

## Removal of Acid Red 151 dye by Advanced oxidation processes

<sup>1</sup>Elsayed A. Khalawy, <sup>1</sup>A. M. Radwan, <sup>2</sup>Sahar M. Ibraheem and <sup>2</sup>Gamal O. El-Sayed\*

<sup>1</sup>Qalyubia drinking water and wastewater company

<sup>2</sup>Faculty of Science, Benha university, Benha, Egypt

E-mail: gamaloelsayed@yahoo.com

### Abstract

The presence of synthetic dyes in wastewater is a great problem as they are relatively stable and most of them are carcinogenic. An intense and successful treatment plan is required to remove dyes from water. By converting organic pollutants into carbon dioxide and water, advanced oxidation processes (AOPs) have demonstrated exceptional efficacy. An intense and successful treatment plan is required to remove dyes from water. By converting organic pollutants into carbon dioxide and water, advanced oxidation processes (AOPs) have demonstrated exceptional efficacy. Acid Red 151 (AR151) is an azo dye used for dyeing wool, silk, polyamide, and wool fabrics. Additionally, polyamide plastic shading is made with it. Some reagents including H<sub>2</sub>O<sub>2</sub>, O<sub>3</sub> and Fenton were used to remove AR151 from aqueous medium in absence and presence of UV radiation. Different parameters controlling color disappearance were studied and optimized. The most effective system is UV/O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub> which cause a complete removal of the dye in few minutes.

**Keywords:** acid red 151, ozone, hydrogen peroxide, UV radiation, AOPs.

### 1. Introduction

The textile, pharmaceutical, leather, ink, paper, food, drink, and cosmetic industries utilize a wide variety of dyes to color items [1,2]. These dyes can be categorized as sulphur, reactive, metal complex, acid, basic, direct, vat, and azoic colors. Over 100,000 dyes are marketed commercially, and the number is growing each [3]. The most prevalent of these dyes, accounting for over 70% of global dye output, are azo dyes [4]. The presence of a nitrogen double bond (-N=N-), which together with another element known as a chromophore, is what distinguishes azo dyes from other types. [5]. Numerous companies release copious amounts of colored industrial waste with high concentrations of an azo dyes into bodies of water including lakes and rivers. Numerous aesthetic issues result from this, and natural waters are penetrated by light retardation. Since azo dyes and their breakdown byproducts are cancerous, poisonous, and hazardous, they may cause a variety of health issues in living things [6]. The reason azo dyes are resistant to biodegradation and are difficult for biological treatments in wastewater treatment plants to remove is because of their high stability in the aquatic environment [7]. Traditional treatment methods are used for removal of azo dyes from water, which including adsorption [8-11], electrocoagulation [12,13], and electrooxidation [14,15].

Conventional treatment techniques for dye removal are either not effective and/or expensive [16]. Therefore, research is required to create

stronger and more efficient techniques for eliminating these contaminants and their byproducts from wastewaters for the purpose to stop the potentially harmful effects on the planet. Advanced oxidation processes (AOPs) are one of these techniques that have been the subject of extensive research in recent decades. In order to effectively eliminate water contaminated by organic contaminants, AOPs is dependent on the creation of potent oxidizing agents which include hydroxyl radicals ( $\bullet\text{OH}$ ) and persulfate radicals ( $\text{S}_2\text{O}_8^{2-}$ ) in substantial quantities. Due to their larger reduction potential (2.8 V) than other oxidizing agents, hydroxyl radicals are the most prevalent and widely recognized oxidizing agents.

Numerous varieties of aliphatic and aromatic amines, medications, dyes, and different insecticides have all been found to degrade via advanced oxidation mechanisms [17–21]. With the exception of Fenton-based processes, advanced oxidation techniques that are capable of fully mineralizing organic pollutants are frequently referred to as "zero sludge" procedures. The attack of oxidizing radicals produced during AOPs on organic molecules may differ based on the specifics of the process, including the catalyst utilized, the chemical structure, the qualities of the pollutant, and the applied technique. In situ OH radical production has led to the development of numerous types of AOPs.  $\bullet\text{OH}$  radicals have been produced using chemical, sonochemical, photochemical, and electrochemical techniques. The main advantage of AOPs techniques

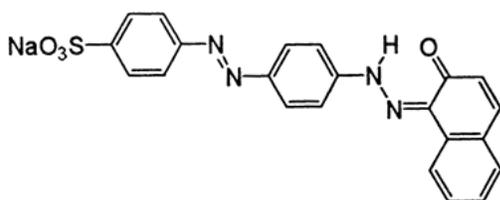
is the possibility of total breakdown and mineralization of the desired organic contaminants.

Very few works have been concerned to the removal of AR151 including aerobic degradation [22], ozonation [23], and ozonation followed by treatment by activated sludge [24]. So, this research sought to examine the degradation efficiency of several AOPs for the aqueous solution degradation of AR151 dye.

## 2. Materials and Methods

### 2.1. Materials

The textile dye AR151 (commercial grade) was selected as a probe pollutant for this study. The chemical structure of the dye is shown in Scheme 1. All chemicals employed in this work ( $\text{Fe}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$  and  $\text{H}_2\text{O}_2$ ) were of AR grade and were applied as received. All experiments were carried out using second distilled water.



