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Innovative approaches for removing reactive Yellow 145 dye pollutants from water sources

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Abstract

The escalating challenge of industrial dye pollution in wastewater necessitates the exploration of effective treatment methodologies. This study introduces a novel approach combining microwave irradiation with the Fenton oxidation process, showcasing a significant leap in the removal of Reactive Yellow 145 pollutants. By systematically manipulating variables such as Reactive Yellow 145 concentration, catalyst presence, and reaction environment's pH, the investigation reveals a substantial increase in the degradation efficiency of complex dye molecules. The synergy between microwave energy and chemical oxidants under optimal conditions results in a remarkable reduction of both color and chemical oxygen demand (COD) levels, with the process achieving over 95% dye elimination and 82% COD reduction within 7 minutes. The analysis of UV-Vis spectroscopy before and after treatment showed that the microwave-enhanced Fenton process efficiently decomposed dye molecules, with a notably faster decomposition rate observed for azo and hydrazine groups compared with aromatic structures. This study not only underlines the potential of microwave-assisted Fenton processes in addressing persistent wastewater contaminants but also sets the groundwork for future research in scalable, environmentally friendly wastewater treatment solutions.

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Introduction

Efforts to remove reactive dyes from industrial wastewater have been a significant challenge. This difficulty arises primarily because these organic compounds, due to their inherent chemical properties, pose a range of direct and indirect environmental risks (Zoqi, 2021). Releasing wastewater with azo dyes into the environment is problematic, not only because the vivid colors are easily observed by people, but also due to potential health risks, including carcinogenic and mutagenic effects on humans. When industries like textile, leather, paper, and plastics fail to properly treat these colorful effluents, it can lead to ecological imbalance and pose threats to human health (Ghasemi et al., 2024).

To confront the challenges associated with the treatment of effluents containing chemical substances, various strategies have been proposed. The most common methods for removing color pollutants from

wastewater include coagulation and flocculation processes, adsorption using activated carbon, membrane filtration, and biological treatment methods. Nonetheless, methods such as coagulation and flocculation, membrane filtration, and adsorption using activated carbon only shift color pollutants from one phase to another without fully breaking them down (Verma et al., 2012). This process could result in the creation of secondary pollutants in the environment (Alardhi et al., 2023). Biological treatments depend predominantly on microorganisms to break down pollutants, but certain synthetic dyes are engineered to withstand the alterations induced by biological processes (Velusamy et al., 2021). Consequently, there is a critical need to develop an alternative eco-friendly approach that more efficiently transforms color pollutants into benign intermediates, or into CO_2 and H_2O, while avoiding the generation of secondary pollution (Mancuso and Iervolino, 2022).

The Fenton process, a prominent advanced oxidation method, operates through the formation of hydroxyl radicals (OH). As a result of the high oxidizing capability of these radicals, the process has gained significant attention in recent years for treating effluents containing highly concentrated and biologically resistant dyes (Ledakowicz and Paździor, 2021). However, challenges such as the slow reaction rate of the Fenton process and the high costs associated with hydrogen peroxide consumption have limited its widespread application in large-scale settings. Nonetheless, the efficiency of the Fenton process can be enhanced through integration with other physicochemical methods (Khan et al., 2021). The application of ultrasonication has been shown to enhance azo dye removal and COD reduction in wastewater treated by the Fenton process (Menon et al., 2021). The photo-Fenton method, which combines the Fenton reagent with light irradiation, has been introduced as an effective approach for wastewater treatment (Ahmed et al., 2011). Light sources such as sunlight and high-pressure mercury lamps can significantly enhance this reaction. The photo-Fenton process facilitates an increased reaction rate, yet its application faces challenges due to limited light penetration in turbid and highly pigmented effluents.

Microwave radiation, a form of electromagnetic wave, engages with molecules via thermal and non-thermal mechanisms, effectively lowering the energy required for activation. In contrast to traditional heating methods, microwaves provide benefits like swift and targeted heating, straightforward control, and the facilitation of more efficient chemical reactions (Barham et al., 2019). Relative to the photo-Fenton method, integrating microwave technology with the Fenton process has been shown to enhance pollutant elimination efficiency, while also minimizing both the expense and duration of the treatment. Additionally, this microwave-assisted Fenton approach helps in lowering the required amount of H_2O_2 (Garcia-Costa et al., 2019). Therefore, the combination of microwave irradiation and the Fenton process presents an innovative approach in wastewater treatment strategies. Recently, a growing number of researchers have been employing microwave technology to boost the elimination of organic contaminants from water-based solutions (Garcia-Costa et al., 2019; Qi et al., 2019). In the study, microwave-enhanced Fenton processes were introduced for treating Rhodamine B (RhB) containing wastewaters, achieving more than 68% COD removal (Vieira et al., 2020).

Reactive Yellow 145 (RY145) serves as a representative of acid dyes that are non-biodegradable. Its release into natural environments poses significant challenges for aquatic life, due to its potential to disrupt ecosystems. Moreover, certain characteristics of RY145 may contribute to genetic mutations and the development of cancer in humans (Singh et al., 2022). Effective treatment of this dye is crucial for aquatic environments, highlighting the environmental protection imperative. RY145's complex molecular structure, characterized by stable aromatic rings and azo bonds, resists breakdown by standard biological treatment methods. This resistance necessitates advanced treatment

techniques to mitigate its impact on aquatic life and human health. Research into efficient methods for decomposing RY145, such as advanced oxidation processes is critical. The urgency to address this issue is underscored by the increasing prevalence of RY145 and similar dyes in industrial effluents, and the growing awareness of their long-term ecological and health consequences.

