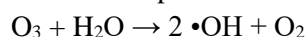
Kasprzyk-Hordern et al. [6] reported that the indirect pathway dominates at $pH > 8$ and enhances the oxidation of non-ionic dyes and refractory organic compounds.

The efficiency of ozonation depends on several factors:

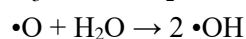
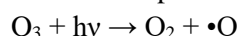
- pH (higher pH promotes radical generation)
- Contact time
- Initial dye concentration
- Ozone dose and mass transfer efficiency

The chemical equations illustrate the mechanism of the advanced oxidation process are explained:

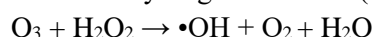
1. Ozone Decomposition to Hydroxyl Radicals:



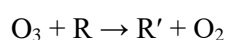
2. Ozone Decomposition with UV Light:



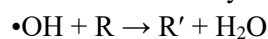
3. Ozone and Hydrogen Peroxide (O_3/H_2O_2 Process):



4. Direct Reaction between Ozone and Pollutants:



5. Reaction between Hydroxyl Radicals and Pollutants:



2.3. Ozonation performance in color and COD removal

Multiple studies have demonstrated the effectiveness of ozonation in removing color and COD from textile effluents. Kuo [7] found that ozonation achieved 92% color removal and 65% COD reduction in synthetic dye wastewater after 60 minutes of treatment at pH 10. Ozonation effectively cleaves chromophore groups such as azo bonds and conjugated aromatic structures, leading to rapid decolorization.

However, COD removal is generally lower than color removal because oxidation of intermediates into carbon dioxide and water is incomplete in short reaction times [5, 7]. Esplugas et al. [8] emphasized that ozonation is highly effective as a pre-treatment to enhance biodegradability or as a post-treatment to polish effluents before discharge.

Ozonation followed by biological treatment has been reported to increase the BOD_5/COD ratio, indicating improved biodegradability [8]. In the following Table 1, it represents the comparison between ozonation and other advanced oxidation processes to demonstrate the efficiency of ozonation in pollutant removal.

Table 1. The Comparison Table Between Ozone and other AOPs Process Showing the Advantages and Disadvantages of Different Technologies in Pollutant Removal

AOP type	Main reactant(s)	Hydroxyl radical generation	Pollutant degradation efficiency	Advantages
Ozonation	Ozone (O ₃)	Yes	High	Effective for a wide range of pollutants
O ₃ /H ₂ O ₂	Ozone (O ₃), Hydrogen Peroxide (H ₂ O ₂)	Yes	Very High	Enhanced radical formation with H ₂ O ₂
O ₃ /UV	Ozone (O ₃), UV Light	Yes	Very High	Rapid ozone decomposition with UV light
UV/TiO ₂	UV Light, Titanium Dioxide (TiO ₂)	Yes	High	Highly effective for organic contaminants
Fenton's Reagent	Hydrogen Peroxide (H ₂ O ₂), Iron (Fe ²⁺)	Yes	Very High	Very effective for organic pollutants and dyes

2.4. Limitations of ozonation

Although ozonation is efficient for color removal and partial oxidation, it has some limitations:

- High operational cost due to ozone generation.
- Incomplete mineralization of organics.
- Possible formation of toxic byproducts.
- Limited performance in high-strength wastewater unless combined with other methods [6, 8].

To overcome these limitations, ozonation is often integrated with coagulation, activated carbon adsorption, or biological processes.

Regarding the limitations of ozone treatment, although expensive, scalable, and polluting, ozone treatment eliminates microorganisms and oxidizes. Ozone production is energy-intensive and expensive for large enterprises. Reactivity and the water solubility of ozone can produce byproducts and impair treatment efficacy. These variables can slow mass transfer in large reactors, affecting scalability. Ozone concentrations or contact times may need to be increased for optimal treatment. Scaling up ozone treatment systems to accommodate additional water requires major engineering changes. Ozone is unstable; hence, more equipment is needed to remove it from effluent gas streams. It raises costs and complexity. Thus, ozone treatment could be an effective in removing dyes from wastewater.

Rekhate et al. [9] remove recalcitrant colors from genuine TDE. Fenton (O₃/Fe²⁺/H₂O₂) and enhanced ozonation were considered. The goal is to optimize process parameters, including starting pH, ozone concentration, Fe²⁺ concentration, and H₂O₂ concentration. RSM is commonly used to optimize processes by utilizing input factor correlations with expected outcomes. High coefficients of determination (R²=0.9599 and R²=0.9761) indicate a substantial correlation between color and COD measurements. RSM predicted that the best color removal efficiency would be 89.52% and 89.17% when using 70 mgL⁻¹ of ozone, 1748 mgL⁻¹ of Fe²⁺, 8.65 mL⁻¹ of H₂O₂, and a pH of 3. Compared to ozonation alone, the O₃/Fe²⁺/H₂O₂ method demonstrated improved treatment efficiency and cost-effectiveness.