**Scheme 1.** Chemical structure of acid red 151 dye.

### 2.2. Apparatus

A batch mode glass beaker reactor with 50 mL of dye solution was employed to examine the dye's degradation behaviour. Ozone generator model Aqua-6 (A2Z Ozone Inc., USA) was used as the source of ozone gas with a capacity 600 mg/h  $\text{O}_3$ . The gas was bubbled in the working solution through a stone diffuser. A UV-Lamp (PHILIPS) was the source of UV radiation, which was fixed over the glass reactor at a distance of 30 cm.

The remaining dye concentration was followed by measuring its absorbance and compared with the initial absorbance using a JASCO V-350 UV/Vis a spectrum analyzer. A magnetic stirrer (100 - 700 rpm) was used for experiments not using ozone. With using a pH device (HANNA instruments HI 8014, USA), the pH of the dye solutions was determined.

### 2.3. Degradation Processes

Eight different systems were applied for dye degradation experiments:  $\text{H}_2\text{O}_2$ , UV/ $\text{H}_2\text{O}_2$ ,  $\text{O}_3$ , UV/ $\text{O}_3$ ,  $\text{O}_3/\text{H}_2\text{O}_2$ , UV/ $\text{O}_3/\text{H}_2\text{O}_2$ ,  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ , and UV/ $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ . The efficiency of removal of the dye was determined by using the formula below:

$$\text{Removal}\% = \frac{A_0 - A_t}{A_0} \times 100 \quad (1)$$

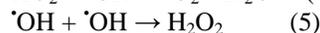
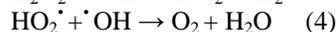
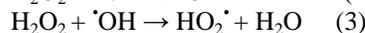
Where,  $A_0$  and  $A_t$  are absorbances at the beginning and the end of treatment time  $t$  (min).

## 3. Results and discussion

In order to extract CR from water through an oxidation process via interactions with hydroxyl radicals ( $\bullet\text{OH}$ ), four distinct systems of AOPs processes were created.

### 3.1. $\text{H}_2\text{O}_2$ and UV/ $\text{H}_2\text{O}_2$ system

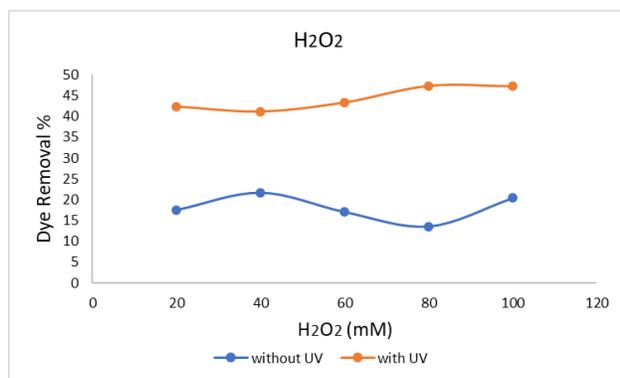
When various amounts (20 - 100 mM) of  $\text{H}_2\text{O}_2$  were added to the dye solution (10 mg/L), the dye removal percent reached a maximum (21.7 %) at 40 mM  $\text{H}_2\text{O}_2$ . Hydrogen peroxide decomposes slowly into water and elemental oxygen when exposed to normal light. In UV/ $\text{H}_2\text{O}_2$ , the generation of  $\bullet\text{OH}$  radicals is directly aided by the photolysis of  $\text{H}_2\text{O}_2$ . The homolytic portion of the oxidant's O-O bonds shapes the radicals, which alter the target organic agent's chemical structure [25]. The initial step that precedes subsequent reactions is the generation of the  $\bullet\text{OH}$  radical via direct photolysis of  $\text{H}_2\text{O}_2$ . Equations [26] that show the reactions describing UV/ $\text{H}_2\text{O}_2$  are as follows:



The mechanistic pathways of reactions (2) and (3) suggest that the creation of  $\bullet\text{OH}$  and  $\text{HO}_2\bullet$  is responsible for the oxidizing ability of UV/ $\text{H}_2\text{O}_2$ .

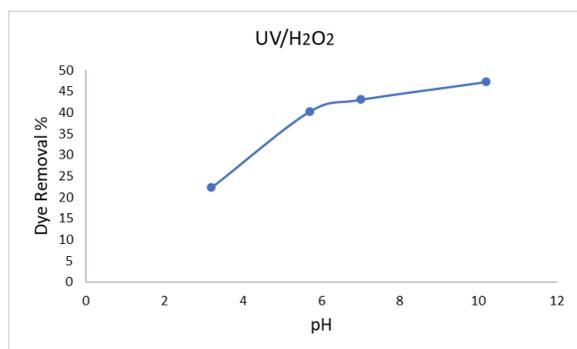
The attack of an organic molecule's preferred carbon, which results in the removal of hydrogen, the addition of electrons to an unsaturated bond electrophilically, or electron transfer (redox reactions) are the predicted events caused by the  $\bullet\text{OH}$  radical [27]. Compared to other procedures that use UV radiation, this one demands a comparatively high concentration of  $\text{H}_2\text{O}_2$  and/or a substantially extended UV exposure time [28]. On the other hand, Hydrogen peroxide photolysis has been found to be pH-dependent, with higher rates occurring in more alkaline environments.

