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Synergistic sonochemical degradation of methyl orange using chemical additives with ZnO nanoparticles

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To clarify the decomposition mechanism, a study was conducted on the degradation of dye molecules in an aqueous medium in the presence of various additives under the influence of ultrasonic radiation. In this investigation, Methyl Orange (MO) was used as a representative of azo dye and inorganic salts like NaCl and Na_2SO_4 were used as additives, 10 mg of each per liter of CCl_4 solution and 20 mg per liter of H_2O_2 solution, respectively. The volume of all solutions was 100 mL and contained 25 mg/L of MO. The sonication of dye molecules was conducted for 0, 5, 15, and 25 minutes. From the experiments, it is clear that an acidic environment is favorable for the decomposition of the dye. When evaluating the results, we also found that all the additives contributed to the decomposition to a relatively greater or lesser extent depending on their amount used in the solution. The incorporation of ZnO nanoparticles enhances the degradation rate. The degradation mechanism was examined in detail using UV-visible spectroscopy. In conclusion, this clearly demonstrates the feasibility of effective removal of azo dyes from wastewater using sonochemical irradiation under acidic conditions.

Keywords: azo dye; methyl orange; sonochemical irradiation; additives; decomposition rate

Синергетичне сонохімічне розкладання метилоранжу за допомогою хімічних добавок з наночастинками ZnO. Jahangir Hossain, M. Shahinuzzaman*, Md. Shaharul Islam*, Md. Samiul Bari Avick, Shirajum Monira, S.M. Abdur Razzaque, Md. Helal Uddin*

Для уточнення механізму розкладання було досліджено деградацію молекул барвника у водних середовищах за наявності різних добавок за допомогою ультразвукового опромінення. У цьому дослідженні метилоранж (МО) використовувався як представник азобарвника, а неорганічні солі, такі як NaCl та Na_2SO_4, використовувалися як добавки, де 10 мг обох брали на літр розчинів CCl_4 та 20 мг для розчинів H_2O_2 відповідно. Об'єм усіх розчинів становив 100 мл, що містив 25 мг/л МО. Ультразвукову обробку молекул барвника проводили протягом 0, 5, 15 та 25 хвилин. З експериментів видно, що кислі умови сприяють

розкладанню барвника. Оцінюючи результати, ми також виявили, що всі добавки сприяли розкладанню порівняно більшою або меншою мірою залежно від їх кількості в розчині. Включення наночастинок ZnO підвищує швидкість розкладу. Механізм розкладання був детально вивчений з використанням УФ-видимих спектрів. Зрештою, це чітко свідчить про те, що азобарвники зі стічних вод можна ефективно видалити за допомогою сонохімічного опромінення в кислих умовах.

1. Introduction

Natural water serves as the home to a wide variety of biological organisms that are closely related to non-biological organisms. Pollution has a negative effect on natural water, modifies its quality, and frequently causes the extinction of aquatic species. Human health depends on biotic life that provides water and nutrients, and is enhanced by an unpolluted environment that supports aquatic life. Depending on their sources, water pollutants are divided into three categories: physical, chemical, and biological. All forms of pollution introduced foreign substances such organic molecules, which when oxidized or reduced, reduce the amount of oxygen in water [1, 2].

Dyes are a component having a significant capacity for coloring and are used extensively in the food, textile, cosmetic, paper, photography, and plastics industries. The transparency and aesthetic appeal of bodies of water, including rivers and lakes, are significantly reduced by the presence of extremely small amounts of dyes (1 mg/l for several dyes), which are still very noticeable [3]. This harms the aquatic ecology. Unfortunately, azo dyes in particular have been discovered to be poisonous and mutagenic and are now prohibited globally. But azo dyes are still used and produced due to their availability and other desirable properties. A very unique problem is the decomposition and elimination of azo dyes from wastewater [1, 4]. The dyes are capable of adhering to suitable surfaces by physical adsorption, mechanical retention, covalent bonds formed with salts or metals in solution, or by development using these substances [1, 2]. Removing dyes from these chemicals is one of the most challenging tasks facing textile wastewater treatment plants.

The waste water must therefore be treated to remove these dangerous dye particles. The methods used for dye detoxification are based on chemical or physical principles, such as membrane filtration [5, 6], electrochemical technology [7, 8], and advance oxidation processes (AOPs), including photochemical oxidation [9], photocatalysis [10, 11], and ultrasonic waves [12, 13]. The oxidation processes known as AOPs are those that frequently produce enough hydroxyl radicals to have an impact on water treatment. This technique links the chemical processes occurring in a single bubble with the chemical processes occurring throughout the entire sonochemical reactor (solution) [14]. AOPs work by producing and using reactive oxygen species (ROS), namely HO*, O_2*-, and H_2O_2, to break down organic pollutants. Photochemical, electrochemical, and sonochemical AOPs all produce ROS [15, 16]. Carbon dioxide, short-chain organic acids, and inorganic ions are the final products of degradation reactions; these are frequently less dangerous and more favorable to biodegradation. Oxidative reactions can lead to full mineralization. Since excited hydroxyl radicals are more powerful oxidants than molecular O_3 or H_2O_2, the AOPs frequently produce them by combining catalysts (TiO_2), oxidizing agents (O_3), and irradiation (UV, ultrasound) [14, 15, 17-24].