In the process of decolorization based on the Microwave-Fenton method, several influential variables are identified. The importance of these parameters stems from their critical role in determining the efficiency of the Microwave-Fenton process. The initial pH significantly affects the generation of hydroxyl radicals, essential for dye degradation. The dye concentration is a crucial factor as it can impact the absorption of microwave energy and subsequent chemical reactions. Similarly, the concentrations of H_2O_2 and Fe^{2+} are vital for generating a sufficient amount of hydroxyl radicals (Wang et al., 2022). The optimization of these parameters is necessary for maximizing the decolorization efficiency while minimizing chemical usage and energy consumption. The inclusion of UV-Vis spectroscopy provides a robust analytical tool to quantify the degradation of the RY145 dye and to understand the breakdown products formed during the treatment. It allows for the monitoring of changes in the dye's molecular structure, offering insights into the degradation pathways and the effectiveness of the microwave-enhanced Fenton process.

This research employed the microwave-enhanced Fenton process for the treatment of RY145. Key operational parameters such as initial pH, dye concentration, and the concentrations of H_2O_2 and Fe^{2+} were studied to determine the optimal conditions for treatment. Furthermore, to investigate the mechanism of dye molecule removal by this process, UV-Vis absorption spectra of the RY145 dye solutions were measured.

Materials and Methods

In this study, the chemical reagents used were sourced from Merck. These included iron (II) sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), a 30% hydrogen peroxide solution (H_2O_2), sodium hydroxide (NaOH), hydrochloric acid (HCl), sodium sulfite (Na_2SO_3), and sulfuric acid (H_2SO_4). Reactive Yellow 145, a dye with the chemical formula $C_{28}H_{20}ClN_9Na_4O_{16}S_5$, was procured from the Alvan Sabet Company in Iran.

Methods

The UV-Vis absorption spectra of RY145 solutions were recorded using an AquaLytic AL800 UV-Vis spectrophotometer, made in Germany, in the wavelength range of 180 to 750 nanometers. The spectral absorption curve of these solutions was also obtained using the same spectrophotometer, revealing a peak absorbance at 419 nanometers. To prepare standard solutions of RY145 at various concentrations, a stock solution with a concentration of 500 mg/L was utilized. The absorbance of these standard solutions at 419 nanometers was measured using the same spectrophotometer to generate a calibration curve. Based on this curve, the concentrations of RY145 solutions post-reaction were calculated. COD was measured using a spectrophotometer device. To plot the calibration curve, stock, digestion, and catalyst solutions were first prepared. All the steps involved in this process are detailed in Method 5220 D (Rice et al., 2012). Additionally, a solution of sodium sulfite (Na_2SO_3) was employed to neutralize the oxidation effects induced by the Microwave-Fenton reaction prior to analysis by the spectrophotometer. This step is crucial to ensure the accuracy of the spectral data, as residual oxidizing agents can potentially interfere with the absorbance measurements. The use of the Na_2SO_3 quenching solution thus allows for a more precise determination of the remaining dye concentration after the treatment process. This approach provides a reliable means of quantifying the efficiency of the Microwave-Fenton method in degrading the RY145 dye.

Conventional Fenton Experiments

Conventional Fenton tests were carried out in an array of 500 mL flasks. Each flask was filled with Fenton reagents and 100 mL of RY145 aqueous solution at a starting

concentration of 50 mg/L. The beginning concentrations for Fe^{2+} and H_2O_2 were established at 20 mg/L and 100 mg/L, respectively. To ensure thorough mixing, the solutions were stirred magnetically at a rate of 300 rpm for different durations. Following this, the dye concentration in the treated solution was immediately measured. The experimental setup was designed to systematically evaluate the efficiency of the Fenton process under controlled conditions. The selection of flask volume and RY145 solution volume was crucial to ensure a sufficient reaction medium for the Fenton reagents to interact effectively with the dye molecules. The chosen concentrations of Fe^{2+} and H_2O_2 were based on preliminary studies indicating their effectiveness in generating hydroxyl radicals necessary for the degradation of the RY145 dye. The stirring speed and duration of contact were adjusted to facilitate optimal mixing and reaction kinetics. The immediate measurement of dye concentration post-treatment was essential to evaluate the immediate impact of the Fenton reaction on the dye degradation, minimizing the interference of any secondary reactions or environmental factors.

Microwave-Enhanced Fenton Process Procedure

In the microwave-enhanced Fenton process, initially, a 500 mL flask was filled with 100 mL of RY145 solution, having a starting concentration of 50 mg/L, along with the necessary Fenton reagents. The beginning amounts of Fe^{2+} and H_2O_2 were established at 20 mg/L and 100 mg/L, respectively. Following this, adjustments were made to the initial pH levels, as well as to the concentrations of Fe^{2+} and H_2O_2, and the dye, in order to identify the most favorable conditions. The flask was then heated in a Geepas GMO-1871 household microwave oven with a power of 800 watts and a frequency of 2.5 GHz, for durations ranging from 1 to 7 minutes. The selection of microwave power and frequency was based on their suitability for inducing effective heating without damaging the integrity of the solution. The microwave irradiation was pulsed, with 20-second intervals of irradiation followed by 20-second pauses. The pulsed irradiation strategy was employed to maintain a consistent temperature and prevent overheating and boiling of the solution, thus ensuring uniform treatment of the dye. The flask was sealed with a plastic lid to prevent the escape of water vapor. Sealing the flask was a crucial step to minimize the loss of reactants due to evaporation. Following this, the dye concentration in the solution treated by the microwave-enhanced Fenton process was immediately measured. Each experiment was performed three times, and the mean of these values was presented as the conclusive results.