In order to investigate how UV affects the rate of breakdown at various doses of hydrogen peroxide, the same doses of  $\text{H}_2\text{O}_2$  (20 - 100 mM) were added to a solution of AR dye containing 10 mg/L and exposed to UV radiation. The rate of change of remaining dye concentration compared to the initial concentration were followed till equilibrium at 60 min. As shown in Fig. 1, applying UV radiation enhanced the breakdown of dye and the maximum removal occurred at 40 mM of  $\text{H}_2\text{O}_2$  in absence of UV, while maximum removal in the presence of UV was observed at 80 mM, then the removal efficiency decreased.



**Fig. 1.** Effect of H<sub>2</sub>O<sub>2</sub> concentration on AR dye removal in the present and absence of UV radiation. [AR151] = 10 mg/L, pH = 10.2.

Different dye solutions with variable pH values (2.4, 5.7, 7.2, and 10.2) were exposed to UV radiation so as to look the effect of pH on the influence of photodegradation. The removal percents at equilibrium were then calculated (Fig. 2). As shown, the removal increases with increasing pH and maximum removal is observed at pH 10.2. It is well known that temperature, light, and pH all have a significant impact on hydrogen peroxide's stability [29]. Both under the impact of appropriate energy radiation and at higher temperatures, breakdown is encouraged. For optimum stability of pure H<sub>2</sub>O<sub>2</sub>, the pH range below 4.5 is convenient and above pH 5, the decomposition increases sharply [30]. Also, the presence of impurities in the H<sub>2</sub>O<sub>2</sub> solution accelerates its decomposition. In UV/H<sub>2</sub>O<sub>2</sub>, The photolysis of H<sub>2</sub>O<sub>2</sub> marginally promotes the production of •OH radicals [31]. as a complete dye removal was attained at shorter time under radiation (Fig. 4).



**Fig. 2.** Effect of pH on removing dye by H<sub>2</sub>O<sub>2</sub> under UV radiation, [AR151] = 10 mg/L, H<sub>2</sub>O<sub>2</sub> = 80 mM.

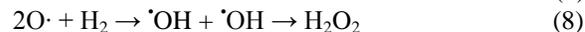
### 3.2. O<sub>3</sub>, UV/O<sub>3</sub> and UV/O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub> system

The gas ozone is highly reactive and poorly soluble in water. It is an unstable gas with a poor utilisation rate because it can break down fast into molecular

oxygen [32]. Strong oxidant (2.07 V), it can break down organic contaminants by molecular ozone's direct electrophilic attack as well as •OH radicals' indirect attack. The efficiency of ozone oxidation is primarily reliant on the structure of organic molecules and is selective [33]. Most organic compounds react with •OH radicals in a largely diffusion-controlled manner [34]. Sometimes the organic component is not completely oxidised by ozone on its own. Numerous dyes have been reported to be successfully removed from textile effluents by ozonization [35]. Many researches have shown that reactive dyes degrade with O<sub>3</sub> to a high degree, whereas basic dyes degrade with an intermediate degree and disperse colours with a low degree of efficiency [36].

Three tests were conducted at three distinct pH values (3.4, 8.8, and 11.7) in order to investigate the influence of O<sub>3</sub>. As Fig. 3 illustrates, there is a modest impact of pH variation on dye degradation. Since 8.8 was found to be the ideal pH, UV light was utilized to cause the dye to deteriorate at the same pH. In case of UV/O<sub>3</sub> system, the rate at which dyes deteriorated increased slightly with UV exposure and complete degradation was observed after about 15 min of treatment (Fig. 4). It has been noted that while rising ozone concentrations slow down the breakdown of some other pollutants, they accelerate the breakdown of certain organic pollutants. This may be attributed to the mode of direct reaction between ozone and the polluting molecule which includes oxidation–reduction, cycloaddition, electrophilic and nucleophilic reactions [37].

When ozone gas and UV are coupled, exposure to UV causes more free •OH radicals, which speeds up the dye's breakdown. [38] according to the following equations:



At all pH levels, azo dye is more likely to degrade when O<sub>3</sub> and UV are combined [39] and as expected, The UV/O<sub>3</sub> process's decolorization efficiency was higher than the O<sub>3</sub> system's. [40].

In the UV/O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub> system, the presence of H<sub>2</sub>O<sub>2</sub> can speed up ozonolysis and produce more hydroxyl radicals (•OH) in the UV/O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub> system, the oxidation process of •OH takes centre stage. Different concentrations of H<sub>2</sub>O<sub>2</sub> (20 - 100 mM) were added to a fixed amount of dye and exposed to UV during O<sub>3</sub> bubbling. As shown in Fig. 5, the change of H<sub>2</sub>O<sub>2</sub> content slightly accelerates dye decomposition rate.

To evaluate the effect of this system on varying concentrations of AR171 dye, ozone gas was introduced to a solution containing 20 mM of H<sub>2</sub>O<sub>2</sub>

and varying amounts of dye (100, 500 and 1000 mg/L). Increasing the dye content decreases the rate and percent of its removal as shown in Fig. 6.

