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Original Research Article

Study of Photo-catalytic Degradation of Disperse B-SE2R with UV/H_2O_2/TiO_2 and Solar Light

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KEYWORDS

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Water quality parameters

ABSTRACT

Currently, the presence of dyes in sewage, drinking, and surface water is a serious concern. To remove dye toxicity from the water reservoirs, substantial efforts were made. Among different procedures, the Advanced Oxidation Process (AOPs) is a highly recommended process for degrading disperse dyes due to its accuracy. Due to the greater efficiency of AOPs, solar light and UV/H_2O_2/TiO_2-based advanced oxidation processes were utilized to degrade the disperse dye blue SE2R (DB-SE2R). The impact of various factors, such as pH effect, H_2O_2 dosage concentration, and dye concentration, on dye degradation was investigated. A 94% degradation was achieved by the ultraviolet/hydrogen peroxide/TiO_2 method, which involves breaking down the disperse dye blue SE2R molecule into less harmful components or eliminating its toxicity from water or wastewater to the maximum extent. A 62% degradation efficacy was optimized after solar light irradiation with the TiO_2 photocatalyst. The optimal conditions for maximum degradation of DB-SE2R were 0.9 mL H_2O_2 at pH 3, achieved in 60 minutes. The assurance of results was achieved through improvements in toxicological tests (Hemolysis and Mutagenicity evaluation) and water quality parameters, including dissolved oxygen, chemical oxygen demand, and biological oxygen demand. After treatment with solar light and ultraviolet radiation, the intermediates and end products were investigated. All the major peaks disappeared after Fourier Transform Infrared Spectroscopy (FT-IR) analysis, except for some minor peaks. From the results, it was found that UV/H_2O_2/TiO_2 is an efficient method for degrading the DB-SE2R.

1. Introduction

Presently, more than 10,000 dyes have been effectively commercialized. Although many of these dyes are banned for commercial sale and use, they are still readily available and used in the textile industry, posing a significant environmental threat. Water pollution is primarily caused by industrial effluents, including those from the textile, cosmetics, and pharmaceutical industries. Among those, dyes contribute the most to water pollution because 50% of the amount is discharged into water reservoirs and remains unspent (Jaime-Acuña et al., 2016). Many dyes, including their byproducts, are considered carcinogenic due to their highly toxic nature to living organisms. The various methods comprising desiring, decolorizing, coloring, production, and finishing are the primary reasons for varying the characteristics of wastewater generated from industries (Adeel et al., 2015). The conventional methods are insufficient to remove dyes from textile industries due to their intractable nature against light, oxidizing agents, and biodegradation processes. Therefore, to break down and remove the dye effluents in the wastewater, novel treatment procedures are desperately needed (Rohilla et al., 2012). Dyes are known as the primary chemical pollutants in textile wastewater. One of the most pressing environmental problems that needs to be addressed is the removal of dyes.

The release of intensified dye wastage is hazardous and can destroy aquatic life by blocking the light pathway. Furthermore, azo dyes and their derivatives are known for their cytotoxicity (Abbas et al., 2018). A large amount of dyestuff is being directly discharged into water bodies due to inefficiencies in the dying process, and it automatically becomes part of the environment. Among various classes of dyes, the most challenging class to handle is disperse dyes due to their highly toxic nature and resistant behavior in response to traditional biological and chemical methods (Saratale et al., 2011). Because of these issues, managing dye effluents in wastewater remains a significant challenge.

The disperse dyes class is considered one of the most important and frequently used classes in various industrial products (Parab et al., 2016). Considering different properties of these dyes, the availability of the azo group (N=N) attached to two substituents is crucial and significant (Ameta & Jhalora, 2014). There is a need to develop modern methods due to the specific characteristics of this class, such as toxicity and mass production. Traditional biological methods have proven to be a significant failure in degrading and dispersing dyes (Agarry & Ayobami, 2011). For non-destructive physical water treatment processes, advanced oxidation processes (AOPs) are desirable alternatives because they have the potential to degrade organic water pollutants (Ashar et al., 2016). In AOPs, UV radiation is the primary method used for the decolorization of pollutants. Ultraviolet radiation, in combination with H2O2, is a shining process

through chemical oxidation (Bokhari et al., 2015). Basically, the production of hydroxyl radicals occurs in the presence of UV radiation accompanied by H_2O_2. These radicals react with the organic matter in wastewater due to their short-lived and highly reactive nature. The key steps that occur during the UV/H_2O_2 process are hydrogen abstraction, electrophilic addition, and electron transfer reactions (Sima & Hasal, 2013). The UV/H_2O_2 technique is highly efficient and beneficial due to several advantages, including the fact that the O_2 produced during the treatment is crucial for organic breakdown (Bokhari et al., 2020). Moreover, under feasible conditions, production of final products such as water, carbon dioxide and other products (with a lower molecular weight) (Bokhari et al., 2015). Furthermore, in various advanced oxidation processes, degradation can be performed using solar irradiation, as the photons receive the wavelengths from the sun that are essential for these processes (Buscio et al., 2015).

This research aims to utilize solar light and ultraviolet radiation in conjunction with H_2O_2 and H_2O_2/TiO_2 to degrade the disperse B-SE2R (Figure 1A, Table 1) without requiring a massive amount of chemical reagents and to yield mineral entities, such as carbon dioxide and water. The end product was finally characterized by applying different parameters, including Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD). The toxicity reduction was assessed using the hemolysis and Ames tests. Furthermore, FT-IR and LC-MS investigations were carried out to confirm the degradation of disperse B-SE2R.

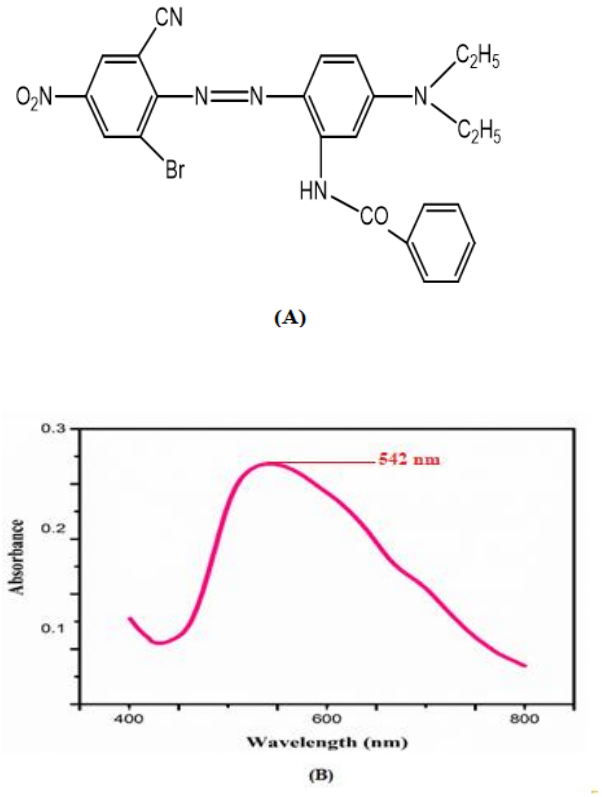

Figure 1: Structural formula of Disperse Blue SE2R (A) and the absorption spectrum of Disperse Blue SE2R dye (B)

The peak appears at a 542nm value in the visible region because of the blue chromophore, at which the sample absorbs the maximum light.