Sonochemical deterioration provides major advantages over other methods of dealing with organic contaminants, including cleanliness, safety, and energy saving without generating secondary contamination [25, 26]. As a pioneering technology, ultrasound can be used to eliminate contaminants from water and wastewater. This technique of oxidation is more sophisticated. Through a variety of chemical and physical changes throughout the cavitation route, the use of this technology results in the degradation of numerous complex organic substances into much simpler compounds [17]. Ultrasound is a flexible method that can effectively remove a number of contaminants from a range of water samples [18].

This study presents the results of studying the effect of ultrasonic waves on organic pollutants during their purification, as well as the decomposition characteristics of the azo dye methyl orange (MO) with various additives under different conditions, such as acidic and alkaline environments.

2. Methodology

2.1 Chemicals

The following chemicals were used in this study: Methyl orange ($C_{14}H_{14}N_3NaO_3S$), Merck

Figure 1. Synthesis of ZnO nanoparticle

Life Science, Vadhroli East, Mumbai-400079, India; Sodium Chloride (NaCl), RANBAXY Fine Chemicals Limited A-3, New Delhi-l10020, India; Sodium Sulphate (Na_2SO_4), Merck Specialties Private Limited, Mumbai-400018, India; Hydrogen Peroxide (H_2O_2), Merck KGaA, 64271 Darmstadt, Germany; and Carbon Tetrachloride (CCI_4), Merck, D-6100 Darmstadt, Germany. None of the compounds were further purified before usage. An ultrasonic sonicator (YZ5120-1, China) with 40 kHz and the power density of 30 W/L at a temperature of 24.7-27.1°C was used for the experiment. A UV-visible spectrophotometer (Shimadzu UV-1900I) was used for the measurement of the concentration from absorbance.

2.2 Synthesis of Zinc Oxide Nanoparticles

A sol-gel process was used to produce nanoparticles of zinc oxide. At first, 2.28 g of $Zn(NO_3)_2$ were dissolved in 75 mL of demineralized water to create a $Zn(NO_3)_2$ solution. Then, 0.6 g of KOH was dissolved in 150 mL of demineralized water to prepare a KOH solution. Under vigorous stirring, the KOH solution was gradually incorporated into the $Zn(NO_3)_2$ solution. This solution then stirred for 2 hours and a white precipitate was formed (Figure 1). The solution was then centrifuged for 15 min. It was then filtered.

During filtration, the precipitate was cleaned 3 times by ethanol to remove the impurities. Finally, it was washed by demineralized water. Then it was dried for 30 minutes at 62 °C in an oven. After drying, it was cooled to room temperature. Then it was calcined in a furnace for 2 hours at 260 °C. It was then cooled to room temperature and stored for further use.

2.3 Preparation of Solutions

Solutions of MO with a concentration of 25 mg/l were prepared. In order to prepare the solutions of inorganic salts such as NaCl and Na_2SO_4 in 100 mL of distilled water, their maximum saturation points were taken into account, equal to 36 g and 13.9 g of each of them, respectively. H_2O_2 solutions of 10 and 20 mg/L have been prepared by adding 1.02 mL and 2.04 mL of H_2O_2 in 1.0 L distilled water. Typically, the concentration of dyes in wastewater ranges from 10 to 50 mg/L, however at a concentration of 1.0 mg/L, the dyes become visible and can be considered as pollutants and cause unwanted reactions [27, 28].

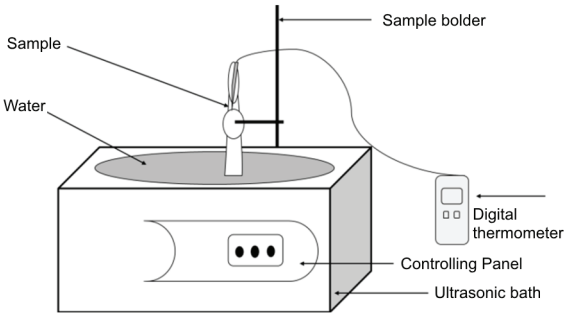

Figure 2. Experimental setup of Sonochemical degradation process

2.4 Calorimetric power measurement during irradiation

The study used a quantitative assessment method using ultrasonic response field. Figure 2 depicts the experimental configuration for the sonochemical degradation process. Sonochemistry depends on a number of key elements, one of which is ultrasonic power. One of the widely used techniques for determining the real ultrasonic power delivered to a solution is calorimetry [29, 30].

The ultrasonic output power (P) is calculated by using the following equation:

$$P = M\, C_p\, dT/dt\,, \qquad (1)$$

where T is the temperature of the sample solution, M is the mass of water, C_p means the heat capacity of water, and t is the irradiation time.