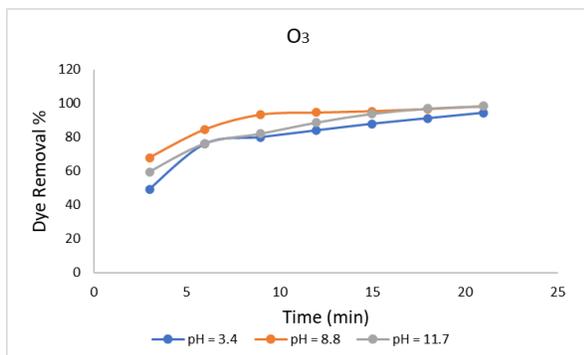


Fig. 3. Effect of pH on dye removal by O<sub>3</sub>.

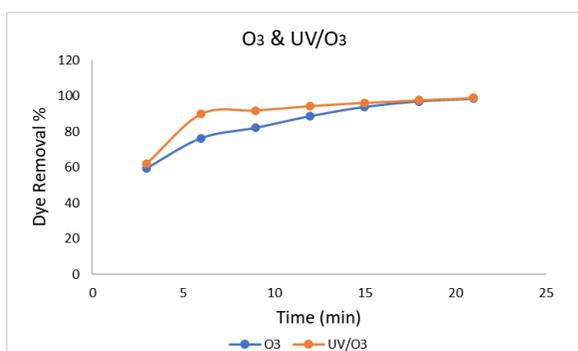


Fig. 4. Effect of treatment time on dye removal by O<sub>3</sub> with and without UV radiation.

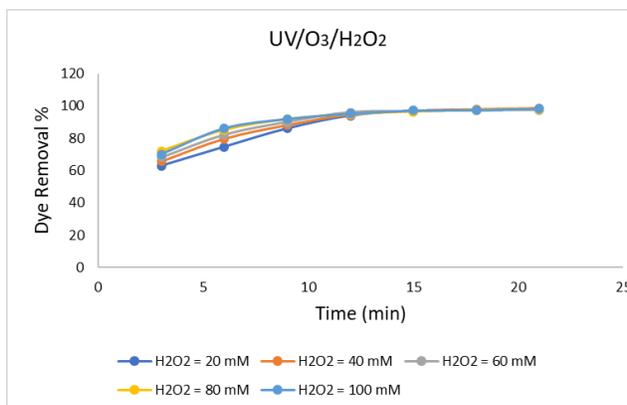


Fig. 5. Effect of H<sub>2</sub>O<sub>2</sub> concentration on dye removal in presence of O<sub>3</sub> under UV radiation. [dye = 100 mg/L, pH = 8.8]

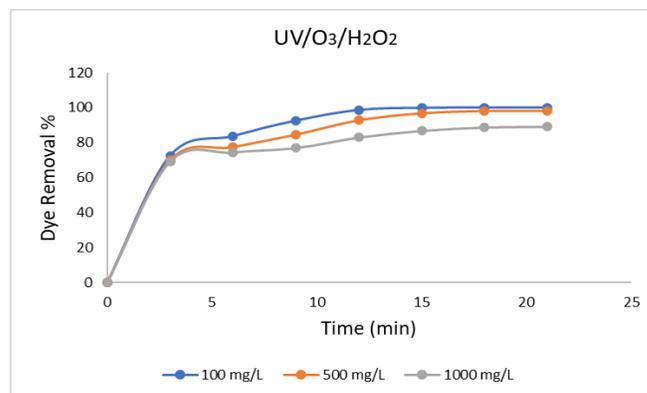
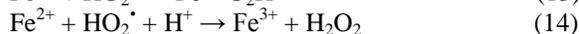
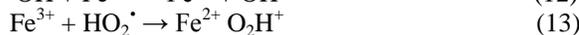
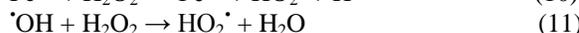
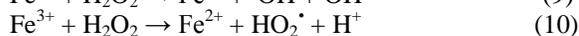
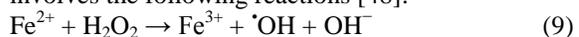


Fig. 6. Effect of dye concentration on dye removal in presence of O<sub>3</sub> under UV radiation. [dye = 100 mg/L, H<sub>2</sub>O<sub>2</sub> = 20 mM, pH = 8.8]

### 3.3. H<sub>2</sub>O<sub>2</sub>/Fe(II) and UV/H<sub>2</sub>O<sub>2</sub>/Fe(II) system

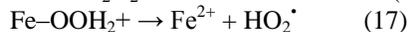
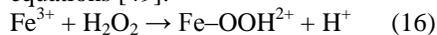
H<sub>2</sub>O<sub>2</sub> is added to the pollutant solution in the Fenton process when Fe<sup>2+</sup> ions are present. The creation of •OH radicals, a potent oxidizing species, is the reaction's goal. One of the most useful advanced oxidation techniques for getting rid of a lot of dangerous organic contaminants from wastewater is the Fenton reaction. It has several benefits, including less sludge generation and great oxidation efficiency. Since •OH activity is strongly influenced by the pH of the solution, the Fenton process is often carried out in an acidic environment. As pH decreases, •OH's oxidation potential rises [41]. Because inactive iron oxohydroxides and Fe<sub>2</sub>O<sub>3</sub> precipitate are formed, there is less Fe<sup>2+</sup> activity as pH rises, which lowers the Fenton reagent's efficiency. Furthermore, at high pH levels, H<sub>2</sub>O<sub>2</sub> seems to auto-decompose [42]. Whereas the concentration of the oxidant directly influences the amount of pollutants destroyed, the dose of iron influences Fenton's reaction rate [43]. The pH level, the H<sub>2</sub>O<sub>2</sub>/Fe<sup>2+</sup> ratio, the amount of iron salt injected, and other variables all affect how quickly the Fenton reaction oxidizes [44]. Additional factors that affect the Fenton process's efficiency include the organic pollutant's structure and concentration, the presence of inorganic species, the treatment's duration, temperature, and whether any byproducts are produced as a result of the •OH's lack of selectivity.