Table 1: Properties of disperse dye Blue SE2R

Name	Disperse Blue SE2R
Molecular formula	$C_{24}H_{21}BrN_6O_3$
Molecular weight (g/mol)	521.37
Chemical nature	Anionic Blue SE2R
Color Index name	Blue
Color Index number	11078
λ_{max} (nm)	542
Reactive group	Azo

2. Materials and methods

To conduct this research, analytical-grade chemicals and reagents were used. The Chemical Index (C.I.) disperse B-SE2R (chemical formula: $C_{24}H_21BrN_6O_3$, MW: 521.37 g · mol-1, Molecular structure in Figure 1A and B

) was taken from Khawaja & Company Dyes and Chemicals, Faisalabad, with no further purification. Hydrogen peroxide (Sigma Aldrich) and TiO_2 (Sigma Aldrich) were used as parameters. Dilute HCl (0.1 M) and NaOH (0.1 M) were used to adjust the pH of disperse B-SE2R in its aqueous solution, which was then irradiated using the UV/H_2O_2/TiO_2 method as a model compound for this investigation. The solution was monitored through a spectrophotometer (CE Cecil 7200). Samples were prepared in distilled water for further processing.

2.1. Samples Irradiations and Analysis of Disperse B-SE2R

A 1000 ppm dye solution was prepared by mixing 1 g of dye in 1 mL of ethanol and 999 mL of distilled water, with constant stirring for 30 min. to achieve solution homogeneity. The dilution method was further used to dilute the stock solution to the required concentrations, i.e., 50 ppm, 100 ppm, and 150 ppm. These concentrations were applied for ultraviolet treatment using different amounts of H_2O_2 (0.3 mL, 0.6 mL, 0.9 mL) and TiO_2 (0.2 g, 0.4 g, 0.6 g) in a UV chamber. Experiments were also performed under solar light at different times (30 min, 45 min, 60 min, 75 min) with weather conditions mostly sunny in the summers. The UV reactor model (Zam Micro Technologies ZM144W), 144 Watts, with a light intensity of 254 nm wavelength, was used for irradiation for 30 minutes, 45 minutes, and 60 minutes. The absorbance of all samples is noted at λmax = 542 nm before and after treatments. Before UV radiation treatment, the solution of disperse B-SE2R was stirred with the help of a magnetic stirrer with the availability of TiO_2 without light for one hour to extend the adsorption equilibrium. To filter the solutions of disperse dye B-SE2R, a Millipore membrane (pore size 0.45 µm) was used, and the calibration curve method was employed to determine the UV-Vis absorbance characteristics using a UV-Vis spectrophotometer (model CE Cecil 7200) in the Department of Chemistry, University of Agriculture, Faisalabad. The %age degradation was evaluated using:

$$\% \text{ Degradation} = 100 \times (C0 - C) / C0 \quad (1)$$

Where C_0 = initial concentration of dye solution, C = concentration of dye solution after photo irradiation.

2.2. Toxicity evaluation & H_2O quality measures

The MnO_2 in minute quantities (< 1 mg mL-1) was used to UV-treat samples to lessen and reduce the toxic effect of H_2O_2. Specific toxicity tests (hemolysis and Ames test) of cleared solutions were performed after the required time of 60 minutes. For the evaluation of cytotoxicity, hemolytic experiments were performed against human red blood cells (RBCs). As a positive control, Triton X-100 was used. Microbes are considered the primary cause of hemolysis in infectious diseases (Rashid et al., 2025). In the present research, the degradation effect of disperse B-SE2R and the percentage hemolysis of human erythrocytes were investigated. The hemolysis efficiency was associated with the degradation of disperse B-SE2R. The Ames test was conducted to assess the mutagenic response of degraded samples of disperse dye B-SE2R. The strains used were *Salmonella typhimurium* strains TA98 and TA100. A test was performed to optimize the dose range by identifying the concentration. At which every compound stopped the development of strain TA98 in microtiter plates containing the accompanying medium, which permitted cell growth. A positive test indicates the carcinogenic behavior of B-SE2R, since this disease is often associated with transmutation. The test proves to be a rapid and beneficial way to check the carcinogenic nature of disperses dye B-SE2R. This evaluation assay was carried out at the Biochemistry Laboratory, Department of Biochemistry, University of Agriculture, Faisalabad.

The Hi-Tech Lab performed the dissolved oxygen identification at the University of Agriculture, Faisalabad, Pakistan. The DO meter used for analysis was an inoLab Multi 720 WTW 82362 Weilheim. The samples with hydrogen peroxide and titanium dioxide parameters were checked both with and without irradiation. Complete oxidation of organic matter should be performed to determine the chemical oxygen demand, as per the University of Agriculture, Faisalabad, Pakistan. The test for determining chemical oxygen demand was performed using the $K_2Cr_2O_7$ process. In this method, approximately 2 mL of the 50 ppm dye solution was used. The silver sulphate catalyst was also added to this solution, and then the dye solution was added. Then, refluxing of this sample was performed for about 3-4 hours, with the temperature set at 150°C. Various factors affect the specific decrease in the chemical oxygen demand values. Decreases in the COD values are also associated with the added amount of H_2O_2 and titanium dioxide. In the biological oxygen demand, the amount of O_2 used in the process is identified by comparing the remaining O_2 after 5 days with the initial O_2, whose quantity had already been determined. The amount of DO at room temperature is about 8 mg/L. The Biological oxygen demand can be calculated by the following formula:

$$\frac{\text{BOD} = [(\text{BOD observed}) - (\text{Fraction seed})] \times (\text{BOD of seed})}{\text{Fraction sample}} \quad (2)$$

2.3. FT-IR and LC-MS

Fourier transform infrared spectroscopy analysis was used for both treated and untreated samples of disperse dye blue SE2R to assess degradation. A Fourier transform infrared spectrometer (U-2001, Shimadzu, Japan) at the HI-TECH lab, GCUF, was employed, with a range of 4000-400 cm-1 for the IR study. By using the extraction method, acetone was used to prepare the samples. The organic layer was poured, and with the help of $MgSO_4$, it was dehydrated. Fourier transform infrared spectrophotometer analysis was performed after the evaporation of the organic phase.

LIT-MS (LTQ XL, Thermo Scientific, USA) equipped with an electrospray ionization (ESI) source. Methanol was used to dissolve the dispersive dye samples, and then, through the direct insertion method, these were injected into the mass spectrometer with a flow rate of 10 µL. min-1. Both negative and positive scan ion modes were used for the screening of samples. The capillary voltage was 4.2 kV, and the capillary temperature was 280 °C. The flow rate of the sheath gas was adjusted to 20 units per minute. The scanning range for the disperse dye samples was 50 -2000 m/z.

2.4. Statistical analysis

A one-way ANOVA using Minitab 13 at a 95% confidence interval was employed to test the results of the dispersive dyes statistically.

3. Results and discussion

3.1. Initial dye concentration impact on degradation

Various concentrations (50 ppm, 100 ppm, and 150 ppm) of disperse B-SE2R were treated with ultraviolet radiation while maintaining all other conditions constant, with different irradiation times to determine the maximum percentage degradation of DB-SE2R. Figure 2A represents the degradation pattern. Effective degradation (68.7%) was achieved at a 50 ppm dye concentration after 30 minutes. The degradation efficiency decreased (61.05%) with increasing initial dye concentration (150 ppm) because the solution became more turbid. Experiments were performed repeatedly at several time intervals, i.e., 45 min and 60 min. Moreover, the degradation was 71.8% and 74.5% at a 50 ppm DB-SE2R dye concentration. It has also been found that by enhancing the irradiation time, the decolorization of dispersive B-SE2R also increased at the initial dye concentration. These findings are in agreement with the previously presented study by Qiu, Shou, Ren, and Jiang.