Gomes et al. [10] Ozone reacts with colors at different rates. In a dye blend, these data may indicate that one dye is over-oxidized and the other under-oxidized, causing color. The AO7 decolorization rate is increased by two orders of magnitude from pH 3 to 8.2. Adding the radical scavenger only slightly reduced this effect. In a competitive trial, researchers compared AO7 to Acid Green 27 (AG27), an anthraquinone dye with a faster response rate. Mixing both dyes accelerates the color loss of AO7, even at pH = 2.7, which favors the undissociated species. This is a practical benefit because the two colors consume charged ozone almost equally.

Sevimli and Sarikaya [11] used a semi-batch reactor to treat wastewater. During 15 minutes of high ozone treatment, samples A and C lost 95% and 97% of their color. With less ozone, the color removal was 81% and 87%. During 15 minutes of high-ozone ozonation, wastewater samples A and C removed 95% and 97% of their

colors. At modest ozone exposure, efficiency was 81% and 87%. Sample A had 15-46% COD and 10-20% DOC removal efficiency at various ozone doses during a 15-minute ozonation period. In Sample C, 15-33% and 9-19% were found. COD and DOC clearance rates and ozone consumption per unit color were similar regardless of ozone dosage. Ozone consumption of 300 mg dm^{-3} during ozonation can enhance Sample A's BOD₅/COD ratio by 1.6 times. Acid dye ozonation was dye-specific pseudo-first-order. When the amount of Acid Red 183 (AR-183) dye was raised to 500 mg dm^{-3} , the amount of ozone used for each milligram of dye went up from 0.32 to 0.72 mg-O₃.

Fedorov et al. [12] conducted that cavitation-based technologies are an excellent choice for post-treatment in water treatment plants. Cavitation-AOP hybrids are more effective oxidation-capable techniques. Hybrid techniques destroy persistent pollutants faster and with less energy and oxidants than cavitation and AOPs alone (e.g., O₃, H₂O₂, Fenton's process). The synergistic index assesses how interdependent technologies function together, helps hybrid methods outperform their separate counterparts. Oxidant type, pH, hydraulic and ultrasonic characteristics, and Kow affect oxidation. Comparative analysis highlighted the approaches' benefits and limitations. The economic feasibility study examined hybrid wastewater treatment for large-scale applications.

Fernández et al. [13] to treat municipal wastewater, this study sought to compare three advanced oxidation methods: Fenton, UV/Fenton, and O₃/Fenton. COD, BOD 5, TC, and FC were tested using three AOPs: ferrate, UV/Fenton, and O₃/Fenton. The effects of pH, reaction time, and the ratio of H₂O₂ to Fe²⁺ were also examined. The standardized procedures were used to measure all parameters. The optimal H₂O₂:Fe²⁺ mole ratio for maximum pollution clearance was determined to be 0.7:1. Additionally, when the pH rose from 4 to 7, there was an increase in the elimination of COD and BOD 5.

Even though contact time affected COD, BOD 5, TC, and FC up to the point of equilibrium, it lost most of its significance beyond the point of equilibrium. The following ranking presents the removal efficiencies of all parameters based on a comparative study of various AOP systems: O₃/H₂O₂/Fe²⁺ > UV/H₂O₂/Fe²⁺ > H₂O₂/Fe²⁺. Finally, Fenton and its tweaked procedures show enormous promise for cutting-edge sewage treatment in urban areas.

Hassanshahi and Karimi-Jashni [14] compared and optimized three different processes: photo-Fenton, photocatalysis, and ozone/H₂O₂/UV. The photo-Fenton process was shown to be most affected by the H₂O₂/Fe²⁺ ratio, whereas the ozone/H₂O₂/UV experiment was impacted by the concentrations of O₃, H₂O₂, pH, and reaction time. Similarly, the photocatalytic process was found to be most affected by the concentrations of TiO₂, pH, and reaction time. In terms of COD elimination efficiency, photo-Fenton achieved 90%, ozone/H₂O₂/UV 92%, and photocatalytic 55%. After analyzing the results using design expert software, second-order models were suggested for all three processes to simulate the efficiency of COD elimination. Since the ozone/H₂O₂/UV procedure removed 92% of the COD and 93% of the turbidity, it is recommended for treating gray water.

Dong et al. [15] stated that Ozone (O₃), ultraviolet (UV)/O₃, and UV/O₃/persulfate (PS) methods for marine oily wastewater treatment are examined in a tabletop circulating flow photoozonation reactor for degrading performance, acute toxicity, and oil flocs analysis. Total oil concentrations, specific oil components (n-alkanes and PAHs), and total organic carbon (TOC) breakdown rates have been examined. UV/O₃/PS had above 90% removal efficiency in 30 min, outperforming the other two methods. Acute toxicity analysis demonstrates that wastewater quality improves by fourfold; the EC₅₀ of *Vibrio fischeri* and *Artemia franciscana* mortality drops from 100% to 0% after 48 h. Further characterization of floc shape and functional groups shows that the UV/O₃/PS procedure can disintegrate floating flocs. Our study raised questions about using O₃-based systems directly on-site, considering how well they work, their toxicity, and the characteristics of the flocs. Controlling how strong the oxidation is and improving the reaction system might be possible for treating oily wastewater from the sea on-site.