Results and Discussion

Dye Removal Using the Fenton Process

The objective of this study was to investigate the decolorization of RY145 using both the conventional Fenton and microwave-Fenton processes. Figure 1 depicts the effectiveness of removing RY145 through these methods, charted against the treatment duration. In the standard Fenton procedure, the breakdown of RY145 occurs in two distinct phases: an initial phase of rapid removal, succeeded by a phase where equilibrium is reached. As indicated in Figure 1, during the rapid removal phase, RY145 treatment efficiency increased from approximately 18% in 1 minute to about 80% in 20 minutes. Subsequently, the removal efficiency of RY145 slightly increased, reaching around 87% in 60 minutes. Previous research indicates that the central mechanism in the Fenton treatment method involves the catalytic breakdown of H_2O_2, leading to the formation of highly reactive hydroxyl radicals. These radicals serve as the key agents in catalytically decomposing organic contaminants in water-based solutions. The general reaction suggested for creating these hydroxyl radicals is outlined as follows (Li et al., 2019):

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

Furthermore, the trivalent iron hydroxides formed during the Fenton process act as coagulating agents, playing a role in adsorbing and removing certain organic

pollutants (Shokri and Fard, 2022). As a result, the generation of hydroxyl radicals (OH·) initiates the swift initial breakdown of RY145 molecules. This is followed by a steady increase in RY145 removal during the equilibrium phase, a process that could be due to the adsorption of the pollutant onto trivalent iron hydroxides. Additionally, the formation of intermediate products, which are more resistant to degradation, can play a significant role in this process. These intermediate compounds, being more challenging to decompose compared to the original substance, may gradually exert their effects on the overall treatment process over time, potentially impeding the removal of RY145 in this phase (Muneer et al., 2020).

As per Figure 1, utilizing microwave irradiation to boost the ability of the Fenton process to decolorize RY145 led to an increase in the dye removal rate in correlation with the length of microwave exposure. For instance, the eradication of RY145 rose from roughly 38% in a single minute to more than 95% within a span of 7 minutes. This clearly demonstrates that microwave irradiation markedly improves the efficiency of the Fenton process in removing RY145. The efficiency of RY145 removal in 3 minutes using microwave-enhanced Fenton is approximately equivalent to the efficiency of conventional Fenton in 60 minutes. The quickened and improved transformation of RY145 through microwave exposure can be attributed to the swift and targeted heating of water and H_2O_2 molecules (Xu et al., 2016). In this study, to avert the boiling of the solution, the microwave was switched off for 20 seconds following every 20-second period of irradiation. Yet, the peak temperature in the microwave system could surpass 90 °C. Elevated temperatures expedite the production of OH· radicals and enhance the probability of interactions between OH· radicals and RY145 molecules. Furthermore, the trivalent iron hydroxides produced during the Fenton process also absorb microwaves and enhance the removal of RY145 (Shokri and Fard, 2022).

In the Fenton process, Fe^{2+} ions act as homogeneous catalyst in the solution. These ions facilitate the production of OH· and subsequently are oxidized to Fe^{3+}. In the microwave-assisted treatment process, the existing Fe^{3+} ions in the solution are reduced by microwave irradiation back to Fe^{2+}. This reduction process, a result of the thermal effects and the energy provided by the microwaves, aids in the regeneration of Fe^{2+} ions (Hirano et al., 2020).

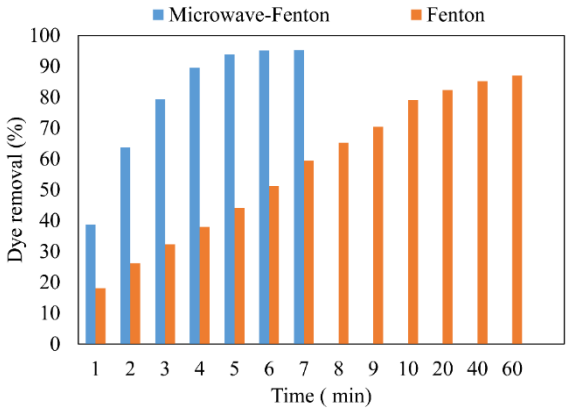

Figure 1. RY145 Removal in Conventional and Microwave-Enhanced Fenton Process (RY145 = 50 mg/L, Fe^{2+} = 20 mg/L and H_2O_2 = 100 mg/L)

The cyclic conversion of Fe ions between their 2+ and 3+ states is a critical component of the Fenton reaction. The addition of microwave energy into this system introduces a novel element that enhances this cycling process. Microwaves induce localized heating, which accelerates the reduction of Fe^{3+} to Fe^{2+}, thereby replenishing the catalyst necessary for the continued generation of hydroxyl radicals.

This enhancement is particularly significant as it addresses one of the limitations of the conventional Fenton process – the depletion of the Fe^{2+} catalyst. By continuously regenerating Fe^{2+} ions, the microwave-enhanced Fenton process maintains a higher and more consistent rate of hydroxyl radical production, leading to more efficient and rapid degradation of pollutants like RY145. This innovative approach marks a significant advancement in wastewater treatment technologies, providing a more efficient and time-effective solution for the removal of persistent organic pollutants.