Numerous scholarly works provide a detailed and equation-based description of the intricate Fenton process mechanism [45–46]. In the absence of organic compounds, the classical Fenton mechanism involves the following reactions [48]:

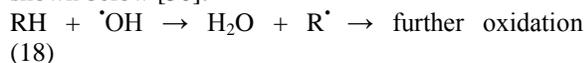




The catalytic roles of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  are significant in the processes mentioned above. The generation of  $\text{Fe}^{2+}$  from  $\text{Fe}^{3+}$  seems to occur through the following equations [49]:



The dye is destroyed by the hydroxyl radicals created when hydrogen peroxide and ferrous ions interact, as shown below [50]:



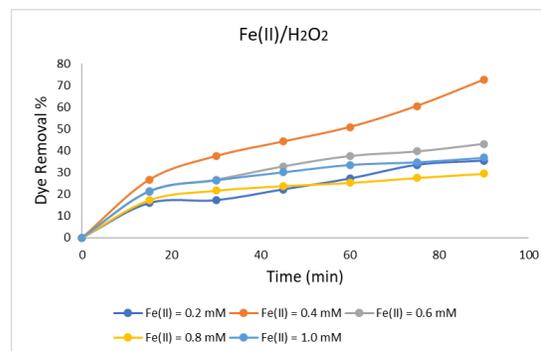
A significant circumstance is the impact of hydrogen peroxide and ferrous sulfate concentrations on dye degradation [51].

The decolorization of polluting dyes was found dependent on Fe(II) content and the  $\text{H}_2\text{O}_2$  content [52]. To optimize the  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratio, varying amounts (0.2-1.0 mM) of Fe(II) were added to a fixed concentration of  $\text{H}_2\text{O}_2$  (8 mM) at a dye solution contains 10 mg/L AR dye. As shown in Fig. 9 maximum removal is observed at  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratio 20:1 without and under UV radiation. It is clear that UV radiation can accelerate the Fenton reaction. The removal percent reached 96.8% under the effect of UV radiation. UV light can be used to completely mineralize a variety of chemical compounds that are present in aqueous solutions. The process that converts  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$  ions and creates new  $\text{OH}^\bullet$  with  $\text{H}_2\text{O}_2$  is thought to be responsible for the efficiency of UV irradiation [53].

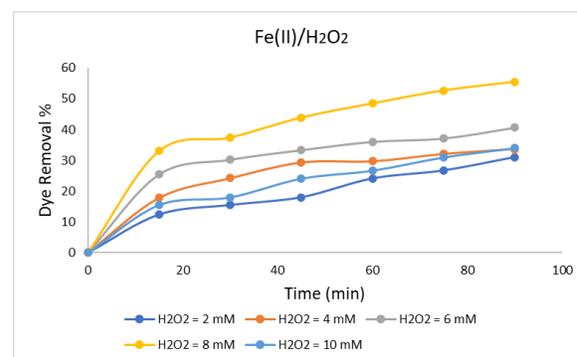
As dyes mostly depend on their own chemical structures, the mechanisms underlying their degradation can differ [54]. During the procedure, a reaction route that doesn't look as beneficial could occur. Gaining insight into the mechanism will assist future dyes enhance their elimination procedure.

attributed to the development of hydroxoferric compounds The  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratio is the primary determinant of the rank of significance of oxidation and coagulation. At lower  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratios, chemical coagulation is more prevalent, while chemical oxidation is more prevalent at higher  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratios [55]. The synthesis of  $\text{OH}^\bullet$  may be increased and the organic pollutant's breakdown efficiency raised by adding  $\text{Fe}^{2+}$  ions at the right concentration. Conversely, self-quenching of  $\text{OH}^\bullet$  is anticipated in the event that the solution contains an excessive amount of  $\text{Fe}^{2+}$  [56] as a result of production of  $\text{Fe}^{3+}$  through reaction (12).

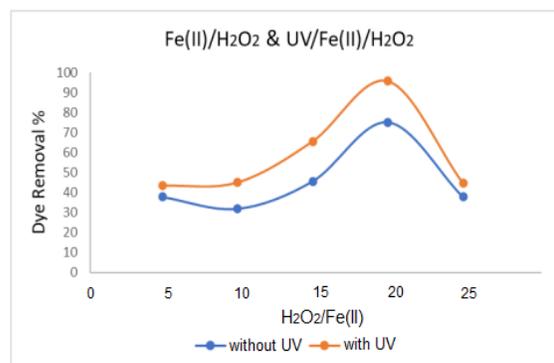
When more hydroxyl radicals are present, adding more  $\text{H}_2\text{O}_2$  can result in the production of hydroperoxyl radicals ( $\text{HO}_2^\bullet$ ), which do not contribute to the oxidative degradation of organic molecules and are significantly less reactive [57].