Ozonation can lower the levels of some pollutants, but it can also make toxic byproducts. These intermediates, especially the hazardous ones created during the ozonation process, raise concerns about the safety of the effluent.

Advanced oxidation processes like ozonation are utilized to break down contaminants in wastewater. It is very important to find and measure the toxicity of these intermediate molecules to make sure that ozonation is safe as a therapeutic technique. Using ozonation along with other techniques of treatment, such as biological or photo-Fenton approaches can make detoxification work better and cut down on the production of hazardous byproducts.

This research deals with the comparatively evaluate ozonation treatment for turbidity, COD and color removal artificially prepared textile industry water. In the (AOPs) a reactor made of transparent plastic and ozone generator where many factors affecting the efficiency of removal has been studied.

3. Experimental procedure for methylene blue removal using ozonation process

This research investigates the efficiency of ozonation in removing color and COD from textile wastewater. A laboratory-scale ozonation setup was used to treat real textile effluent. Key operational parameters such as pH, ozone dosage, contact time, and initial pollutant concentration were varied to determine optimal treatment conditions.

The methodology involved five main stages:

- Collection and characterization of synthetic textile wastewater.
- Preparation of the ozonation system.
- Adjustment of pH and control variables.
- Application of ozone treatment under different conditions.
- Measurement of color and COD removal efficiency.

3.1. Preparation of processed water

A synthetic wastewater sample is prepared by mixing methylene blue which contains a known concentration of the dye, 12 mg/L, with distilled water. The solution's pH is set to 7, either with based on earlier research. The solution is agitated to mix well prior to commencing the oxidation process.

3.2. Experimental setup

An ozonation procedure is carried out in a Acrylic square reactor with 3 liters of volume (15 cm × 15 cm × 15 cm) and 6 mm thick walls. The reactor has a connection to a 6 L water sample storage box. An ozone generator is connected to the reactor to enable continuous water sample ozonation. The solution is dosed with ozone gas through a diffuser located at the bottom of the reactor. The ozonation chamber is coupled with a 3 L compartment which functions as an initial storage vessel for water prior to ozonation and serves as the feed tank the ozone device is connected to an oxygen vial, where oxygen enters the ozone apparatus and the Ozone gas connected to the container containing industrial water comes out of it for the purpose of treatment. As presented in the Figure 1.



Figure 1. The Ozonation System for the Experimental Process

The operating conditions were a temperature of 27°C, pH=7, and a dye concentration of 12 mg/L. They were used in the experimental study. Moreover, the ozonation rates used in this research are 0.2, 0.4, 0.6, and 0.8 g/hr. Different time intervals were investigated, starting from time zero and reaching 180 min as the contact time. Several parameters are tested, such as COD, turbidity, and color removal efficiency.

This research investigated how much ozone was given to a system in its gaseous form, but it didn't study how well or how much of that ozone dissolves into the liquid phase or how efficiently it goes from the gas phase to the liquid. The study only measured the ozone gas in the air, not how well it mixed with or dissolved in the water. The ozone (O_3) is added to a system, whether a reaction chamber or a water treatment process, in its gas state. It is measured as the flow rate or concentration in milligrams per liter.

3.3. Steps in the ozonation process

The process initiates with an ozone generator being engaged to inject an ozone solution at various concentrations (10%,20%,30%,40%,50%). Each concentration reacts with the solution containing the dye for three hours and we take doses from the reactor every 15 minutes to establish the best contact time for maximum reaction. The experiment is conducted maintaining a temperature of 27 degrees (+/- 2 degree Celsius).

3.4. Collection and analysis of samples

Following the ozonation process, samples are taken at different contact time intervals for analysis. The indicators measured to ascertain the efficiency of the process are as follows Measurement of color removal efficacy by means of a UV-Vis spectrophotometer at 664nm. Determination of Chemical Oxygen Demand (COD) in a COD reactor. Determination of turbidity (NTU) by means of a turbidity meter. Figure 2 shows the experimental procedure for the ozone treatment.