3.2. pH impact

Different concentrations of the selected dye (50 ppm, 100 ppm, 150 ppm) were subjected to various pH levels (3, 5, 7, 9) to assess the impact of pH on the degradation efficacy of DB-SE2R. The pH factor is crucial in the discoloration of dye using the hydrogen peroxide/UV/TiO_2 technique. Acidic conditions favored the decolorization of dispersive dyes (Hamed, Alabdraba, & Mohammed, 2018a; Khamparia, Gupta, Tyagi, Malviya, & Jaspal, 2015), showing that the degradation of dispersive B-SE2R was enhanced with a decreasing pH value, with the highest color elimination exceeding 85% at pH 3. Enhancing the pH from 3 to 9 resulted in a reduction in efficiency from 85% to 38%. The decrease in efficacy at basic pH can be attributed to the fact that hydrogen peroxide was utilized for the oxidative breakdown of alkalis, forming dioxygen and H_2O despite generating the OH with ultraviolet radiation treatment. Furthermore, the H_2O_2/UV/TiO_2 method is crucial to the scavenging effect of carbonate at greater pH (Ferraz et al., 2013). Therefore, there is a decrease in the instantaneous concentration. Of OH results in the reduction of degradation efficacy. Figure 2B depicts the pH impact on the degradation efficacy of dispersive B-SE2R.

3.3. Effect of solar light irradiations on the % degradation of DB-SE2R

Degradation efficacy of disperse B-SE2R was investigated by solar light in combination with photo-catalyst TiO_2. Solar light offers the benefit of being a free irradiation process and exhibiting non-toxic behavior towards the environment. 50ppm solution of the disperse B-SE2R was treated with 0.1g.L^{-1} of TiO_2. Results were taken at several time intervals, ranging from 30 to 75 minutes. TiO_2 proved to be a more active photo-catalyst under solar light, as it gave 62% degradation efficacy with the parameter SL/TiO_2 after 75 minutes of SL irradiations, as shown in Figure 3A.

3.4. Effect of hydrogen peroxide dose

The dye degradation in combination with H_2O_2 is one of the most popular advanced oxidation processes (AOPs). The availability of H_2O_2 is the key parameter for the decomposition of dye molecules. The dispersed Blue SE2R degradation in the ultraviolet light system,

in combination with the effects of various H_2O_2 concentrations, was studied. The H_2O_2 concentrations ranged from 0.3 to 0.9mL. It was noted that 89.91% degradation was achieved in 60 minutes when combining H2O2 (0.9 mL) with UV, compared to 71.38% decolorization without H_2O_2. The degradation efficiency of DB-SE2R is enhanced due to the increased production of hydroxyl radicals with ultraviolet radiation treatment. These results are in accordance to previous work that hydrogen peroxide may change the efficiency of advanced oxidation process since it increased the production of hydroxyl radicals during photo-catalytic process resulting increase in degradation efficacy of DB-SE2R (Bibi, Kamal, et al., 2017; Bibi, Nazar, et al., 2017; Iqbal et al., 2015; Iqbal & Nisar, 2015). Results are shown in Figures 3B and 3C.

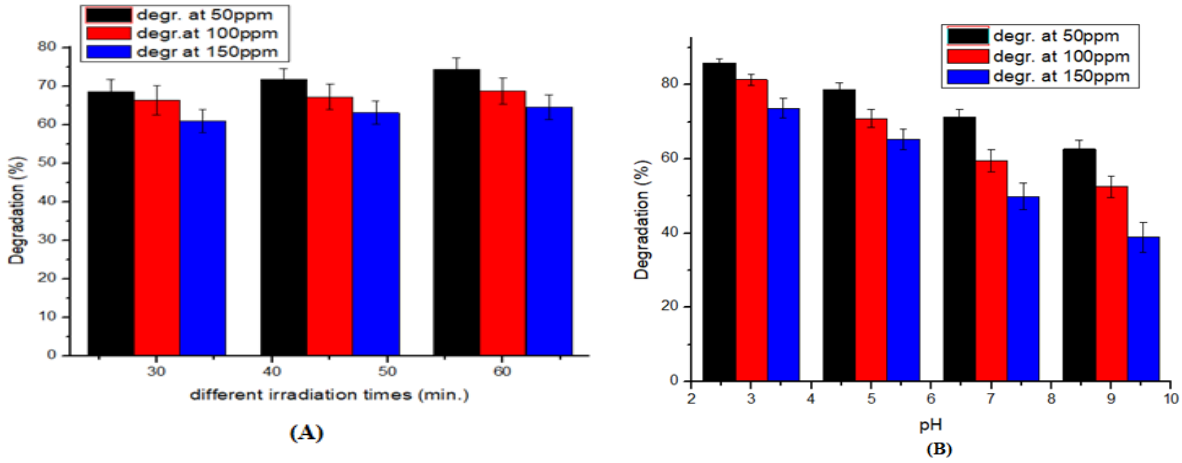

Figure 2. Degradation of the DB-SE2R dye at various concentrations with different irradiation times (A) and degradation of the DB-SE2R at different pH levels of the medium (B)

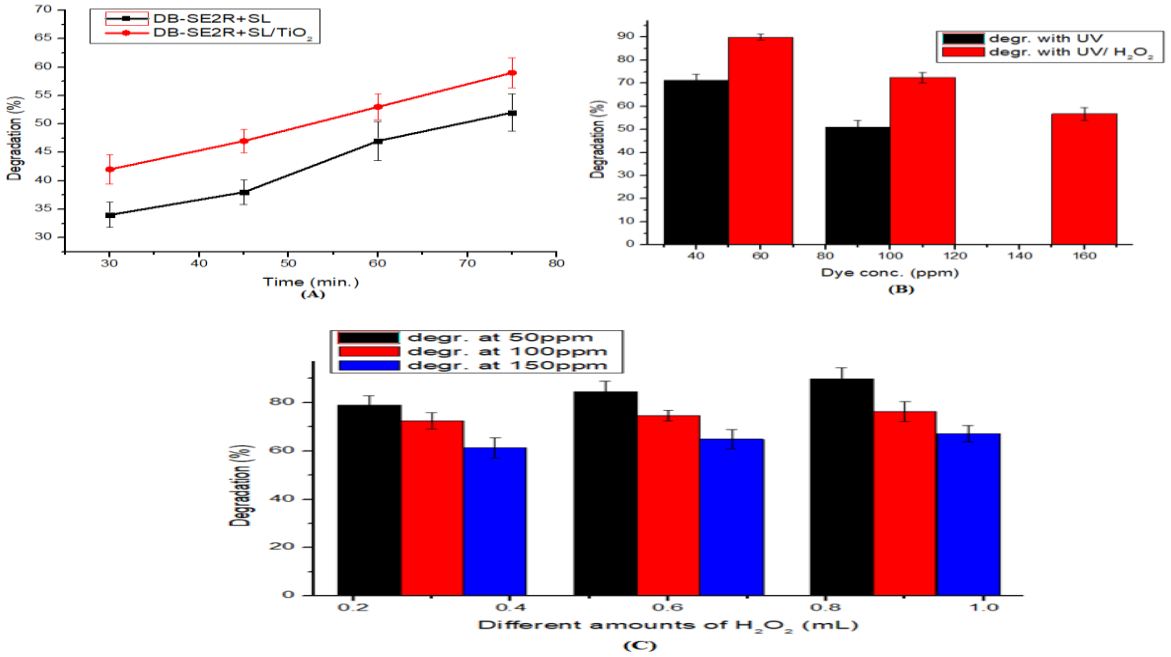

Figure 3: A. Photo-catalytic degradation of DB-SE2R under solar light with TiO_2 photo-catalyst. B. Comparison between the degradation of disperse dye Blue SE2R with UV and UV/H_2O_2. C. Degradation of disperse Blue SE2R with different amounts of H_2O_2 and dye concentrations