The Effect of Initial RY145 Concentration

The impact of the initial dye concentration on the removal of RY145 is demonstrated in Figure 2. According to this figure, the removal of RY145 increases with a rise in the initial dye concentration. Specifically, the capability of dye reduction increases from around 88% at an initial concentration of 50 mg/L to approximately 96% at 200 mg/L. With higher initial dye concentrations, the availability of RY145 molecules increases. Hydroxyl radicals have a very short lifespan, lasting just a handful of nanoseconds, signifying that their reactivity is primarily during their initial formation (Liochev, 2013). Therefore, the dye molecules must encounter these hydroxyl radicals within this brief time window. As the initial dye concentration increases, more RY145 molecules are available to react with the Fenton reagent, thereby enhancing the removal efficiency. However, beyond a certain concentration, due to a lack of sufficient hydroxyl radicals to react with the additional dye molecules, no significant improvement in removal efficiency is observed (Zoqi and Doosti, 2020). As indicated in Figure 2, a rise in the initial RY145 concentration from 200 mg/L to 500 mg/L did not result in a noticeable change in dye removal efficiency. These findings highlight the importance of optimizing dye concentration in the Fenton treatment process to achieve maximum efficiency in dye removal.

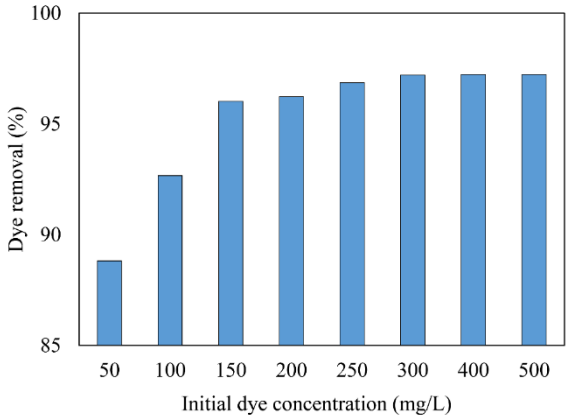

Figure 2. Effect of RY145 in Microwave-Enhanced Fenton Process (Irradiation Time = 5 Min, Fe^{2+} = 20 mg/L and H_2O_2 = 100 mg/L)

The Effect of Initial H_2O_2 Concentration

Figure 3 demonstrates the impact of H_2O_2 dosage on the removal of RY145 by the microwave-enhanced Fenton process. Given that H_2O_2 plays an essential role in the composition of the Fenton reagent, generating reactive hydroxyl radicals, its initial concentration has a major impact on the elimination of RY145. The removal of RY145 rapidly increases from less than 1% at an H_2O_2 concentration of 10 mg/L to about 92% at 80 mg/L. An increase in H_2O_2 concentration to 100 mg/L did not further enhance RY145 removal due to the limitation in the available concentration of Fe^{2+}. Alternatively, excessively increasing the concentration of H_2O_2 can lead to the scavenging of hydroxyl radicals (·OH), resulting in a decreased rate of decolorization, as explained by the

following reactions (Gül and Özcan-Yıldırım, 2009).

The consumption of hydroxyl radicals reduces their availability in the reaction system. Consequently, as Figure 3 indicates, with the increase of the initial H_2O_2 concentration to 150 mg/L, the rate of decolorization decreased. Additionally, as described by the following reaction, excess H_2O_2 can oxidize Fe^{2+} to Fe^{3+}, thereby diminishing the efficiency of ·OH radical production and the overall decolorization efficiency (Gül and Özcan-Yıldırım, 2009). An increase in H_2O_2 concentration to 350 mg/L resulted in a reduction of the removal efficiency to about 80%.

$$Fe^{2+} + H_2O_2 + H^+ \rightarrow Fe^{3+} + \cdot OH + H_2O \quad (5)$$

It should be noted that at very low H_2O_2 concentrations (10 mg/L), the efficiency of RY145 degradation dropped to less than 1%. This result can be linked to the low levels of H_2O_2 and the brief duration of the reaction, which lasted merely 5 minutes. During microwave irradiation, a portion of H_2O_2 is heated and decomposes into water and oxygen. At extremely low concentrations, the decomposition of H_2O_2 under microwave irradiation primarily leads to the formation of water and oxygen, rather than the generation of the necessary hydroxyl radicals for the degradation of RY145. The balance between H_2O_2 concentration and reaction time is crucial, as insufficient H_2O_2 levels and short reaction durations fail to produce the required concentration of hydroxyl radicals for effective dye degradation. This insight emphasizes the need for optimizing both the concentration of H_2O_2 and the duration of the microwave-enhanced Fenton process to achieve maximum removal efficiency of contaminants like RY145.

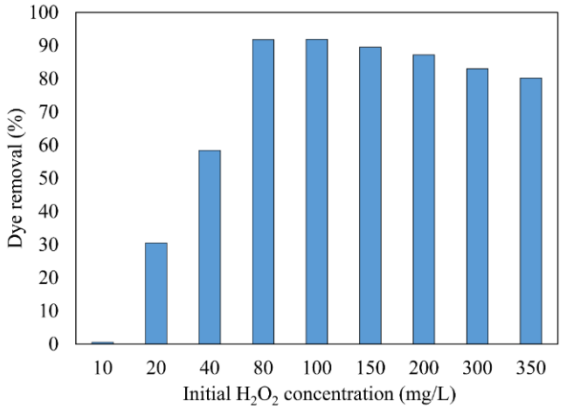

Figure 3. Effect of H_2O_2 in Microwave-Enhanced Fenton Process (Irradiation Time = 5 Min, Fe^{2+} = 20 mg/L and RY145 = 50 mg/L)