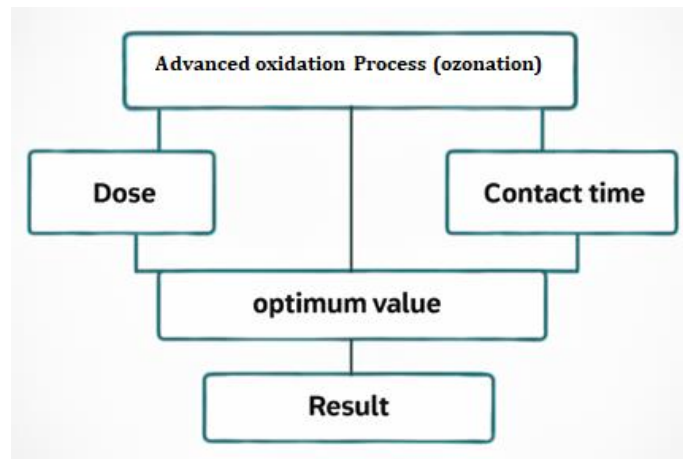


Figure 2. The Flowchart of the Experimental Study for Ozone Treatment

4. Results and discussion

Finding the best possible value conditions for the research variables while keeping the associated expenditures and contact time requirements to a minimum is the primary focus of this phase. The conditions were maintained at a pH of 7 and a dye concentration of 12 mg/L. Higher pH removal efficiencies were achieved with ozone for all parameters compared to neutral pH removal efficiency. Ozone can produce free hydroxyl radicals in environments with a high pH. To evaluate the efficiency of the ozone generator, it is necessary to lower the starting turbidity, color, and chemical oxygen demand levels. Using ozone at concentrations ranging from 3 to 18 mg/min and for durations ranging from 10 to 120 minutes, this treatment made use of ozone technology. Whether organic dyes undergo direct oxidation via ozonation or indirect oxidation via hydroxyl radicals depends, in large part, on their molecular structure. More potent oxidants, hydroxyl radicals, aren't particularly selective about which color chromophores they destroy.

The effects of contact time and ozone concentration on color removal are shown in Figure 3. The operating conditions are 12 mg/L dye concentration, and the pH is 7. Adjusting the amount of ozone used from 0.3 g/hr to 0.5 g/hr produces this result. The presence of hydroxyl radicals, which can oxidize substances more effectively than molecular ozone, might explain why decolorization happens a bit faster in alkaline conditions. For each dosage, the contact time is modified every 15 minutes, with a range of 10 to 180 minutes. The effectiveness of removal rose by around 20% between 10 and 70 minutes but by only about 5% between 70 and 180 minutes.

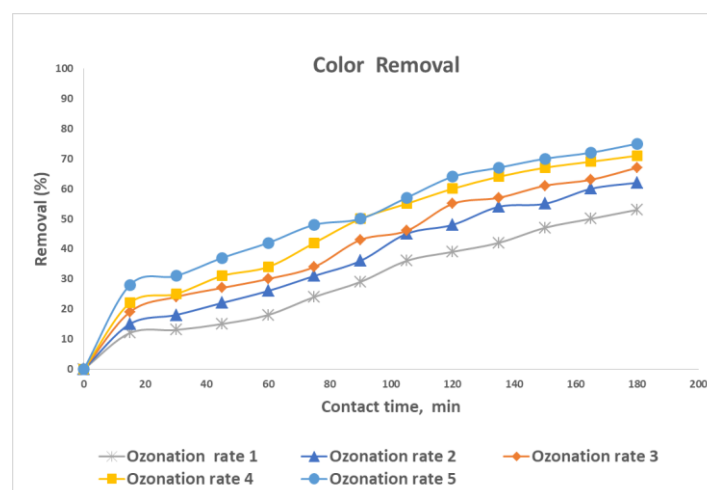


Figure 3. The Relation Between Contact Time and the Removal Efficiency for Methylene Blue

This specifies that the elimination efficiency was minimal after 70 minutes, reaching its peak at 180 minutes. During this time, the rise was shown at rates of 0.2, 0.4, 0.6, 0.8, and 1 g/hr which correspond to 50%, 59%, 64%, 68%, 74%, and 85%, respectively. We achieve removal rates that are in line with what is found in the literature [16]. An optimal ozonation rate of 18 mg/min over 180 minutes was achieved.

It is evident that the concentration of ozone in the air bubbles grows with increasing service time. This evidence suggests that the atomic oxygen used in the ozone process is very reactive, effectively binding organic substances in wastewater. Ultimately, this procedure leads to more efficient color removal with less sludge. Over time, the decolorization of wastewater is linked to an increase in the mass transfer of ozone from air-ozone bubbles to the liquid phase. This is because the bubbles' capacity to produce radial momentum grows.

The Y-axis shows the proportion of color loss. This assesses how well the ozonation process removes color, probably from organic or inorganic pollutants, such as dyes or pigments. This curve directs the contact time required for ozone to interact with impurities and decolorize the treated water. Every line denotes a particular ozonation procedure; each procedure indicates how color removal changes with time. The lines relate to various experimental setups: starting from about 20% at 0 minutes and ending at approximately 50% at 180 minutes, ozonation rate (0.2 g/hr) has the lowest color removal efficiency over time. At ozonation rate (0.8 g/hr), with color removal increasing from roughly 25% at 0 minutes to about 60% at 180 minutes. At ozonation (0.4 g/hr), with color removal beginning at 30% and nearing 70% at 180 minutes, this ozonation system operates better. Ozonation rate (1 g/hr) shows great efficiency, achieving approximately 75% color removal after 180 minutes. Although it is somewhat less efficient than ozonation (1 g/hr), this treatment shows a significant improvement in color removal, achieving around 65% at 180 minutes. Longer contact time enhances removal. All ozonation treatments reveal increased color loss as the contact time rises, suggesting that the process is more efficient over longer periods. With results nearing 75% at 180 minutes, ozonation (0.8 g/hr) and ozonation rate (1 g/hr) show the greatest color removal efficacy. These processes can be thought of as the most effective ways to achieve noticeable color removal in water treatment.