**Fig. 7.** Effect of Fe(II) concentration on AR dye removal at constant  $\text{H}_2\text{O}_2$  concentration without UV radiation.



**Fig. 8.** Effect of  $\text{H}_2\text{O}_2$  concentration on AR dye removal at constant Fe(II) concentration without UV radiation.



**Fig. 9.** Effect of  $\text{H}_2\text{O}_2/\text{Fe}^{2+}$  ratio on AR dye removal without UV and under UV radiation. (0.4 mM Fe).

## Conclusion

The application of various advanced oxidation techniques on removal Acid Red 151 from water has

been studied. Many systems were applied for this purpose including  $\text{H}_2\text{O}_2$ , UV/ $\text{H}_2\text{O}_2$ ,  $\text{O}_3$ , UV/ $\text{O}_3$ , UV/ $\text{O}_3/\text{H}_2\text{O}_2$ ,  $\text{H}_2\text{O}_2/\text{Fe(II)}$ , UV/ $\text{H}_2\text{O}_2/\text{Fe(II)}$ . Different factors affecting the removal efficiency such as oxidant dose, pH,  $\text{Fe}^{2+}/\text{H}_2\text{O}_2$  ratio, and exposure time to UV radiation were studied and evaluated. Complete decolorization was attained by using  $\text{O}_3/\text{H}_2\text{O}_2$  system under the influence of radiation after about 15 min.

## References

- [1] R. Salazar, E. Brillas, I. Sirés. Finding the best  $\text{Fe}^{2+}/\text{Cu}^{2+}$  combination for the solar photoelectro-Fenton treatment of simulated wastewater containing the industrial textile dye Disperse Blue 3. *Appl. Catal. B*; 115-116, 107–116. 2012
- [2] V. Khandegar, A.K. Saroha. Electrocoagulation for the treatment of textile industry effluent – a review. *J. Environ. Manage*; 128:949-63. 2013
- [3] T. Robinson, G. McMullan, R. Marchant, P. Nigam. Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. *Bioresour. Technol*; 77(3), 247–255. 2001
- [4] J.H. Ramirez, F.M. Duarte, F.G. Martins, C.A. Costa, L.M. Madeira. Modelling of the synthetic dye Orange II degradation using Fenton's reagent: From batch to continuous reactor operation. *Chem. Eng. J.*; 148(2-3), 394–404. 2009
- [5] B. Lodha, S. Chaudhari. Optimization of Fenton-biological treatment scheme for the treatment of aqueous dye solutions. *J. Hazard. Mater*; 148 (1-2), 459–466. 2007
- [6] E. Brillas, C.A. Mart, H. Pii, E. Brillas, A. Mart. Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. *Appl. Catal. B Environ*; 166 : 603–643. 2015
- [7] B. Santos, F.J. Cervantes, J.B. Van Lier. Review paper on current technologies for decolourisation of textile wastewaters: perspectives for anaerobic biotechnology. *Bioresour. Technol*; 98: 2369–2385. 2007
- [8] Gokulan Ravindiran, Hemavathi Sundaram, Ezhilkumar Marimuthu Rajendran, Saravanan Ramasamy, Al-Zaqri Nabil, Boshala Ahmed. Removal of azo dyes from synthetic wastewater using biochar derived from sewage sludge to prevent groundwater contamination. *Urban Climate*;49 (6): 101502. 2023
- [9] T. G. Ambaye, M. Vaccari, E. D. van Hullebusch, A. Amrane, S. Rtimi. Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *Int. J. Environ. Sci. Technol*; 18: 3273–3294. 2021
- [10] John Perez-Caldero, Diego Alejandro Marin-Silva, Noemi Zaritzky, Eco-friendly PVA-chitosan adsorbent films for the removal of azo dye Acid Orange 7: Physical cross-linking, adsorption process, and reuse of the material, *Advanced Industrial and Engineering Polymer Research*, 2023, in press.
- [11] Removal of the industrial azo dye crystal violet using a natural clay: Characterization, kinetic modeling, and RSM optimization Mouna Boulahba, Moulay Abderrahmane Malouki, Moises Canle, Zakaria Redouane-Salah, Sandhanasamy Devanesan, Mohamad S. AlSalhi, Mohammed Berkani, *Chemosphere*, 306 (2022) 135516.
- [12] Techno-economical aspects of electrocoagulation optimization in three acid azo dyes' removal comparison Mahsa Taheri, *Cleaner Chemical Engineering*, 2 (2022) 100007.
- [13] Aygun, A., Nas, B., Sevimli, M.F., 2021. Electrocoagulation of disperse dyebath wastewater: optimization of process variables and sludge production. *J. Electrochem. Sci. Eng.* 12 (1), 82–91.
- [14] Bassyouni, D.G., Hamad, H.A., El-Ashtoukhy, E.S.Z., Amin, N.K., Abd El-Latif, M.M., 2017. Comparative performance of anodic oxidation and electrocoagulation as clean processes for electrocatalytic degradation of diazo dye acid brown 14 in aqueous medium. *J. Hazard. Mater.* 335, 178–187.
- [15] Bendaia, M., Hazourli, S., Aitbara, A., Merzoug, N.N., 2021. Performance of electrocoagulation for food azo dyes treatment in aqueous solution: optimization, kinetics, isotherms, thermodynamic study and mechanisms. *Sep. Sci. Technol.* 56 (12), 2087–2103.
- [16] Akash P. Bhat, Parag R. Gogate, Degradation of nitrogen-containing hazardous compounds using advanced oxidation processes: A review on aliphatic and aromatic amines, dyes, and pesticides, *Journal of Hazardous Materials*, 403 (2021) 123657.
- [17] Removal of pharmaceutical micropollutants from real wastewater matrices by means of photochemical advanced oxidation processes – A review, Alena Kuliš'áková, *Journal of Water Process Engineering*, 53 (2023) 103727.
- [18] Recent advances in the removal of emerging contaminants from water by novel molecularly imprinted materials in advanced oxidation processes— A review Yang Zhang, Xiaodong