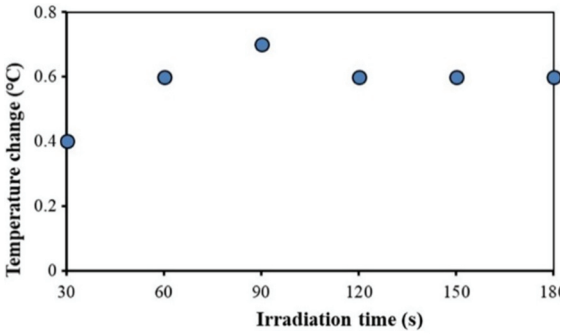

Figure 3. Graphical representation of temperature changes with sonication time

Figure 3 show that the temperature at the reaction site rises as the sonication time increases. Furthermore, as the temperature rises, the reaction rate does as well. Therefore, as the sonication period is increased, the rate of dye molecule degradation will also increase.

3. Results and discussion

3.1 Sonochemical Degradation of MO under various pH

Based on the first-order kinetics model function, exponential curves are depicted in the figure as solid curves.

$$x = ae^{-kt} \quad (2)$$

where the constant 'a' is the initial concentration of MO, 25mg/L, k is a fitting parameter to be optimized and t is the degradation time. Below, the MO decomposition rates in the absence of additives using sonochemical irradiation under different conditions are presented and discussed. The pH level of the solution was maintained using NaOH and H_2SO_4 solutions.

Figure 4 demonstrate that the rate of MO decomposition in an acidic environment with pH 3 is higher than in a neutral environment (pH 7) and an alkaline environment (pH 8). When using additives that maintain an acidic environment during sonochemical degradation, there is a high probability of increasing the rate of MO decomposition.

3.2 Effect of Inorganic Salts

NaCl and Na_2SO_4 were added in amounts of 10 mL (Figure 5a) and 20 mL (Figure 5b) each to the solution of MO to determine how the addition of inorganic salts affects dye degradation. The figure shows that the addition of both salts accelerated MO decomposition. Previous studies have shown that, in various synthetic dye solutions with different mixtures of Na_2SO_4 and NaCl,

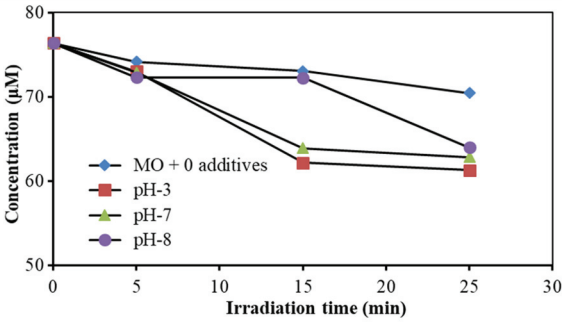

Figure 4. Time dependence of sonochemical degradation of MO in various pH without additives

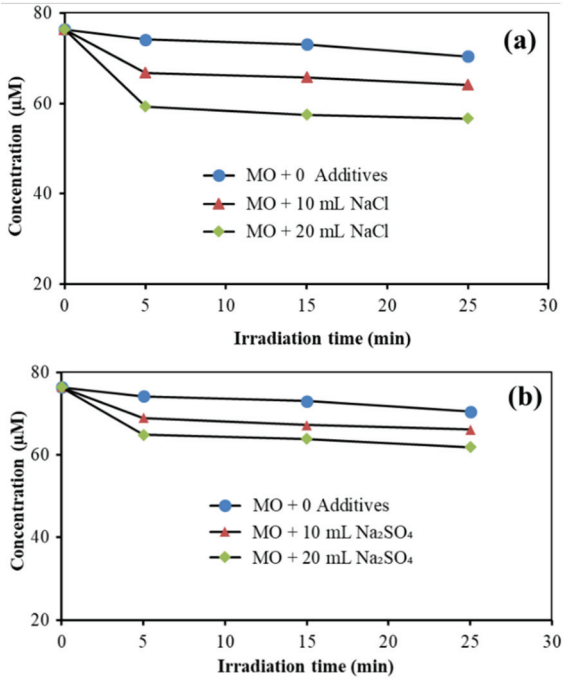

Figure 5. Sonochemical degradation of MO; (a) presence and absence of 10 mL and 20 mL additives

Na_2SO_4 had a somewhat greater influence on the decolourization efficiency than NaCl. High Na_2SO_4 concentration did not impede the decolorization process in dye solutions with the same salt or Na+ concentrations, and it substantially increased the effectiveness of reactive brilliant red K-2BP decolorization [2]. The deterioration rate was also accelerated by the higher salt concentration. Analyzing the results, it can be said that NaCl is superior to Na_2SO_4 in terms of its ability to degrade MO. Uddin et al. (2016) reported on the sonochemical degradation of 4-chlorophenol, phenol, catechol, and resorcinol in the presence and absence of Na_2SO_4 or NaCl and published data for anaerobic Ar environment [31]. The