Gopalakrishnan et al. [17] emphasize the link between ozonation efficiency, color removal, and reaction time. The data shows that ozonation is a successful color removal technique; longer reaction periods result in more efficient color degradation. With over 70% removal at 180 minutes, the ozonation rate (1 g/hr) and (0.8 g/hr) treatments show the greatest removal rates, thereby being the best options for handling color-polluted wastewater. The results are shown in Figure 3, which explains the relation between different ozone concentrations with different contact times (min) and the removal efficiency for color removal.

At pH 7, Figure 4 shows how the length of contact and concentration of ozone affect NTU elimination. Changing the amount of ozone used in different ratios accomplishes this. How effective the turbidity reduction is will dictate the duration and dosage. The effectiveness of removal rose by around 20% between 10 and 70 minutes but only by about 8% between 70 and 120 minutes. This shows that after 70 minutes, the removal efficiency didn't improve much, but it was much better at 120 minutes, with increases at rates 0.2, 0.4, 0.6, 0.8, and 1 g/hr reaching 68%, 72%, 79%, 83%, 89%, and 92%, respectively, which means that the amount of ozone used and the contact time it was in contact made a big difference in how much turbidity was removed. This aligns with the percentages seen in other research [18]. Since the ozone technique uses highly reactive atomic oxygen, it effectively reduces turbidity with little sludge by binding organic material in the wastewater.

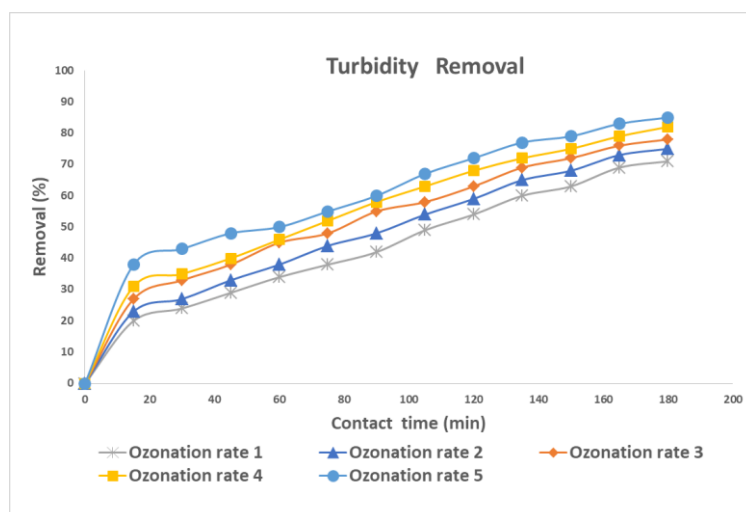


Figure 4. The Relation Between Dose of Ozonation and the Turbidity Removal (%) at Different Time

Turbidity is a measure of the cloudiness or haziness of a liquid caused by the presence of particles. In water treatment, turbidity removal is a crucial parameter as it indicates the effectiveness of the treatment in removing suspended particles and pollutants.

Longer reaction times generally result in greater degradation of contaminants, hence improving turbidity removal. Different ozonation processes are represented by five distinct lines, each corresponding to a different experimental setup. The lines indicate the turbidity removal efficiency over the reaction time. Ozonation rate (0.2 g/hr) shows the lowest turbidity removal efficiency, with a gradual increase in removal over time. Ozonation 4 (0.8 g/hr) shows better removal efficiency compared to Ozonation (0.2 g/hr), indicating an improvement in the ozonation process. Ozonation rate (0.4g/hr) shows a higher turbidity removal rate, suggesting that Ozonation (20%) is more efficient than Ozonation (10%). Ozonation rate (0.8 g/hr) shows significant turbidity removal efficiency, better than other ozonation rates. Ozonation rate (1 g/hr) demonstrates the most effective turbidity removal (85%), achieving the highest percentage of removal as contact time increases, but slightly less effective than ozonation (0.8 g/hr).

As the contact time increases from 0 to 180 minutes, all ozonation processes show an increase in turbidity removal, which is consistent with expectations. This trend suggests that ozonation is more effective at removing turbidity over a longer treatment period. Ozonation rates (0.8 and 1 g/hr) are the most efficient. Among the five ozonation processes, ozonation (1 g/hr) shows the highest turbidity removal efficiency, approaching 85% removal at 180 minutes of contact time.

The data suggests that the effectiveness of ozonation in removing turbidity is influenced by the contact time and the specific experimental setup (ozonation method). Ozonation (40%) and (50%) provide the most efficient treatment for turbidity removal, and they are preferable for practical applications in water treatment. Ozonation rate (0.6 g/hr) is effective but slightly less efficient than Ozonation (0.8 /hr and 1 g/hr). Ozonation (10%) is less effective and would likely need optimization in terms of ozone concentration or other factors.