The Effect of Initial Fe^{2+} Concentration

Fe^{2+} plays a pivotal role in the Fenton reaction as it facilitates the decomposition of H_2O_2 and the production of hydroxyl radicals. Therefore, as depicted in Figure 4, the removal of RY145 rapidly rose with the rise in the initial concentration of Fe^{2+}. Specifically, raising the initial Fe^{2+} concentration from 5 mg/L to 30 mg/L resulted in an increase in color removal efficiency from approximately 1% to 93%. However, raising the initial Fe^{2+} concentration beyond 30 mg/L had a marginal effect on RY145 removal due to the limitation of the initial concentration of H_2O_2. For instance, raising the initial Fe^{2+} concentration from 30 mg/L to 80 mg/L led to a slight increase in dye removal efficiency to 94%. At high Fe^{2+} concentrations (above 30 mg/L), Fe^{2+} competes with dye molecules for reactions with hydroxyl radicals, which can paradoxically decrease the decolorization efficiency (Tavares et al., 2020). Additionally, the coloration caused by intermediate products from the reaction of

Fe^{2+} with ·OH can lead to color rebound, potentially increasing additional treatment costs (Muneer et al., 2020). Therefore, the concentration of Fe^{2+} must be carefully controlled to achieve optimal decolorization over the course of the reaction. Consequently, an initial Fe^{2+} concentration of 30 mg/L was determined to be the optimal dose for the microwave-enhanced Fenton process.

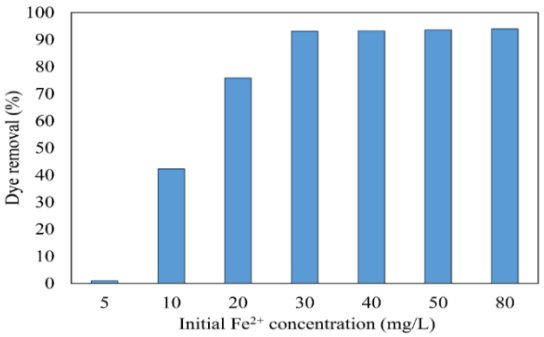

Figure 4. Effect of Fe^{2+} in Microwave-Enhanced Fenton Process (Irradiation Time = 5 Min, H_2O_2 = 100 mg/L and RY145 = 50 mg/L)

The Effect of Initial pH

In the Fenton oxidation process, the starting pH is significant as it affects the overall efficiency of Fenton reagents and the production of hydroxyl radicals. When the pH of the solution is high, meaning there are more hydroxide ions (OH-) present, this can reverse the Fenton reaction (Eq. 1) and reduce the activity of the Fenton reagents. In other words, in alkaline environments (high pH), Fenton reagents are less effective and less capable of generating hydroxyl radicals. Additionally, at high pH, ferric and ferrous hydroxide complexes form, which have significantly lower catalytic abilities compared to Fe^{2+} (Kasiri et al., 2008). On the other hand, when the pH is below 2.5, the production of hydroxyl radicals is limited. This limitation is due to specific reactions that occur at low pH (Fischbacher et al., 2017):

$$HO^{\cdot} + H^{+} + e^{-} \rightarrow H_2O \quad (6)$$

$$H_2O_2 + H^{+} \rightarrow H_3O_2^{+} \quad (7)$$

Considering Equations 6 and 7, fewer hydroxyl radicals are produced at low pH levels due to a tendency towards water molecule formation, which in turn reduces the efficiency of the Fenton process. Additionally, the scavenging of ·OH radicals by H^+ in low pH environments and the generation of oxonium ions ($H_3O_2^+$) owing to the strong proton-donating capability of H_2O_2 further decrease the decolorization efficiency. The formation of complex species like $[Fe(H_2O)_6]^{2+}$ and $[Fe(H_2O)_6]^{3+}$ also contributes to reduced dye removal efficiency at pH levels below 2.5. Therefore, precise adjustment of the pH of the solution is essential for achieving optimal results in the Fenton process.

This study has examined the effect of initial pH on the removal of RY145 in microwave-enhanced Fenton processes. The results have demonstrated that initial pH variations significantly impact the efficiency of RY145 removal. The initial pH of the RY145 solutions used in this study was approximately 5.5. As shown in Figure 5, the removal efficiency of RY145 slightly decreases with the increase of initial pH from 2.5 to 5.5. However, when the initial pH exceeds 5.5, the removal of RY145 significantly diminishes. Specifically, increasing the pH from 6.5 to 10 results in a decline in color removal efficiency from 76% to less than 1%. Conversely, when the initial pH is reduced from 2.5 to 1.5, the removal of RY145 also decreases from 95% to 61%. These changes in RY145 removal concerning the initial pH are consistent with the findings of previous studies (Bokhari et al., 2013). Based on Figure 5, it is observed that the most effective pH level for the microwave-assisted Fenton process is 2.5. This outcome is in line with results obtained for photo-Fenton and microwave-enhanced Fenton processes in past research (Verma and Samanta, 2018; Tanveer et al., 2022).

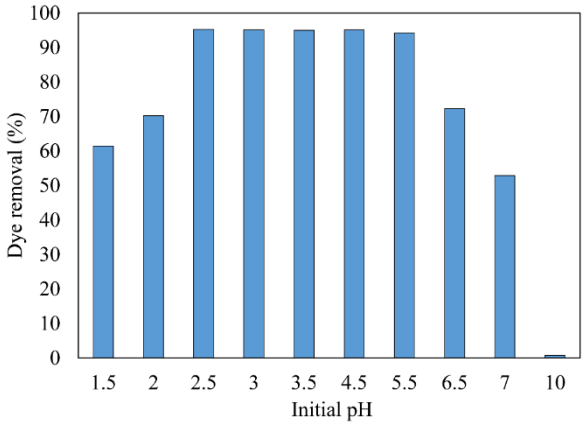

Figure 5. Effect of pH in Microwave-Enhanced Fenton Process
(Irradiation Time = 5 Min, H_2O_2 = 100 mg/L, Fe^{2+} = 20 mg/L and RY145 = 50 mg/L)