Table 1. Structural characteristics of the obtained ZnO nanoparticles

Synthesized NPs	Peak position, (101) (2θ°)	Peak height, (a.u.)	Crystallite size, (nm)	Microstrain, ε ($\times 10^{-3}$)	Dislocation density, δ ($\times 10^{10}$ cm^{-2})
Pure ZnO	36.24	21093.83	48.62	2.266	4.23

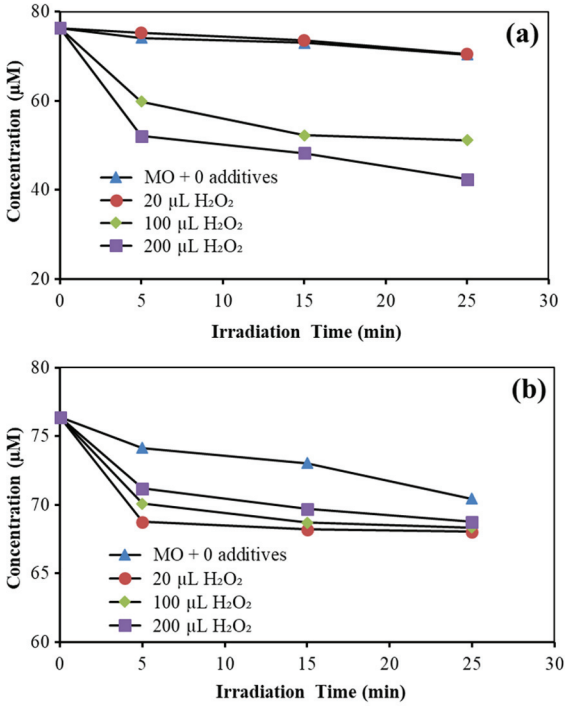

Figure 6. Dependence of time on sonochemical degradation of MO; (a) Without and with different concentration of (10 mg/L) H_2O_2, (b) Without and with different concentration of (20 mg/L) H_2O_2

rate of phenolic compound decomposition obeyed a pseudo-first-order rate constant [1].

3.3 Effect of H_2O_2

From Figure 6(a), it is evident that for 10 mg/L H_2O_2 solution, the decomposition rate increases with the rise of the amount of H_2O_2. Small amount (20 μL) almost shows the similar result as the pure solution but it is clear from the data that the larger amount (100 μL, 200 μL) increased the rate of deterioration in comparison to pure MO. Figure 6(b) demonstrate the graphical representation of the degradation of MO in presence of 20 mg/L H_2O_2 solution. It is noticeable here that Fig. 6(b) shows the exact opposite picture compared to Fig. 6(a). The lowest amount (20 μL) of 20 mg/L H_2O_2 solution added to the MO solution shows the highest degradation rate as compared with the increased amount (100 μL, 200 μL) of that H_2O_2 solution. The formation of free radicals as active species has been used to explain the H_2O_2 reaction process for dye discolouration.

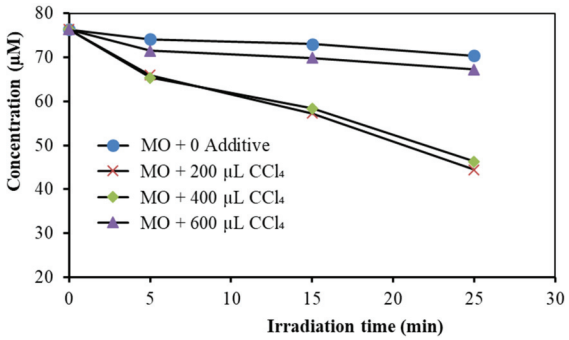

Figure 7. Sonochemical degradation of MO in the presence and absence of CCl_4

$$H_2O_2 \rightarrow \cdot OH + \cdot OH \quad (3)$$

Studies had showed that malachite green was degraded most efficiently using the US/UV/H_2O_2 method, since the scission of H_2O_2 is facilitated by the use of ultrasound in addition to photolysis [3]. A recent experiment demonstrated the effect of adding hydrogen peroxide by varying its concentration to 0.05, 0.10, and 0.15 M. Treatment with 0.10 M H_2O_2 at 45 W was successful and energetically feasible, resulting in a removal of 62.9% of the adsorbent from the actual water tested [32]. When compared to earlier studies, it is evident that a variety of applications for hydrogen peroxide (H_2O_2) have been developed because of its relative safety and ease of use in the water treatment field.

3.4 Effect of CCl_4

Figure 7 represents the time dependence of irradiation of MO with different concentrations of CCl_4. From the figure it is seen that as the irradiation time and doses of CCl_4 increase, the rate of degradation also does. The rate is also considerably improved in the presence of 200 μL or 400 μL CCl_4, but at concentrations above 600 μL a sharp decrease in the decomposition rate is observed. During the experiment, CCl_4 was added directly to the solution.