Zhou et al. [19] discuss how ozonation is a key process for removing contaminants from wastewater, including turbidity. The study highlights the role of contact time in optimizing ozonation for turbidity removal. Another study [15] focuses on the removal of COD and turbidity in textile wastewater using ozonation. It confirms the trend observed in the turbidity results, in which increasing contact time results in greater turbidity removal.

Figure 5 shows the effect of contact time and ozone concentration on COD removal at pH 7. Contact duration and dosage rate are influenced by COD elimination. From 10 to 70 minutes, removal efficiency increased by around 20%, but from 70 to 120 minutes, it only increased by about 10%. At 70 minutes, the removal efficiency was minimal, but it peaked at 180 minutes and an optimal dosage ozonation rate of 1 g/hr. The ozonation rate was gradual at 0.2, 0.4, 0.6, 0.8, and 1 g/ hr with values of 56%, 60%, 66%, 70%, and 74%, respectively. As time passes, it is noticed that the air bubbles' ozone concentration grows, which acts as a propellant for ozone transfer. Smelly compounds can break apart their main structures because ozone destroys the building blocks of aromatic substances. The water's COD levels rise as smaller soluble particles form. Reduced COD removal and wastewater decolorization are outcomes of these metamorphic molecules' ozone-induced tenacity and resistance to breakdown. Several investigations, including this one, have demonstrated that ozonation is not successful for reducing COD, but it shows promise when applied in a single process for color removal and partial oxidation to increase biodegradability.

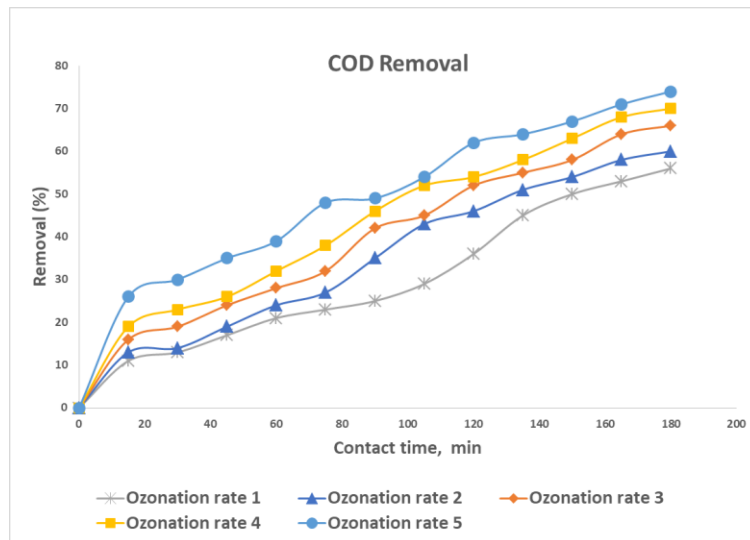


Figure 5. The Relation between Contact Time and Dose of Ozonation

The Figure 5 shows the percentage of COD removal, which reflects how well the ozonation process degrades organic contaminants in the water. Ozonation is applied to the water across the response time, or horizontal axis, measured in minutes. Generally, the efficacy of COD elimination gets significant as the contact time rises. Different ozonation rates are shown by separate lines. These lines indicate the proportion of COD reduction obtained with various ozonation rates. Ozonation (0.2 g/hr) is the first treatment, demonstrating a considerably slower rate of COD elimination than the others. Ozonation (0.8 g/hr) has average COD elimination efficacy in comparison to others. Ozonation rate (1 g/hr) indicates more effective breakdown of pollutants since it removes more COD than the prior ones. Ozonation (0.6 g/hr) is still effective; this treatment performs well but somewhat lags behind the others for COD elimination.

In Table 2, it shows the removal efficiency of MB, which included COD, turbidity, and color removal. Based on the results, it is shown that ozonation rate (1 g/hr) is more efficient than others in the removal of COD, turbidity, and color.

Table 2. The Removal Efficiency of MB Including COD, Turbidity and Color

Stage No.	COD removal	Turbidity removal	Color removal
Ozonation rate (0.2 g/hr)	56	71	53
Ozonation rate (0.4 g/hr)	60	75	62
Ozonation rate (0.6 g/hr)	66	78	67
Ozonation rate (0.8 g/hr)	70	82	71

As anticipated, all ozonation techniques enhance COD removal with rising reaction time. Usually, longer response times let the ozone interact more completely with the impurities in the water. Reaching around 70% removal at 180 minutes of reaction time, Ozonation 2 and Ozonation 5 exhibit the greatest performance in terms of COD removal. Though it falls a little behind the other treatments, ozonation 3 exhibits a rise in COD elimination. The least elimination efficiency is shown by Ozonation 1, which reflects the baseline procedure. Contact time has a major impact on ozonation's efficacy in lowering COD. Longer ozonation times lead to more COD removal, suggesting the need for optimized reaction times in water treatment operations. Of the ozonation techniques, ozonation 2 and 5 offer the most effective treatment; hence, they are most suited for practical use in wastewater treatment. This research likely supports findings in advanced oxidation processes (AOPs), which are often used to break down pollutants like COD. A frequently applied AOP is ozonation; research usually shows the rise in efficiency with extended reaction times. Research on ozonation for wastewater treatment, for example, emphasizes the need for contact time and ozone doses in enhancing COD removal [14, 15]. This paper addresses the optimization of ozonation in wastewater treatment, demonstrating how reaction times, ozone dosages, and other variables influence COD removal efficiency [16, 20, 21].