3.5. Effect of TiO_2 concentration

Different concentrations of Titanium dioxide (0.2g, 0.4g, 0.6g, 0.8g) were used (Figure 4) to achieve the maximum degradation efficacy of disperse blue SE2R. During this process, all other parameters were kept constant. Results indicated that the increased degradation efficiency of DB-SE2R was achieved by increasing the TiO_2 amount, due to the greater accessibility of TiO_2 active sites during the process. This resulted in the highest degradation (94.2%) with 0.4 g of Titanium dioxide, even at a 50 ppm dye concentration. By achieving the maximum degradation efficiency of disperse B-SE2R with UV/ H_2O_2/

TiO_2 combination compared to UV/ H2O2, which confirms the photo-catalytic nature of TiO_2 (Jamil et al., 2020).

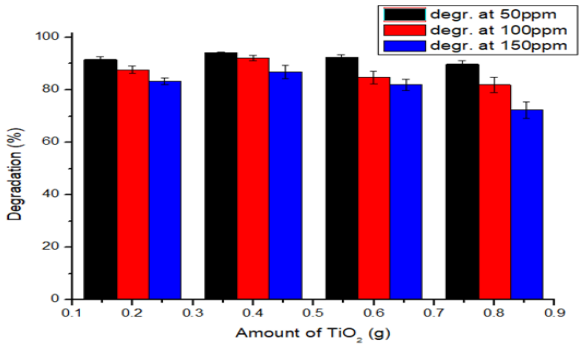

Figure 4. Degradation percentage of dye disperse B-SE2R at different concentrations of TiO_2

3.6. Water Quality Parameters

Different Dissolved oxygen is the amount of non-bonded and free oxygen present in liquids or water. The solution of DB-SE2R (183) treated with UV/TiO_2/H_2O_2 was evaluated for DO, BOD and COD. The optimum conditions for the UV-treated sample were a 50 ppm dye concentration, 0.9 mL H_2O_2, and 0.4 g TiO_2. The DO value for unirradiated samples was 3.72 mg/L. This value was significantly increased to 7.02 mg L-1 for the UV-treated sample (Figure 5A). The DO work is based on the reported work of reference (Suriyaprabha & Fulekar, 2018). BOD reduction of various concentrations of disperse Blue SE2R was examined in this work. An apparent reduction in BOD was observed after UV/H_2O_2/TiO_2. Dye concentration was 50 ppm. These values, prior to irradiating the samples, were 474.78 mg/L and 425.24 mg/L. With UV radiation treatment, these values decreased to 288.65 mg/L and 265.23 mg/L, as shown in Figure 5 B. Jamil et al. (2020) reported the reduction in BOD in the fabric wastewater sewages. Chemical oxygen demand was helpful for the breakdown of DB-SE2R. The values of chemical oxygen demand decreased with UV radiation treatment due to the decomposition of organic matter after treatment. The presence of hydrogen peroxide enhanced the COD reduction. The 50 ppm solution of dye has a COD value of 712.17 mg/L without any irradiation, but this value decreases to 432.98 mg/L after UV irradiation, as shown in Figure 5C. The comparison of previously reported COD values of the acidic azo dye reference in the literature can be compared to recommend the COD values of disperse DB-SE2R (Keshmirizadeh & Farajikhajehghiasi, 2014). Table 2 is added as a comparative summary of degradation efficiencies from related studies for a better comparison of results.

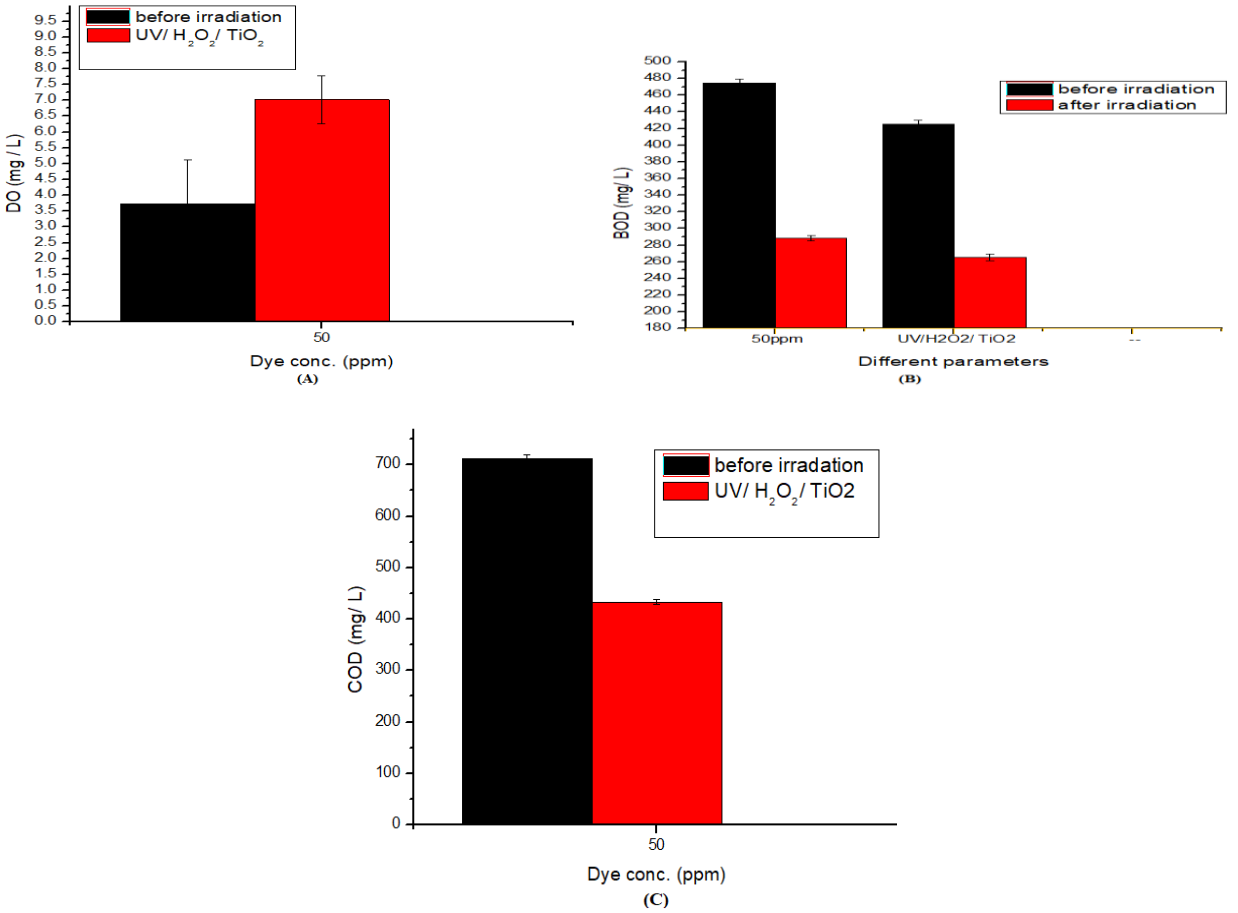

Figure 5: DO values for untreated and UV-treated samples (A) and BOD values of disperse Blue SE2R dye treated at optimum conditions versus the untreated sample (B), and COD in mg/L before and after UV treatment (C)