This enhancement is due to the pyrolytic decomposition of CCl_4, which releases oxidants that can interact with molecules of dye. The complete reaction process is represented by the equations (4 - 11).

$$CCl_4 \rightarrow \cdot CCl_3 + \cdot Cl \quad (4)$$

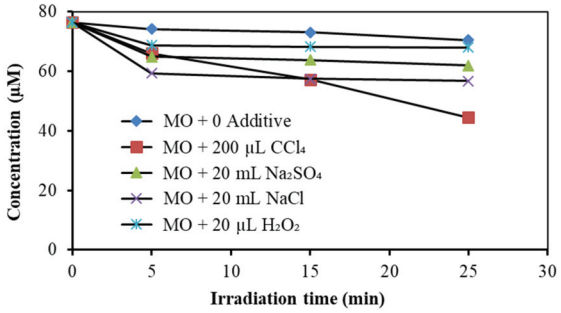

Figure 8. Comparison of dependence of time on sonochemical degradation of MO without and with CCl_4, Na_2SO_4, NaCl and H_2O_2

$$CCl_4 \rightarrow \cdot CCl_2 + Cl_2 \quad (5)$$

$$\cdot CCl_3 \rightarrow \cdot CCl_2 + \cdot Cl \quad (6)$$

$$\cdot CCl_3 + \cdot CCl_3 \rightarrow CCl_4 + \cdot CCl_2 \quad (7)$$

$$\cdot CCl_3 + \cdot CCl_3 \rightarrow C_2Cl_6 \quad (8)$$

$$\cdot CCl_2 + \cdot CCl_2 \rightarrow C_2Cl_4 \quad (9)$$

$$\cdot Cl + \cdot Cl \rightarrow Cl_2 \quad (10)$$

$$Cl_2 + H_2O \rightarrow HClO + HCl \quad (11)$$

A series of recombination reactions caused by the decomposition of CCl_4 generates $\cdot Cl$ radical which produces extra strong oxidizing species such as HClO, Cl_2, and other radicals containing chlorine like Cl, CCl_2, and CCl_3. These radicals significantly accelerate the degradation of MO in aqueous solution.

Recently, similar reactions have shown that the main factors causing the rapid degradation of safranin O(SO) are the levels of reactive chloride species (RCS) formed by the action of CCl_4 in heated bubbles [33]. The production of RCS: CCl_3, CCl_2, Cl, and HOCl as well as an increase in the yield of OH radicals when sonication is carried out with CCl_4 have been shown to promote the sonolytic decomposition of nonvolatile pollutants [34, 35]. The sonochemical degradation of MO in the presence and absence of CCl_4 is shown in Figure 7, and the sonochemical decomposition of MO in the presence and absence of various additives is shown in Figure 8.

3.5 Effect of ZnO nanoparticles

Figure 9 compares the degradation of methyl orange after sonication in all three exceptional cases. The initial concentration was the same in all three samples. In the initial solution, the degradation rate after 5 minutes was significantly higher than in the acidified solution.

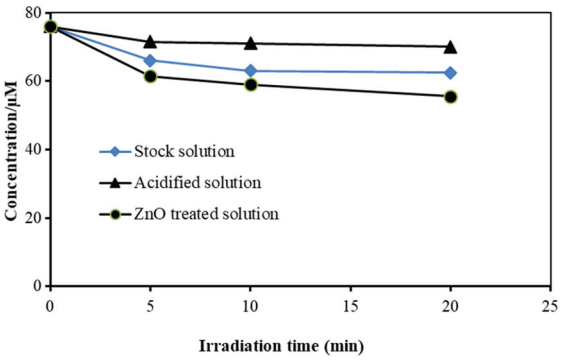

Figure 9. Degradation of methyl orange using neutral, acidified and ZnO treated solution

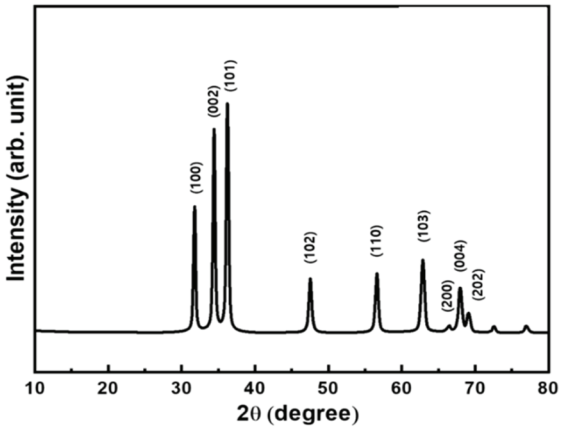

Figure 10. XRD Spectrum of synthesized ZnO Nanoparticles

However, it was lower than in the ZnO-treated solution. The addition of ZnO caused more degradation, which was recorded in the table even before the onset of degradation at time 0 min. This rate rises with the increase in sonication time. After 10 minutes, the degradation rate of the acidified solution was much lower than that of the original solution and the ZnO-treated solution. The concentration was much higher in the acidified solution after 10 minutes of degradation.