The Figure 6 shows how varied ozonation rates affect the removal rates of COD, turbidity, and color when the contact duration is always 180 minutes. In general, the removal efficiencies for all three parameters go better

when the ozonation rate goes up from 0.2 g/hr to 1 g/hr. The blue bars reflect the efficiency of removing COD, which gets better as the ozonation rate goes up. This shows that more ozone exposure makes organic chemicals in the water break down faster. The orange bars show that the turbidity removal also gets better as the ozonation rate goes up, but not as much as the COD removal. The gray bars illustrate that color removal follows a similar pattern to turbidity, but the rate of improvement is a little slower. The graphic shows that increased ozonation rates help get rid of pollutants better, with COD being the most affected.

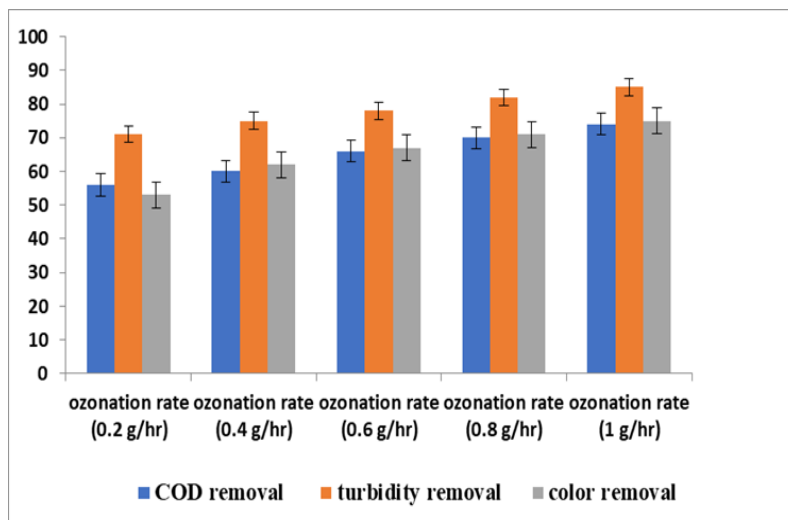


Figure 6. The Errors Bars with Standard Bars for COD, Turbidity and Color Removal

Regarding the molecular structure of dyes influences their ozonation behavior. The way methylene blue molecules are put together has a big effect on how it reacts to ozone. First, aromaticity, ozone can easily attack the conjugated electron system in the aromatic ring, which breaks down the dye and removes its color (75% color removal). In the Nitrogen with an electron deficiency, the positive charge on the nitrogen atom makes the dye more reactive to ozone, which helps remove 74% of the COD when ozone breaks down the dye into tiny organic pieces. Second, sulfonate Group makes the dye more soluble in water, which helps the ozonation process and removes 85% of the turbidity by making particles that can be easily grouped together and removed. Third, Aromatic Ring Breakdown in which the breaking up of the aromatic rings lowers both color and COD, which shows that the process is oxidative. In short, the way methylene blue molecules are put together makes them break down a lot when exposed to ozone, which makes the effluent less colored, less COD, and less cloudy. The results show that ozonation is a successful way to get rid of methylene blue, but the fact that byproducts are formed and mineralization is not complete means that more treatment may be needed to fully break it down. The error bars on the figure show the standard errors, which tell you how far off the individual measurements could be from the average. For all the ozonation rates and removal methods, the error bars are rather small. This signifies that the measurements are right and can be done again. This check shows that the results are correct and that doing the tests or measurements again doesn't indicate any substantial changes. The error bars show that the patterns we found are statistically significant and not greatly affected by changes made to the experiment.

Finally, using ozone-based advanced oxidation processes (AOPs) to remove dye from wastewater works well, but how well it works can vary depending on the specific dye and other substances involved. Some dyes can be more effectively and affordably treated using ozone-based treatments than with other AOPs, such as Fenton or UV-based methods. While some AOPs may be more effective at removing certain dyes than others, it is common practice to combine multiple AOPs into a single treatment plan to achieve the best possible outcome.

Our result is in a line with [22] in which it was found that ozone is an effective approach in removing dyes. Under optimal operating conditions (ozone flow 300 mg/h, pH 7.1, temperature 25°C), ECS/O₃ decolorized and removed almost 99.7% COD. COD and color removal were 95.6% and 97%, respectively, with ECS/photo-Fenton. Minimum dye and COD removal required 1.58 kWh/m³ of ECS electrical energy. ECS/ozonation decolorizes 100% but is expensive. Considering treatment and energy usage, ECS/photo-Fenton was second-best. Thus, a combined ECS-AOP treatment system seemed most viable and eco-friendly. That could lead to the reuse and recycling of treated wastewater in industry.