Table 2: Comparative data summarizing degradation efficiencies of different disperse dyes from similar studies

Sr No.	Name of dye	pH	AOPs	H_2O_2	Photo-catalyst	%age degr.	Biological treatments	Reference
1	Textile dyes	-	UV	-	TiO_2	-	-	(Sima & Hasal, 2013)
2	Disperse dye	2	UV	180 mg/L	-	72%	-	(Boucherit et al., 2012)
3	Disperse orange 288	-		10-50 ml/L	-	-	COD removal	(Huang et al., 2011)
4	Disperse blue 56	3	Fenton/ H_2O_2	30-100 mM	-	72%	COD removal	(Keshmirizadeh & Farajikhajehghiasi, 2014)
5	Disperse red 73	4	UV	-	TiO_2	60-90%	COD removal	(Buscio et al., 2015)
6	Disperse yellow 23	-	UV	-	TiO_2	97.4%	-	(Nikazara et al., 2007)
7	Disperse Red F_3BS	5.2-5.9	UV	-	TiO_2	-	COD, BOD	(Bokhari et al., 2015)
8	Dyeing wastewater	-	Fenton/ H_2O_2	different values	-	95%	COD	(Mohan, 2016)
9	Textile wastewater	-	O_3/H_2O_2, O_3/UV	Different values	-	-	BOD, TOC	(Hassaan & El Nemr, 2017)
10	Textile wastewater	-	UV/H_2O_2	Different values	-	80%	TOC	(Volmajer Valh et al., 2012)
11	Textile dye	3	UV/H_2O_2	25 mg/L	-	-	-	(Khalaf et al., 2018)
12	Disperse blue 79	-	Fenton process	150 mg/L	-	85%	COD removal	(Hamed et al., 2018b)
13	Dye mixture	-	Photo-degradation	-	-	-	COD, BOD removal	(Gupta et al., 2015)
14	Disperse red 354		UV/H_2O_2, Photo-fenton	Different values	-	85%	COD removal	(Neamtu et al., 2004)
15	Dye wastewater	6-10	UV/H_2O_2	-	-	-	COD removal	(Kalra et al., 2011)

COD = Chemical Oxygen Demand ;BOD = Biological Oxygen Demand ;TOC = Total Organic Carbon

3.7. FT-IR and LC-MS analysis

FT-IR is a technique used to study the IR (Infrared) spectrum of absorption or emission of any material (Ali et al., 2018). To identify the degraded end products, both untreated and treated samples of disperse dye Blue SE2R were analyzed using an FTIR spectrometer (U-2001, Shimadzu, Japan) at the HI-TECH lab, GCUF, in the range of 4000-400 cm^{-1}. The results are presented in Figures 6A and 6 B. Without any treatment, specific vibrational peaks appeared at 3250 cm-1 (NH), 2995 cm^{-1} (CH, CH_2 and CH_3), 1700 cm-1 (C=O), 1550 cm-1 (N=N), 1305 cm-1 (NO_2), 1117 cm^{-1} (C-OH) and 600 cm-1 (halogens) positions due to the characteristics of the dye molecule. These peaks disappeared after UV irradiation, and a minor peak of 1083.97 cm^{-1} was observed due to CH bending, which assured the destruction of DB-SE2R. The results showed that the large DB-SE2R molecule was destroyed, producing smaller acidic units, which assured the degradation of DB-SE2R. The results are in strong comparison with earlier presented work (Iqbal & Bhatti, 2015). To confirm the results and verify the breakdown of the DB-SE2R into low-molecular-weight inorganic compounds, LC-MS analysis was performed on the UV-treated samples of DB-SE2R at Nuclear Institute of biotechnology and Genetics Engineering (NIBGE), Faisalabad (Figure 7). The LC-MS was operated in positive mode using full scan MS with a scan

range of m/z 150-550 in enhanced scan mode for improved resolution. The absence of a base peak is likely due to product degradation. It may also result from a low analyte concentration, the presence of compounds that interfere with ionization, such as salts, or even from an instrumental origin. The expected peaks of intermediate products with their *m/z* values in the spectrum were benzoic acid (122.12), 2-bromoaniline (172.02), 2-amino-3-bromobenzonitrile (197.03), 2-bromo-6-nitroaniline (217.02), 2-amino-3-bromo-5-nitrobenzonitrile (242.03), 2-bromo-6-cyano-4-nitrobenzenediazonium (254.02), *N*-(3-(diethylamino)phenyl)benzamide (268.03) and 3-nitroanilne (138.12). These functional peaks were observed in the spectrum, which assured the degradation of DB-SE2R and the breakdown of the dye structure into intermediates, which further changed into H2O, carbon dioxide, and NO_2. This work is based on the reported work of Chen et al. (2008), who confirmed the production of intermediates in the LC-MS spectra of methyl orange. A mechanistic pathway was proposed based on LC-MS spectra (Figure 8).

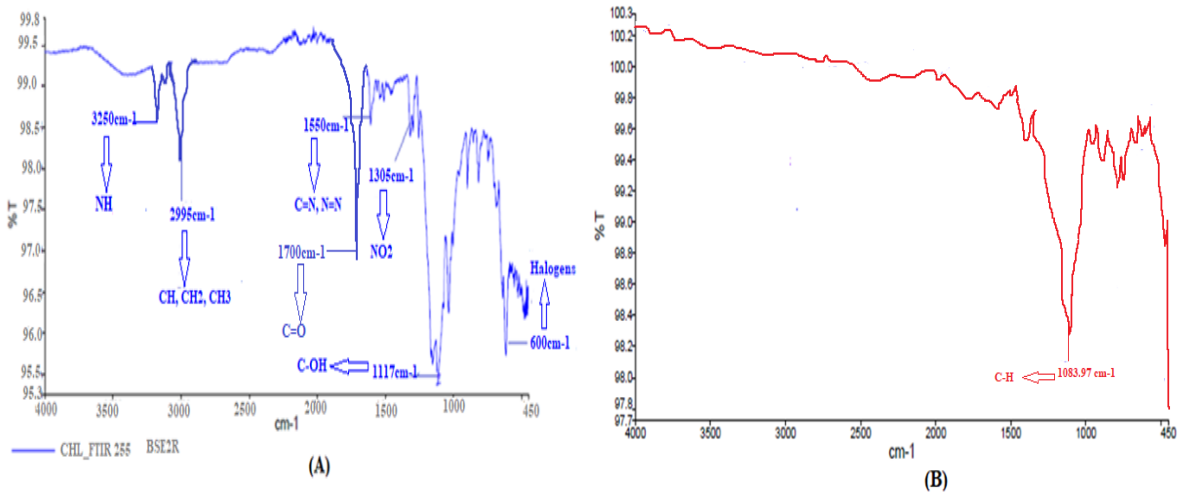

Figure 6: FT-IR spectrum for the untreated sample **(**A) and FT-IR bands of the UV-treated sample of disperse B-SE2R (B).