No significant changes in concentration were found in the case of the acidified solution. The original solution showed a higher decomposition rate compared to the acidified solution. But the zinc oxide-treated solution showed a good result. The incorporation of ZnO particles in the solution enhances the degradation rate as shown by earlier studies by Islam et al. [36]. It showed a good degradation rate in all four periods. After 20 minutes of degradation, it showed a promising result. It can be said that the ZnO nanoparticles enhance the degradation rate. Thus, we can use ZnO nanoparticles

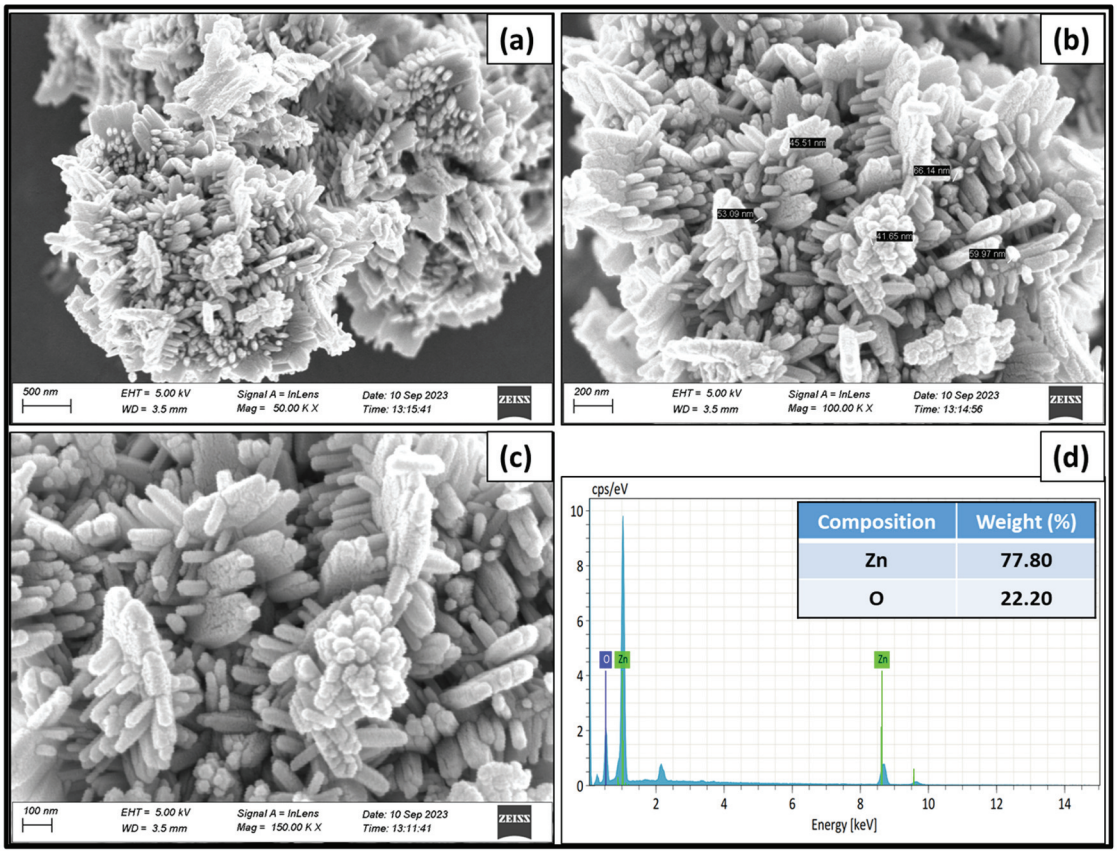

Figure 11. FESEM-EDX analysis of synthesized ZnO nanoparticle

for the treatment of MO since they are nontoxic and inexpensive.

3.6 Characterization of synthesized ZnO NPs

Structural analysis and phase identification of the obtained ZnO nanoparticles were carried out using X-ray diffraction (XRD). Figure 10 shows the XRD spectrum of ZnO nanoparticles.

The XRD pattern reveals several distinct diffraction peaks at 2θ angles, corresponding to various crystallographic planes of the ZnO. The observed diffraction peaks are mainly at 31.76°, 34.38°, 36.22°, 47.54°, 56.64°, 62.92°, 66.55°, 67.98° and 69.06°. These peaks can be assigned to the (100), (002), (101), (102), (110), (103), (200), (004), and (202) planes, corresponding to the hexagonal crystal structure of wurtzite ZnO (JCPDS No. 36-1451). This observation confirms the formation of pure ZnO nanoparticles, as no others peaks corresponding to impurities or secondary phases were identified.

Using the Scherrer equation, the crystalline size (D) of the ZnO nanoparticles was calculated:

$$D = k\lambda/\beta\cos\theta, \qquad (12)$$

where D is the crystallite size, k represents the Scherrer constant (0.94 for this setup), λ is the wavelength of X-ray radiation (Cu Kα, 1.5418 Å), ß is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg angle.

The FWHM values were obtained from the XRD peaks, and the corresponding crystallite sizes were calculated. The average crystallite size was determined to be around 48.62 nm (Table 1), indicating the nanometer range of ZnO nanoparticles.