Oxidation of Reactive Yellow 145

Based on the obtained results, the optimal operational conditions for the decolorization of RY145 were identified as an initial pH of 2.5, a beginning concentration for the dye set at 200 mg/L, an initial Fe^{2+} concentration of 30 mg/L, and an initial H_2O_2 concentration of 80 mg/L. Confirmatory experiments were conducted under these optimal conditions to investigate the relationship between the degradation of RY145 and its decolorization by the microwave-enhanced Fenton process. The results indicated that the removal rate of COD reached 82%, and the decolorization rate achieved 95% within 7 minutes (Figure 6). This demonstrates that the microwave-enhanced Fenton process in optimal conditions is more effective in color removal compared to COD reduction. These findings highlight the efficiency of the microwave-enhanced Fenton process in degrading and decolorizing RY145 under optimal conditions. The higher effectiveness in color removal compared to COD reduction underscores the suitability of this process for treating color-intensive industrial effluents, particularly from textile industries. The rapid and high decolorization rate within a short time frame emphasizes the potential of this method as an efficient and effective solution for wastewater treatment in the textile industry.

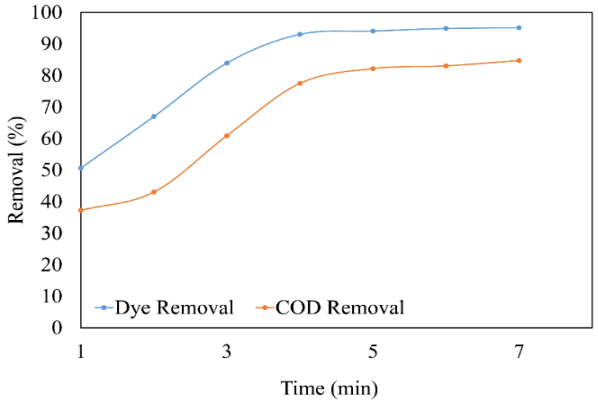

Figure 6. Efficiency of Color and COD Removal in the Microwave-Fenton Process

Mechanism of Elimination

The UV-Vis spectra of RY145, both prior to and following treatment with microwave-enhanced Fenton processes were measured and compared across the wavelength range of 180 to 750 nanometers at different

retention times. Figure 7 shows that, before treatment, the UV-Vis spectra of the RY145 dye display two primary absorption peaks: one in the ultraviolet range (at a wavelength of 280 nm) and two in the visible spectrum (at 419 nm). This UV band is distinguished by the presence of two closely situated rings. These rings, typically containing aromatic structures, are capable of absorbing light in the ultraviolet range. Absorption in this region often indicates the presence of ring structures with π-bond electrons, which can easily absorb light energy. The visible band, observed at 419 nm, is associated with an extended conjugated π system. This combined system, consisting of multiple aromatic rings and consecutive double bonds, leads to light absorption in the visible spectrum. The two azo groups attached to this π system play a significant role in the color properties of this molecule. Azo groups act as chromophores that define the color of the molecule and allow it to absorb light in the visible range (Stoilova et al., 2019). Generally, distinct peaks in the range of 400 to 750 nanometers refer to azo and hydrazine groups in the dye structure and indicate n → π* transitions. In contrast, distinct peaks in the range of 180 to 400 nanometers are related to n → π* transitions in benzene and naphthalene rings (Wang et al., 2015).

Therefore, the absorption peaks in the 400 to 750 nm range were used to detect the decolorization reaction of the dye. Peaks in the 200 to 400 nm range were utilized to detect the breakdown of aromatic structures. The decolorization of RY145 in the treatment system was simultaneously examined at 280 and 419 nanometers.

Following treatment using both conventional and microwave-assisted Fenton methods, the observed absorption peaks at wavelengths of 419 nm and 280 nm, associated with the catalytic degradation of RY145 molecules, significantly diminished, and the color of the RY145-containing solution gradually faded. The reduction in UV band absorption indicates the degradation of aromatic sections in the dye molecule and its intermediates (Kiwaan et al., 2020). As time progresses, a notable reduction in spectral absorption at the visible band (wavelength of 419 nm) occurs, which is considerably more pronounced than the reduction observed in the UV band (wavelength of 280 nm).

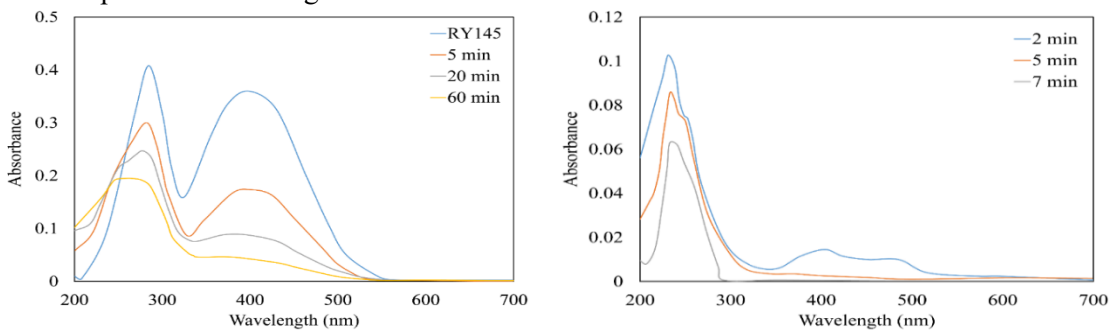

Figure 7. UV-Vis Spectra of RY145 Pre and Post Treatment Using (a) the Conventional Fenton Process, and (b) the Microwave-Assisted Fenton Process at Different Time Increments

This indicates that azo and hydrazine groups in the molecular structure of the dye, particularly in the Fenton process, decompose faster and with higher priority. In other words, these active groups in dye molecules are more vulnerable and reactive under the chemical degradation conditions of the Fenton process compared to other molecular parts. Initially, hydroxyl radicals target the azo groups, cleaving the N=N bonds, which are more susceptible to decomposition than aromatic structures. These experimental results are consistent with previous studies on the decolorization of azo dyes (Kiwaan et al., 2020; Mohammad et al., 2016). However, as indicated in Figure 6, the COD removal rate after 7 min of treatment with the microwave-enhanced Fenton process was about 87%. Figure 7 indicates that, even

after 7 minutes, a minor peak in the UV range remains, implying that the dye molecules are not fully broken down into CO_2 and H_2O. Instead, they seem to have converted into smaller molecular intermediates.