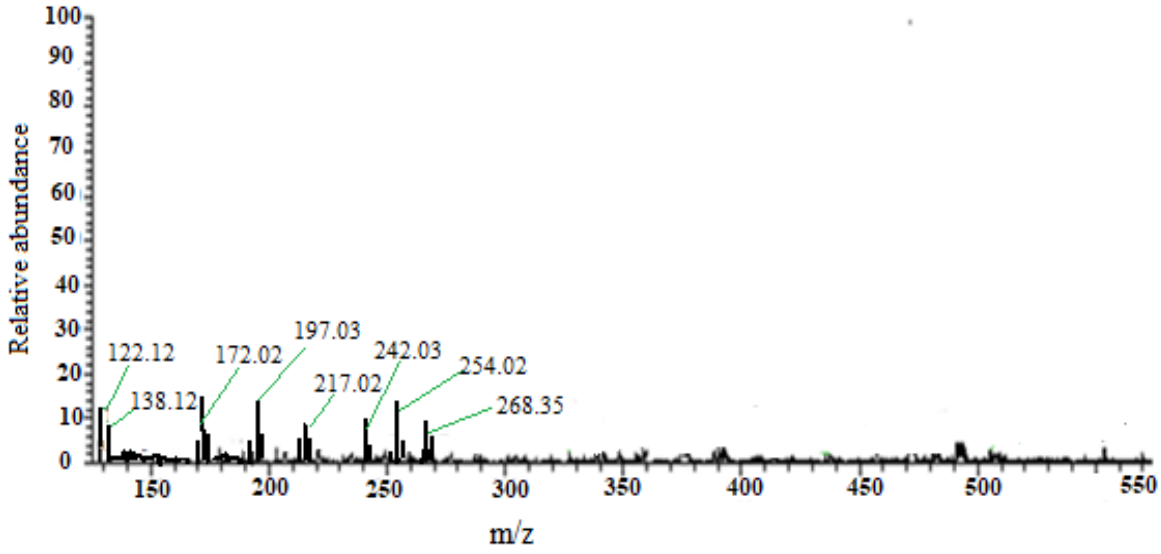

Figure 7: LC-MS spectrum of UV-treated sample

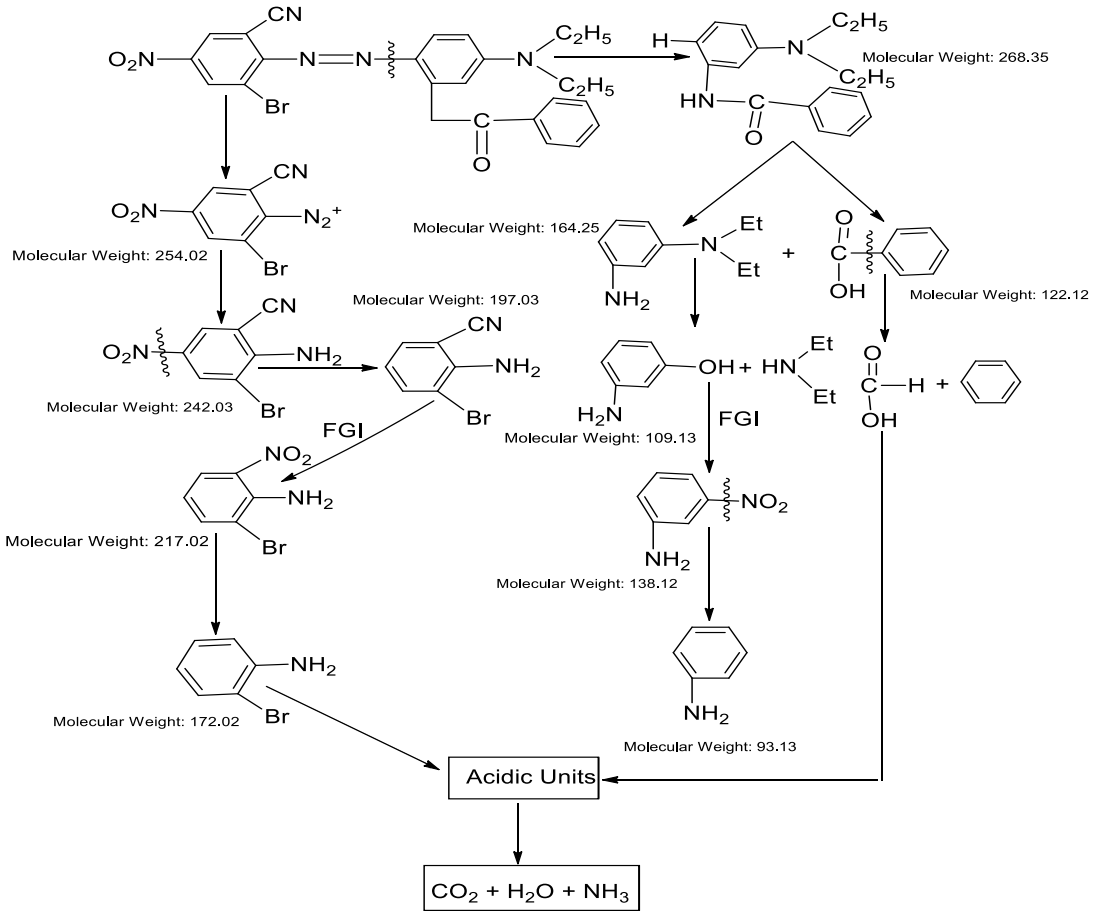

Figure 8: Proposed degradation pathway of disperse dye Blue SE2R

3.8. Cytotoxicity by hemolytic activity and mutagenicity by A test

For the cytotoxic evaluation, hemolytic activity was assessed for the UV-treated sample of DB-SE2R (Mehmood, Shahid, Barkat, et al., 2023; Mehmood, Shahid, ul Huq, et al., 2023). The untreated samples of DB-SE2R showed a great cytotoxic potential (12.1%), but after treatment with UV radiation, this value decreased to 9.5% (Figure 9A). A further decrease in cytotoxicity, up to 6.9%, was achieved with the addition of the photocatalyst TiO_2. Cytotoxicity was reduced to a certain level, indicating that photo-catalytic degradation is more effective in reducing toxicity than non-photo-catalytic breakdown. Results are shown in Figure 8A. A mutagenic evaluation of DB-SE2R was conducted using the previously reported method. The solution of DB-SE2R was analyzed before and after irradiation for mutagenicity using TA98 and TA100 strains. The samples were treated with ultraviolet irradiation, and the mutagenic response was notably lowered, by 61% for TA98 and 56% for TA100. UV/H_2O_2/TiO_2 has been effectively proven to be one of the most effective methods for reducing the mutagenicity of DB-SE2R to the maximum level (Figure 9B).