The morphology of the samples was examined by scanning electron microscopy (SEM). To prevent charging, samples coated with platinum using magnetron sputtering were used. The micrographs were taken at a magnification of 50,100,150. The SEM images of ZnO catalyst at different magnification are shown in Figure 11. It was found that the obtained catalyst had particles of various shapes and sizes in the range from 42 to 66 nm. The chemical composition was also determined using EDX analysis. The mass percent of Zn (zinc) and O (oxygen) in the fresh catalyst was found to be 77.80% and 22.20%, respectively. The agglom-

eration of nanoparticles occurred due to the physical forces of attraction between them.

3. Conclusion

The purpose of the current study was to determine the impact of ultrasound on the decomposition of MO under different operating conditions, namely, when changing the pH of the solution, in the presence of inorganic salts such as NaCl, Na_2SO_4, CCl_4 and H_2O_2 solutions. It was found that each of the additives significantly increases the decomposition rate of the mentioned azo dyes than pure solution. Low pH presumes to be more favorable for higher degradation of MO. For NaCl and Na_2SO_4, it is evident that the addition of both salts accelerated MO degradation but NaCl seems to be more effective than Na_2SO_4. In the presence of H_2O_2 solution, the rate of degradation is higher at a dose of 10 mg/L compared to a dose of 20 mg/L. The rate of decomposition significantly increased in the presence of 200µL and 400µL CCl_4. It is observed from the project that the concentration of methyl orange decreases with the increase of sonication time. The incorporation of ZnO nanoparticles also enhances the degradation rate, and ZnO can be used for the degradation of MO due to low cost and nontoxicity.

Acknowledgement

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Conflict of interest

There is no conflict of interest of Authors to declare.

References

1. Bafana, A.; Devi, S. S.; Chakrabarti, T. Azo dyes: past, present and the future. *Environmental Reviews* 2011, *19* (NA), 350-371.
2. Zollinger, H. Synthesis, properties of organic dyes and pigments, Color Chemistry. VCH Publishers, New York, USA: 1987.
3. Banat, I. M.; Nigam, P.; Singh, D.; Marchant, R. Microbial decolorization of textile-dyecontaining effluents: a review. *Bioresource technology* 1996, *58* (3), 217-227.
4. Yarce-Castaño, J.; Serrano-Arguello, G.; Chavarría-Chavarría, F.M.; Granda-Ramírez, F.; Hincapié-Mejía, G. Study of the effect of radiation intensity and H_2O_2 concentration in the treatment of effluent from the textile industry with UV/H_2O_2. *Ingeniería y competitividad* 2022, *24* (1).
5. Lee, J.-W.; Choi, S.-P.; Thiruvenkatachari, R.; Shim, W.-G.; Moon, H. Submerged microfiltration membrane coupled with alum coagulation/powdered activated carbon adsorption for complete decolorization of reactive dyes. *Water research* 2006, *40* (3), 435-444.
6. Shindhal, T.; Rakholiya, P.; Varjani, S.; Pandey, A.; Ngo, H. H.; Guo, W.; Ng, H. Y.; Taherzadeh, M. J. A critical review on advances in the practices and perspectives for the treatment of dye industry wastewater. *Bioengineered* 2021, *12* (1), 70-87.
7. Wang, B.; Kong, W.; Ma, H. Electrochemical treatment of paper mill wastewater using three-dimensional electrodes with Ti/Co/SnO_2-Sb_2O_5 anode. *Journal of hazardous materials* 2007, *146* (1-2), 295-301.
8. Li, J.; Yan, J.; Yao, G.; Zhang, Y.; Li, X.; Lai, B. Improving the degradation of atrazine in the three-dimensional (3D) electrochemical process using $CuFe_2O_4$ as both particle electrode and catalyst for persulfate activation. *Chemical Engineering Journal* 2019, *361*, 1317-1332.
9. Sánchez-Polo, M.; Rivera-Utrilla, J.; Mendez-Diaz, J.; Canonica, S.; von Gunten, U. Photooxidation of naphthalenesulfonic acids: Comparison between processes based on O3, O_3/activated carbon and UV/H_2O_2. *Chemosphere* 2007, *68* (10), 1814-1820.
10. Chin, P.; Ollis, D. F. Decolorization of organic dyes on Pilkington Activ™ photocatalytic glass. *Catalysis today* 2007, *123* (1-4), 177-188.
11. Mansouri, M.; Sadeghian, S.; Mansouri, G.; Setareshenas, N. Enhanced photocatalytic performance of UiO-66-NH_2/TiO_2 composite for dye degradation. *Environmental Science and Pollution Research* 2021, *28*, 25552-25565.
12. Chan, Y. Y.; Pang, Y. L.; Lim, S.; Lai, C. W.; Abdullah, A. Z.; Chong, W. C. Biosynthesized Fe-and Ag-doped ZnO nanoparticles using aqueous extract of Clitoria ternatea Linn for enhancement of sonocatalytic degradation of Congo red. *Environmental Science and Pollution Research* 2020, *27*, 34675-34691.
13. He, Z.; Song, S.; Zhou, H.; Ying, H.; Chen, J. CI Reactive Black 5 decolorization by combined sonolysis and ozonation. *Ultrasonics Sonochemistry* 2007, *14* (3), 298-304.
14. Dehane, A.; Merouani, S.; Hamdaoui, O.; Ashokkumar, M. An alternative technique for determining the number density of acoustic cavita-