Conclusion

In conclusion, this study comprehensively assesses the microwave-enhanced Fenton process for decolorizing RY145 dye in wastewater, showcasing its superiority over the conventional Fenton process. The optimal conditions were determined to be a dye concentration of 200 mg/L, a pH of 2.5, a Fe^{2+} concentration of 30 mg/L, and an H_2O_2 concentration of 80 mg/L, under which over 95% dye removal and 82% COD reduction were achieved within just 7 minutes. H_2O_2 concentration was crucial, showing rapid RY145 removal up to 80 mg/L, but no significant improvement beyond this due to Fe^{2+} limitations. Fe^{2+} concentration also played a pivotal role, with the removal efficiency increasing significantly up to 30 mg/L, after which additional increases yielded marginal benefits. UV-Vis spectroscopy analysis pre and post-treatment indicated that the microwave-enhanced Fenton process effectively decomposed dye molecules, particularly the azo and hydrazine groups, faster than aromatic structures. Despite high decolorization efficiency, a residual UV peak suggested the transformation of dye molecules into smaller intermediates, rather than complete breakdown. This study thus highlights the microwave-enhanced Fenton process as a highly efficient, rapid method for treating dye-laden industrial wastewater, especially suitable for sectors with high dye loads like the textile industry. The findings enhance the understanding of the microwave-enhanced Fenton process, emphasizing its potential as an effective wastewater treatment technology.

References

Ahmed, B., Limem, E., Abdel-Wahab, A., and Nasr, B. 2011. Photo-Fenton treatment of actual agro-industrial wastewaters. Journal of Industrial and Engineering Chemistry. 50**,** 6673-6680.

Alardhi, S.M., Ali, N.S., Saady, N.M.C., Zendehboudi, S., Salih, I.K., Alrubaye, J.M., and Albayati, T.M. 2023. Separation techniques in different configurations of hybrid systems via synergetic adsorption and membrane processes for water treatment: a review. Journal of Industrial and Engineering Chemistry.

Barham, J.P., Koyama, E., Norikane, Y., Ohneda, N., and Yoshimura, T. 2019. Microwave Flow: A Perspective on Reactor and Microwave Configurations and the Emergence of Tunable Single-Mode Heating Toward Large-Scale Applications. The Chemical Record. 19**,** 188-203.

Bokhari, T.H., Kashif, M., Bhatti, I.A., Zubair, M., Adeel, S., Yousaf, M., Ahmad, M., Iqbal, M., Usman, M., and Zuber, M. 2013. Degradation Study of CI Reactive Yellow 145 by Advanced Oxidation Process. Asian Journal of Chemistry. 25.

Fischbacher, A., von Sonntag, C., and Schmidt, T.C. 2017. Hydroxyl radical yields in the Fenton process under various pH, ligand concentrations and hydrogen peroxide/Fe (II) ratios. Chem. 182**,** 738-744.

Garcia-Costa, A.L., Zazo, J.A., and Casas, J.A., 2019. Microwave-assisted catalytic wet peroxide oxidation: Energy optimization. Separation and Purification Technology. 215**,** 62-69.

Ghasemi, A.H., Zoqi, M.J., and Zanganeh Ranjbar, P. 2024. Enhanced photocatalytic degradation of methylene blue using a novel counter-rotating disc reactor. Frontiers in Chemistry. 12**,** 1335180.

Gül, Ş., and Özcan-Yıldırım, Ö. 2009. Degradation of Reactive Red 194 and Reactive Yellow 145 azo dyes by O3 and H2O2/UV-C processes. Separation and Purification Technology.155**,** 684-690.

Hirano, Y., Beltramini, J.N., Mori, A., Nakamura, M., Karim, M.R., Kim, Y., Nakamura, M., and Hayami, S. 2020. Microwave-assisted catalytic conversion of glucose to 5-hydroxymethylfurfural using "three dimensional" graphene oxide hybrid catalysts. RSC Advances. 10**,** 11727-11736.

Kasiri, M., Aleboyeh, H., and Aleboyeh, A. 2008. Degradation of Acid Blue 74 using Fe-ZSM5 zeolite as a heterogeneous photo-Fenton catalyst. Applied Catalysis B. 84**,** 9-15.

Khan, N.A., Khan, A.H., Tiwari, P., Zubair, M., and Naushad, M. 2021. New insights into the integrated application of Fenton-based oxidation processes for the treatment of pharmaceutical wastewater. Journal of Water Process Engineering. 44**,** 102440.

Kiwaan, H., Atwee, T., Azab, E., and El-Bindary, A. 2020. Photocatalytic degradation of organic dyes in the presence of nanostructured titanium dioxide. Journal of Molecular Structure. 1200**,** 127115.

Ledakowicz, S., and Paździor, K. 2021. Recent achievements in dyes removal focused on advanced oxidation processes integrated with biological methods. Molecular. 26**,** 870.