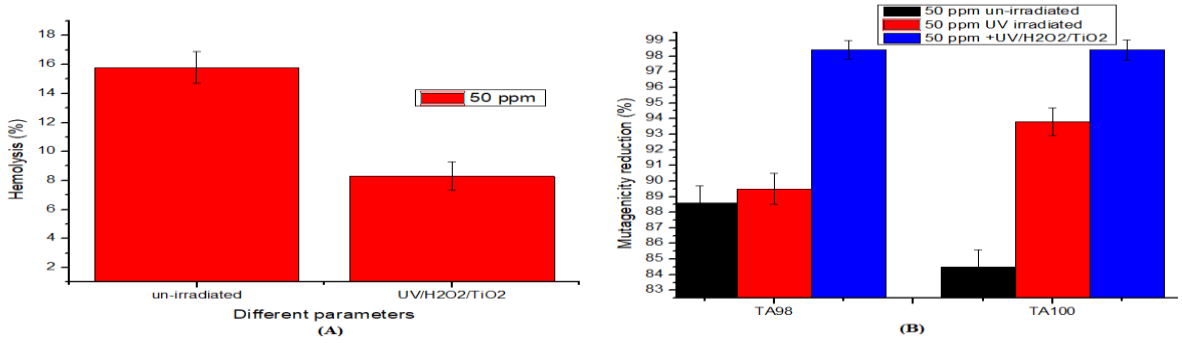

Figure 9: Toxicity profiling (A) and Mutagenicity reduction (B) of disperse dye Blue SE2R after UV radiation treatment with hydrogen peroxide and TiO_2

4. Conclusion

Disperse dyes are one of the most important classes of dyes and are widely used in a vast range of processes across different industries. Sixty per cent of the total dyes belong to dispersive dyes. The important characteristic of DB-SE2R is the presence of an azo bond (N=N), which is attached to two substituents. The development of new strategies and photocatalytic materials for practical environmental solutions remains a significant challenge, particularly due to the enormous energy demands associated with various remediation processes. Different advanced oxidation processes were employed for the degradation of disperse dyes, and promising efficiency was observed for the remediation of dyes. Specifically, ultraviolet radiation assisted with hydrogen peroxide and hydrogen peroxide/TiO_2 have proven to be the most effective methods for the degradation of disperse blue SE2R. The Advanced oxidation process, i.e., (UV/ H_2O_2/TiO_2), was used to get the maximum degradation of about 94% because of the photo-catalytic nature and greater stability of TiO_2. Optimum conditions for maximum degradation were 50 ppm dye concentration, 0.9 mL H_2O_2, and 0.4 g TiO_2 at pH 3. A 62% degradation was achieved after solar light irradiation, as solar light has the advantage of being a free irradiation process and exhibits non-toxic behavior towards the environment. Different toxicity tests decreased the toxic behavior of a selected sample of B-SE2R, which assured the degradation of disperse blue SE2R. A significant improvement in the analysis of water quality parameters, such as dissolved oxygen, chemical oxygen demand, and biological oxygen demand, occurred after ultraviolet irradiation in combination with H_2O_2 and TiO_2. Different techniques, such as FT-IR and LC-MS, were also employed to evaluate the degradation of disperse dye B-SE2R, and their spectra confirmed the degradation of DB-SE2R through the elimination of certain peaks in the disperse B-SE2R structure. Based on the results revealed, it is evident that advanced oxidation processes assisted by radiation efficiently degrade the disperse dye blue SE2R and could be applied for the treatment of textile wastewater containing toxic dyes.

Declarations

Ethics approval and consent to participate
Not applicable.
Ethical consideration
Not applicable.
Consent for publication
Not applicable.
Competing interests
The authors declare that they have no competing interests.
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The data used in this study are included in the article.

References

Abbas, M., Ali, A., Arshad, M., Atta, A., Mehmood, Z., Tahir, I. M., & Iqbal, M. (2018). Mutagenicity, cytotoxicity, and antioxidant activities of different parts of Ricinus communis. *Chemistry Central Journal, 12*, 1–9. [CrosRef].

Adeel, S., Usman, M., Haider, W., Saeed, M., Muneer, M., & Ali, M. (2015). Dyeing of gamma irradiated cotton using Direct Yellow 12 and Direct Yellow 27: improvement in colour strength and fastness properties. *Cellulose, 22*, 2095-2105. [CrosRef].

Agarry, S. E., & Ayobami, O. (2011). Evaluation of microbial systems for biotreatment of textile waste effluents in Nigeria: biodecolourization and biodegradation of textile dye. *Journal of Applied Sciences and Environmental Management, 15*(1). [CrosRef]

Ali, M., Mansha, A., Asim, S., Zahid, M., Usman, M., & Ali, N. (2018). DFT Study for the Spectroscopic and Structural Analysis of p-Dimethylaminoazobenzene. *Journal of Spectroscopy, 2018*(1), 9365153. [CrosRef].

Ameta, R., & Jhalora, P. (2014). Photocatalytic degradation of Azure B in aqueous solution by calcium oxide, J. *Current Chem. Pharma. Sci, 4*, 22–29.

Ashar, A., Iqbal, M., Bhatti, I. A., Ahmad, M. Z., Qureshi, K., Nisar, J., & Bukhari, I. H. (2016). Synthesis, characterization and photocatalytic activity of ZnO flower and pseudo-sphere: Nonylphenol ethoxylate degradation under UV and solar irradiation. *Journal of Alloys and Compounds, 678*, 126–136. [CrosRef].

Bibi, I., Kamal, S., Ahmed, A., Iqbal, M., Nouren, S., Jilani, K., . . . Ata, S. (2017). Nickel nanoparticle synthesis using Camellia Sinensis as reducing and capping agent: Growth mechanism and photo-catalytic activity evaluation. *International journal of biological macromolecules, 103*, 783–790. [CrosRef].

Bibi, I., Nazar, N., Iqbal, M., Kamal, S., Nawaz, H., Nouren, S., . . . Ata, S. (2017). Green and eco-friendly synthesis of cobalt-oxide nanoparticle: characterization and photo-catalytic activity. *Advanced Powder Technology, 28*(9), 2035-2043. [CrosRef].

Bokhari, T. H., Abbas, W., Munir, M., Zuber, M., Usman, M., Iqbal, M., . . . Khan, M. K. (2015). Impact of UV/TiO2/H2O2 on Degradation of Disperse Red F3BS. *Asian Journal of Chemistry, 27*(1), 282–286. [CrosRef].

Bokhari, T. H., Ahmad, N., Jilani, M. I., Saeed, M., Usman, M., Haq, A. U., . . . Javed, T. (2020). UV/H2O2, UV/H2O2/SnO2 and Fe/H2O2 based advanced oxidation processes for the degradation of disperse violet 63 in aqueous medium. *Materials Research Express, 7*(1), 015531. [CrosRef].

Boucherit, N., Abouseoud, M., & Adour, L. (2012). Degradation of disperse dye from textile effluent by free and immobilized Cucurbita pepo peroxidase. In EPJ Web of Conferences (Vol. 29, p. 00008). EDP Sciences [CrosRef].

Buscio, V., Brosillon, S., Mendret, J., Crespi, M., & Gutiérrez-Bouzán, C. (2015). Photocatalytic membrane reactor for the removal of CI Disperse Red 73. *Materials, 8*(6), 3633-3647. [CrosRef].

Chen, T., Zheng, Y., Lin, J.-M., & Chen, G. (2008). Study on the photocatalytic degradation of methyl orange in water using Ag/ZnO as catalyst by liquid chromatography electrospray ionization ion-trap mass spectrometry. *Journal of the American Society for Mass Spectrometry, 19*(7), 997-1003. [CrosRef]

Ferraz, E., Oliveira, G., Grando, M. D., Lizier, T., Zanoni, M. V. B., & Oliveira, D. P. d. (2013). Photoelectrocatalysis based on Ti/TiO2 nanotubes removes toxic properties of the azo dyes Disperse Red 1, Disperse Red 13 and Disperse Orange 1 from aqueous chloride samples. *Journal of environmental management, 124*, 108–114. [CrosRef].

Gupta, V., Khamparia, S., Tyagi, I., Jaspal, D., & Malviya, A. (2015). Decolorization of mixture of dyes: a critical review. *Global Journal of Environmental Science and Management, 1*(1), 71–94. [CrosRef].