- Zhan, Shuguang Wang, *Science of the Total Environment*, 883 (2023) 163702.
- [19] Monali Priyadarshini, Indrasis Das, Makarand M. Ghangrekar, Lee Blaney, Advanced oxidation processes: Performance, advantages, and scale-up of emerging technologies, *Journal of Environmental Management*, 316 (2022) 115295.
- [20] Solar (electrochemical) advanced oxidation processes as efficient treatments for degradation of pesticides, Miguel A. Sandoval, Jorge Vidal, Wendy Calzadilla, Ricardo Salazar, *Current Opinion in Electrochemistry* 2022, 36:101125.
- [21] Sulfate radical based advanced oxidation processes for agro-industrial effluents treatment: A comparative review with Fenton's peroxidation, Eva Domingues, Maria João Silva, Telma Vaz, João Gomes, Rui C. Martins, *Science of the Total Environment*, 832 (2022) 155029.
- [22] German Buitron, Maribel Quezada, Gloria Moreno, *Bioresource Technology* 92 (2004) 143–149. Aerobic degradation of the azo dye acid red 151 in a sequencing batch biofilter,
- [23] Fulya Gökçen, Tulay A. Özbelge, *Chemical Engineering Journal* 114 (2005) 99–104. Enhancement of biodegradability by continuous ozonation in Acid Red-151 solutions and kinetic modeling.
- [24] Fulya Gökçen, Tulay A. Özbelge, Pre-ozonation of aqueous azo dye (Acid Red-151) followed by activated sludge process, *Chemical Engineering Journal* 123 (2006) 109–115.
- [25] M. Muruganandham, R.P.S. Suri, S. Jafari, M. Sillanpää, G.J. Lee, J.J. Wu, M. Swaminathan, Recent developments in homogeneous advanced oxidation processes for water and wastewater treatment, *Int. J. Photoenergy* 2014 (2014) 821674.
- [26] Wenhui Qiu, Ming Zheng, Jing Sun, Yiqun Tian, Meijuan Fang, Yi Zheng, Ting Zhang, Chunmiao Zheng, Photolysis of enrofloxacin, pefloxacin and sulfaquinoxaline in aqueous solution by UV/H<sub>2</sub>O<sub>2</sub>, UV/Fe(II), and UV/H<sub>2</sub>O<sub>2</sub>/Fe(II) and the toxicity of the final reaction solutions on zebrafish embryos, *Science of the Total Environment* 651 (2019) 1457–1468.
- [27] A. Ruiz-Sánchez, G.T. Lapidus, Decomposition of organic additives in the oxidative chalcopyrite leaching with hydrogen peroxide, *Minerals Engineering* 187 (2022) 107783.
- [28] W. H. Glaze, J. W. Kang, and D. H. Chapin, The chemistry of water treatment processes involving ozone, hydrogen peroxide and ultraviolet radiation, *Ozone: Science & Engineering*, vol. 9, pp. 335–352, 1987.
- [29] Chen JH, Xu JW, Shing CX (1993) Decomposition rate of hydrogen peroxide bleaching agents under various chemical and physical conditions. *Journal of Prosthetic Dentistry*, 69(1) 46-48.
- [30] X. Zhao, Y. Li, J. Lu, L. Zhou, J.M. Chovelon, Q. Zhou, Y. Ji, UV/H<sub>2</sub>O<sub>2</sub> oxidation of chloronitrobenzenes in waters revisited: Hydroxyl radical induced self-nitration, *J. Photochem. Photobiol., A* 410 (2021), 113162.
- [31] Coons DM (1978) Bleach: facts, fantasy, and fundamentals, *Journal of the American Oil Chemists' Society*, 55, 104–108.
- [32] Chhaya V. Rekhate, J.K. Srivastava, Recent advances in ozone-based advanced oxidation processes for treatment of wastewater- A review. *Chemical Engineering Journal Advances* 3 (2020) 100031
- [33] U. von Gunten. The basics of oxidants in water treatment. Part B: ozone reactions, *Water Sci Technol* (2007) 55 (12): 25–29.
- [34] J. Wang, Z. Bai, Fe-based catalysts for heterogeneous catalytic ozonation of emerging contaminants in water and wastewater, *Chem. Eng. J.* 312 (2017) 79–98.
- [35] Matsui M. *Environmental Chemistry of Dyes and Pigments*. Edited by Reife A, Fremann HS. JohnWiley and Sons, New York; 1996 Jan. p. 1–352.
- [36] Southern TG. *Color in Dye House Effluents*. Edited by Cooper P. Society of Dyers and Colourists; 1995. p. 1–200.
- [37] J. Wang, H. Chen, Catalytic ozonation for water and wastewater treatment: recent advances and perspective, *Sci. Total Environ.* 704 (2019) 135249.
- [38] M. Tichonovas, E. Krugly, D. Jankunaite, V. Racys, Ozone-UV catalysis based advanced oxidation process for wastewater treatment, *Environ. Sci. Pollut. Res.* 24 (2017) 17584–17597.
- [39] C.V. Rekhate, J.K. Shrivastava, Decolorization of azo dye solution by ozone based advanced oxidation processes: optimization using response surface methodology and neural network, *Ozone: Sci. Eng.* (2020),
- [40] C.H. Wu, Decolorization of C.I. Reactive Red 2 by ozonation catalyzed by Fe (II) and UV, *React. Kinet. Catal. Lett.* 93 (1) (2008) 35–42.
- [41] Duesterberg CK, Mylon SE, Waite TD. pH effects on iron-catalyzed oxidation using Fenton's reagent. *Environmental Science and Technology*. 2008;42:8522-8527.