Li, Z., Wang, L., Li, Z., Tian, R., and Lu, C. 2019. Efficient bacteria inactivation by ligand-induced continuous generation of hydroxyl radicals in Fenton-like reaction. Journal of Hazardous Materials. 369**,** 408-415.

Liochev, S.I. 2013. Reactive oxygen species and the free radical theory of aging. Free Radical Biology and Medicine. 60**,** 1-4.

Mancuso, A., and Iervolino, G. 2022. Synthesis and Application of Innovative and Environmentally Friendly Photocatalysts: Catalysis Reviews. 12**,** 1074.

Menon, P., Singh, T.A., Pani, N., and Nidheesh, P. 2021. Electro-Fenton assisted sonication for removal of ammoniacal nitrogen and organic matter from dye intermediate industrial wastewater. Chem. 269**,** 128739.

Mohammad, E.J., Lafta, A.J., and Kahdim, S.H. 2016. Photocatalytic removal of reactive yellow 145 dye from simulated textile wastewaters over supported (Co, Ni) O/AlO co-catalyst. Polish Journal of Chemical Technology. 18**,** 1-9.

Muneer, M., Kanjal, M.I., Saeed, M., Javed, T., Haq, A.U., Den, N.Z.U., Jamal, M.A., Ali, S., and Iqbal, M. 2020. High energy radiation induced degradation of reactive yellow 145 dye: A mechanistic study. Radiation Physics and Chemistry. 177**,** 109115.

Qi, Y., Mei, Y., Li, J., Yao, T., Yang, Y., Jia, W., Tong, X., Wu, J., and Xin, B. 2019. Highly efficient microwave-assisted Fenton degradation of metacycline using pine-needle-like CuCo2O4 nanocatalyst. Chemical Engineering Journal. 373**,** 1158-1167.

Rice, E.W., Bridgewater, L., and Association, A.P.H. 2012. Standard methods for the examination of water and wastewater, American public health association Washington, DC.

Shokri, A., and Fard, M.S. 2022. A critical review in Fenton-like approach for the removal of pollutants in the aqueous environment. Environmental Challenges. 7**,** 100534.

Singh, A.L., Chaudhary, S., Kumar, S., Kumar, A., Singh, A., and Yadav, A. 2022. Biodegradation of Reactive Yellow-145 azo dye using bacterial consortium: A deterministic analysis based on degradable Metabolite, phytotoxicity and genotoxicity study. Chem. 300**,** 134504.

Stoilova, A., Georgiev, A., Nedelchev, L., Nazarova, D., and Dimov, D. 2019. Structure-property relationship and photoinduced birefringence of the azo and azo-azomethine dyes thin films in PMMA matrix. Optical Materials. 87**,** 16-23.

Tanveer, R., Yasar, A., Ikhlaq, A., Nissar, H., and Nizami, A.S. 2022. Comparison of ozonation, Fenton, and photo-Fenton processes for the treatment of textile dye-bath effluents integrated with electrocoagulation. Journal of Water Process Engineering. 46**,** 102547.

Tavares, M.G., Santos, D.H., Tavares, M.G., Duarte, J.L., Meili, L., Pimentel, W.R., Tonholo, J., and Zanta, C.L. 2020. Removal of reactive dyes from aqueous solution by Fenton reaction: kinetic study and phytotoxicity tests. Water Air Soil Pollution. 231**,** 1-15.

Velusamy, S., Roy, A., Sundaram, S., and Kumar Mallick, T. 2021. A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment. The Chemical Record. 21**,** 1570-1610.

Verma, A.K., Dash, R.R., and Bhunia, P. 2012. A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. Journal of Environmental Management. 93**,** 154-168.

Verma, P., and Samanta, S.K. 2018. Microwave-enhanced advanced oxidation processes for the degradation of dyes in water. Environmental Chemistry Letters. 16**,** 969-1007.

Vieira, Y., Silvestri, S., Leichtweis, J., Jahn, S.L., de Moraes Flores, E.M., Dotto, G.L., and Foletto, E.L. 2020. New insights into the mechanism of heterogeneous activation of nano–magnetite by microwave irradiation for use as Fenton catalyst. Journal of Environmental Chemical Engineering. 8**,** 103787.

Wang, Y., Priambodo, R., Zhang, H., and Huang, Y.H. 2015. Degradation of the azo dye Orange G in a fluidized bed reactor using iron oxide as a heterogeneous photo-Fenton catalyst. RSC Advanced. 5**,** 45276-45283.

Wang, Y., Wang, R., Lin, N., Xu, J., Liu, X., Liu, N., and Zhang, X. 2022. Degradation of norfloxacin by MOF-derived lamellar carbon nanocomposites based on microwave-driven Fenton reaction: Improved Fe (III) /Fe (II) cycle. Chem. 293**,** 133614.

Xu, D., Zhang, Y., Cheng, F., and Dai, P. 2016. Efficient removal of dye from an aqueous phase using activated carbon supported ferrihydrite as heterogeneous Fenton-like catalyst under assistance of microwave irradiation. Journal of the Taiwan Institute of Chemical Engineers. 60**,** 376-382.

Zoqi, M.J. 2021. Application of response surface methodology to optimize the ultraviolet/hydrogen peroxide process for the removal of Reactive Red 195 dye from aqueous solution. Iranian Journal of Health Sciences.14**,** 427-446.

Zoqi, M.J., and Doosti, M.R. 2020. Study of heavy metal accumulation in plants irrigated with well water and wastewater from birjand wastewater plant. Journal of Environmental Health Science and Engineering.7**,** 135-151.