Hamed, H. H., Alabdraba, W. M. S., & Mohammed, A. E. (2018a). Degradation of disperse blue 79 dye in aqueous solution using Fenton (H2O2/Fe2+) process. *Sci. Int, 30*, 605-611.

Hamed, H. H., Alabdraba, W. M. S., & Mohammed, A. E. (2018b). Degradation of Disperse Blue 79 Dye in Aqueous solution using Fenton (H 2 O 2/Fe 2+) Process. *Sci. Int, 30*, 605–611.

Hassaan, M. A., & El Nemr, A. (2017). Advanced oxidation processes for textile wastewater treatment. *International Journal of Photochemistry and Photobiology, 2*(3), 85-93. [CrosRef].

Huang, M., Zhao, K., Zhang, M., Chen, S., Xu, W., Ye, Y., . . . Sun, F. (2011). Removal of disperse dyes from wastewater by nano-iron modified goldmine waste-solid assisted AOPs. *Procedia Engineering, 18*, 358-362. [CrosRef].

Iqbal, M., Abbas, M., Arshad, M., Hussain, T., Ullah Khan, A., Masood, N., . . . Ahmad Khera, R. (2015). Short Communication Gamma Radiation Treatment for Reducing Cytotoxicity and Mutagenicity in Industrial Wastewater. *Polish Journal of Environmental Studies, 24*(6). [CrosRef].

Iqbal, M., & Bhatti, I. A. (2015). Gamma radiation/H2O2 treatment of a nonylphenol ethoxylates: degradation, cytotoxicity, and mutagenicity evaluation. *Journal of hazardous materials, 299*, 351–360. [CrosRef].

Iqbal, M., & Nisar, J. (2015). Cytotoxicity and mutagenicity evaluation of gamma radiation and hydrogen peroxide treated textile effluents using bioassays. *Journal of Environmental Chemical Engineering, 3*(3), 1912-1917. [CrosRef].

Jaime-Acuña, O. E., Villavicencio, H., Petranovskii, V., & Raymond-Herrera, O. (2016). Disperse orange 30 dye degradation by assisted plasmonic photocatalysis using Ag-CdZnSO/zeolitic matrix nanocomposites. *Catalysis Communications, 75*, 103-107. [CrosRef].

Jamil, A., Bokhari, T. H., Iqbal, M., Zuber, M., & Bukhari, I. H. (2020). ZnO/UV/H2O2 based advanced oxidation of disperse red dye. *Zeitschrift für Physikalische Chemie, 234*(1), 129-143. [CrosRef].

Jamil, A., Bokhari, T. H., Javed, T., Mustafa, R., Sajid, M., Noreen, S., . . . Jilani, M. I. (2020). Photocatalytic degradation of disperse dye Violet-26 using TiO2 and ZnO nanomaterials and process variable optimization. *Journal of Materials Research and Technology, 9*(1), 1119–1128. [CrosRef].

Kalra, S. S., Mohan, S., Sinha, A., & Singh, G. (2011, February). Advanced oxidation processes for treatment of textile and dye wastewater: a review. In 2nd International conference on environmental science and development (Vol. 4, pp. 271–5). IACSIT Press Singapore.

Keshmirizadeh, E., & Farajikhajehghiasi, M. (2014). Decolorization and degradation of basic blue 3 and disperse blue 56 dyes using Fenton process. *Journal of Applied Chemical Research, 8*(3), 81–90.

Khalaf, R. M., Kariem, N. O., & Khudhair, A. A. (2018). *Removal of Textile Dye from Aqueous Media Using an Advanced Oxidation Process with UV/H2O2.* Paper presented at the IOP Conference Series: Materials Science and Engineering. [CrosRef].

Khamparia, S., Gupta, V., Tyagi, I., Malviya, A., & Jaspal, D. (2015). Decolorization of mixture of dyes: A critical review. *Global Journal of Environmental Science and Management, 1*(1). [CrosRef]

Mehmood, Y., Shahid, H., Barkat, K., Arshad, N., Rasul, A., Uddin, M. N., & Kazi, M. (2023). Novel hydrolytic degradable crosslinked interpenetrating polymeric networks (IPNs): an efficient hybrid system to manage the controlled release and degradation of misoprostol. *Gels, 9*(9), 697. [CrosRef].

Mehmood, Y., Shahid, H., ul Huq, U. I., Rafeeq, H., Khalid, H. M. B., Uddin, M. N., & Kazi, M. (2023). Microsponge-based gel loaded with immunosuppressant as a simple and valuable strategy for psoriasis therapy: determination of pro-inflammatory response through cytokine IL-2 mRNA expression. *Gels, 9*(11), 871. [CrosRef].

Mohan, P. (2016). Study of fenton oxidation process on dyeing wastewater and improving its catalysis. *J. Sci. Eng. Res, 7*(4), 116-123.

Neamtu, M., Yediler, A., Siminiceanu, I., Macoveanu, M., & Kettrup, A. (2004). Decolorization of disperse red 354 azo dye in water by several oxidation processes—a comparative study. *Dyes and Pigments, 60*(1), 61-68. [CrosRef].

Nikazara, M., Gholivand, K., & Mahanpoor, K. (2007). Using TiO 2 supported on clinoptilolite as a catalyst for photocatalytic degradation of azo dye disperse yellow 23 in water. *Kinetics and Catalysis, 48*, 214–220. [CrosRef].

Parab, R. H., Patel, K. D., Desai, D. J., & Dixit, B. C. (2016). Synthesis and dyeing performance of bisazo disperse dyes based on 3-[4-(4-amino-2-chlorophenoxy) anilino] phenol. *Journal of Saudi Chemical Society, 20*(5), 523–529.

Qiu, M., Shou, J., Ren, P., & Jiang, K. (2014). A comparative study of the azo dye reactive black 5 degradation by UV/TiO2 and photo-fenton processes. *Journal of Chemical and Pharmaceutical Research, 6*(7), 2046-2051.

Rashid, S., Ali, M., Islam, S., Iqbal, M. O., Al-Rawi, M. B. A., & Naseem, M. (2025). Enhancing the antibacterial properties of silver particles coated cotton bandages followed by natural extracted dye. *Journal of Industrial Textiles, 55*, 15280837251320571.

Rohilla, S., Salar, R., Kumar, J., & Bansal, P. (2012). Evaluation of different Aspergillus species for degradation of a reactive dye, Orange M2R. *Annals of Biological Research, 3*(9), 4491–4496.

Saratale, R. G., Saratale, G. D., Chang, J.-S., & Govindwar, S. P. (2011). Bacterial decolorization and degradation of azo dyes: a review. *Journal of the Taiwan Institute of Chemical Engineers, 42*(1), 138–157. [CrosRef].

Sima, J., & Hasal, P. (2013). Photocatalytic degradation of textile dyes in a TiO 2/UV system. *Chemical Engineering Transactions, 32*, 79-84. [CrosRef].

Suriyaprabha, R., & Fulekar, M. (2018). Study on the physico-chemical parameters of dye industry effluents from industrial estate Vatva, Ahmedabad, Gujarat. *Development, 5*(03), 1706-1710. [Ref].

Volmajer Valh, J., Majcen Le Marechal, A., Križanec, B., & Vajnhandl, S. (2012). The applicability of an advanced oxidation process for textile finishing waste streams & fate of persistent organic pollutants. *International Journal of Environmental Research, 6*(4), 863-874.