- [42] Szpyrkowicz L, Juzzolino C, Kaul SN. A comparative study on oxidation of disperse dye by electrochemical process, ozone, hypochlorite and Fenton reagent. *Water Research*. 2001;35:2129-2136.
- [43] Yoon J, Lee Y, Kim S. Investigation of the reaction pathway of  $\cdot\text{OH}$  radicals produced by Fenton oxidation in the conditions of wastewater treatment. *Water Science and Technology*. 2000;44:15-21.
- [44] Y. W. Kang and K.-Y. Hwang, "Effects of reaction conditions on the oxidation efficiency in the Fenton process," *Water Research*, vol. 34, no. 10, pp. 2786–2790, 2000.
- [45] H. Galard, J. De Laat, Kinetic modelling of  $\text{Fe(III)/H}_2\text{O}_2$  oxidation reactions in dilute aqueous solution using atrazine as a model organic compound, *Water Research*, 34 (2000) 3107-3116.
- [46] M. Pera-Titus, V. García-Molina, M. A. Baños, J. Giménez, S. Esplugas, Degradation of chlorophenols by means of advanced oxidation processes, *Water Research*, 34 (2004) 219-256.
- [47] Y. Deng, J. D. Englehardt, Treatment of landfill leachate by the Fenton process, *Water research*, 40 (2006) 3683-3694.
- [48] J. Herney-Ramirez, M. A. Vicente, and L. M. Madeira, Heterogeneous photo-Fenton oxidation with pillared clay-based catalysts for wastewater treatment: a review, *Applied Catalysis B*, 98, (2010) 10–26.
- [49] Gallard H, De Laat J (2000) Kinetic modelling of  $\text{Fe(III)/H}_2\text{O}_2$  oxidation reactions in dilute aqueous solution using atrazine as a model organic compound. *Water Res* 34(12):3107–3116.
- [50] Archina Buthiyappan, Abdul Raman Abdul Aziz, WMAW Daud, Recent advances and prospects of catalytic advanced oxidation process in treating textile effluents, *Rev Chem Eng* 2016; 32(1): 1–47.
- [51] E. Neyens and J. Baeyens, A review of classic Fenton's peroxidation as an advanced oxidation technique, *Journal of Hazardous Materials*, 98, 33–50, 2003.
- [52] Slimane Merouani, Aissa Dehane, a Aouatf Belghit, a Oualid Hamdaoui, Nour El Houda Boussalema and Hassina Daif, Removal of persistent textile dyes from wastewater by  $\text{Fe(II)/H}_2\text{O}_2/\text{H}_3\text{NOH}^+$  integrated system: process performance and limitations, *Environ. Sci.: Adv.*, 2022, 1, 192–207.
- [53] Archina Buthiyappan, Abdul Raman Abdul Aziz, Wan Mohd Ashri Wan Daud, Recent advances and prospects of catalytic advanced oxidation process in treating textile effluents, *Rev Chem Eng* 2016; 32: 1–47.
- [54] Review on effect of different type of dyes on advanced oxidation processes (AOPs) for textile color removal Guntur Adisurya Ismail a,b , Hiroshi Sakai, *Chemosphere*, 291 (2022) 132906.
- [55] Oturan MA, Aaron JJ (2014) Advanced oxidation processes in water/wastewater treatment: principles and applications: a review. *Crit Rev Environ Sci Technol* 44(23):2577–2641.
- [56] Thomas N, Dionysiou DD, Pillai SC (2021a) Heterogeneous Fenton catalysts: a review of recent advances. *J Hazard Mater* 404(PB):124082.
- [57] Hameed, B.H., Lee, T.W., 2009. Degradation of malachite green in aqueous solution by Fenton process. *J. Hazard. Mater.* 164, 468–472.