The energy cost of using ozone to remove methylene blue (MB) dye from wastewater depends on how well the generator works, how much ozone is used, and how much energy costs. The amount of ozone needed depends on how much dye there is and how much color it loses. Electricity is needed to run ozone producers. The amount of ozone needed to remove the dye depends on the initial dye concentration. The cost of ozone-producing energy depends on how well the system works, and the cost of electricity adds to the entire treatment cost. The amount of ozone needed for industrial use depends on the volume of treatment and the rate at which color fades. The amount of ozone needed per cubic meter of treated water can be used to figure out how much energy ozone treatment will cost. The size and efficiency of the treatment system affect its operating expenses.

In [23] the goal was to remove phenol, a test pollutant at a concentration of 1.4 mM (equivalent to 100 mg-C L⁻¹), in order to evaluate the cost-effectiveness of each method. Sludge management, chemical use, and electricity consumption were all factors in the running costs. Electro-Fenton's electrocatalytic activity made it the most cost-effective AOP (108 to 125 € m⁻³), regardless of whether the mineralization objective was 50, 75, or 99 percent. It is possible to use chemical Fenton as an economical pre-treatment option since it was competitive with mineralization up to 50%. Due to its high faradaic yield, electro-Fenton had the lowest AOC_D, whereas UV-based methods often required the largest dose. Lawmakers might find the AOC_D standard useful for deciding the "best available techniques" according to the Industrial Emissions European Union Directive 2010/75/EU, which serves as a reference point for comparing AOPs.

Finally, based on the SPSS analysis, the relation between the COD, turbidity, and color removal efficiency and ozonation rate are analyzed using one-way ANOVA. Thus, based on the Beta coefficients provided, the regression equation can be written as:

$$\text{Ozonation Rate} = \text{Constant} + (\beta_{\text{turbidity}} \times \text{Turbidity}) + (\beta_{\text{color}} \times \text{Color}) + (\beta_{\text{COD}} \times \text{COD})$$

Using the values from the table:

- *Constant* (Intercept) = -17.356.
- $\beta_{\text{turbidity}} = 0.738$.
- $\beta_{\text{color}} = -0.099$.
- $\beta_{\text{COD}} = 0.361$.

This is the predicted equation for the ozonation rate, based on the standardized coefficients (Beta) of the independent variables.

$$\text{Ozonation Rate} = -17.356 + (0.738 * \text{Turbidity}) + (-0.099 * \text{Color}) + (0.361 * \text{COD})$$

The regression results show that *turbidity*, *color*, and *COD* removal do not have a big effect on the ozonation rate in the data we have. To make more accurate predictions, the model may need to be tweaked or have more variables included.

5. Conclusions

The strong oxidizing qualities of ozone, in particular its capacity to break down the conjugated double bonds in dyes, make it an excellent treatment for dye removal from wastewater. This property is known as ozonation. The effluent is decolorized and its biodegradability improves through this process. Using activated carbon or biological treatment along with ozonation helps to completely remove dyes, since ozonation by itself might not be enough to break them down into safe substances. This research is analyzed to remove MB dye using ozone treatment. The results indicate that ozonation is a successful technique for eliminating turbidity, COD, and color removal for removing MB dye, with the removal efficiency rising as the contact time is prolonged. Especially with Ozonation rates (0.8 g/hr and 1 g/hr), the custom-built ozone reactor was quite successful, achieving up to 75% color removal, 74% COD reduction, and 85% turbidity removal, after 180 minutes. It wouldn't cost much electricity to purify wastewater with ozone. But to give a significant idea of the entire cost, real expenses could be different depending on how the system is set up, how well the ozone generator works, and how much electricity costs. Regarding the ozone limitations, ozone treatment is an effective technology in removing MB dye from textile wastewater.

Regarding the future work, future studies should concentrate on ozone dose optimization, investigating how different water qualities affect pollutant removal, and combining ozonation with other sophisticated treatment techniques. It is best to compare ozonation to other AOPs like Fenton's reagent, photocatalysis, or UV-H₂O₂. This would assist in showing how well ozonation works compared to other well-known methods of cleaning up textile waste. Furthermore, evaluating the relevance of the reactor in actual wastewater treatment plants will depend on its size for larger treatment systems

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Funding Information

No funding was received from any financial organization to conduct this research

Author Contributions

All authors proposed the research problem. In addition to author Saja Hamed Latef and Ali Jwaid collected recent articles and organized them in simple shapes. Authors Saja Hamed Latef and Ali Jwaid verified the recommendation in the proposed work. Author Ali Jwaid designed and proposed work. Authors Saja Hamed Latef and Ali Jwaid discussed the proposed design. All the authors discussed the results and the final version of this paper.

Acknowledgments

We thank Dr. Ali for his guidance during the whole study and many thanks to the civil department in the college of engineering at Wasit University for giving us the opportunity to work in their laboratories.

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