tion bubbles in sonochemical reactors. *Ultrasonics Sonochemistry* 2022, *82*, 105872.
15. Ma, D.; Yi, H.; Lai, C.; Liu, X.; Huo, X.; An, Z.; Li, L.; Fu, Y.; Li, B.; Zhang, M. Critical review of advanced oxidation processes in organic wastewater treatment. *Chemosphere* 2021, *275*, 130104.
16. Mohod, A. V.; Momotko, M.; Shah, N. S.; Marchel, M.; Imran, M.; Kong, L.; Boczkaj, G. Degradation of Rhodamine dyes by Advanced Oxidation Processes (AOPs)–Focus on caviatation and photocatalysis-A critical review. *Water Resources and Industry* 2023, 100220.
17. Mahvi, A. Application of ultrasonic technology for water and wastewater treatment. *Iranian Journal of Public Health* 2009, *38* (2), 1-17.
18. Ikehata, K.; Li, Y. Advanced Oxidation Processes for Waste Water Treatment. In *Emerging Green Chemical Technology*, Academic Press, 2018; p 116.
19. Adeyinka, J. S.; Rim-Rukeh, A. Effect of hydrogen peroxide on industrial waste water effluents: a case study of Warri refining and petrochemical industry. *Environmental Monitoring and Assessment* 1999, *59*, 249-256.
20. Kasprzyk-Hordern, B.; Ziółek, M.; Nawrocki, J. Catalytic ozonation and methods of enhancing molecular ozone reactions in water treatment. *Applied Catalysis B: Environmental* 2003, *46* (4), 639-669.
21. Neyens, E.; Baeyens, J. A review of classic Fenton's peroxidation as an advanced oxidation technique. *Journal of Hazardous materials* 2003, *98* (1-3), 33-50.
22. Tarr, M. A. *Chemical degradation methods for wastes and pollutants: environmental and industrial applications*; CRC press, 2003.
23. Bolton, J. Ultraviolet Applications Handbook; Boltons Photoscience Inc. *Ayr, ON, Canada* 1999.
24. Ollis, D. F.; Pelizzetti, E.; Serpone, N. Photocatalyzed destruction of water contaminants. *Environmental science & technology* 1991, *25* (9), 1522-1529.
25. Teo, K. C.; Xu, Y.; Yang, C. Sonochemical degradation for toxic halogenated organic compounds. *Ultrasonics sonochemistry* 2001, *8* (3), 241-246.
26. Hao, H.; Wu, M.; Chen, Y.; Yin, Y.; Lü, Z. Cavitation-induced pyrolysis of toxic chlorophenol by high-frequency ultrasonic irradiation. *Environmental Toxicology: An International Journal* 2003, *18* (6), 413-417.
27. Hamida, M.; Dehane, A.; Merouani, S.; Hamdaoui, O.; Ashokkumar, M. The role of reactive chlorine species and hydroxyl radical in the ultrafast removal of Safranin O from wastewater by CCl_4/ultrasound sono-process. *Chemical Engineering and Processing-Process Intensification* 2022, *178*, 109014.
28. Cheng, R.; Ou, S.; Li, M.; Li, Y.; Xiang, B. Ethylenediamine modified starch as biosorbent for acid dyes. *Journal of hazardous materials* 2009, *172* (2-3), 1665-1670.
29. Goel, M.; Hongqiang, H.; Mujumdar, A. S.; Ray, M. B. Sonochemical decomposition of volatile and non-volatile organic compounds—a comparative study. *Water research* 2004, *38* (19), 4247-4261.
30. Kormann, C.; Bahnemann, D. W.; Hoffmann, M. R. Photocatalytic production of H_2O_2 and organic peroxides in aqueous suspensions of TiO_2, ZnO, and desert sand. *Environmental science & technology* 1988, *22* (7), 798-806.
31. Uddin, M.H.; Nanzai, B.; Okitsu, K. Effects of Na_2SO_4 or NaCl on sonochemical degradation of phenolic compounds in an aqueous solution under Ar: Positive and negative effects induced by the presence of salts. *Ultrasonics sonochemistry* 2016, *28*, 144-149.
32. L Miah. Impact of textile dyeing effluent on environment; a study based on Bangladesh. *International Journal of Advances in Engineering and Management (IJAEM)* 2022, *4*, 1318-1324.
33. Seesuriyachan, P.; Takenaka, S.; Kuntiya, A.; Klayraung, S.; Murakami, S.; Aoki, K. Metabolism of azo dyes by Lactobacillus casei TISTR 1500 and effects of various factors on decolorization. *Water research* 2007, *41* (5), 985-992.
34. Chung, K.-T.; Cerniglia, C. E. Mutagenicity of azo dyes: structure-activity relationships. *Mutation Research/Reviews in Genetic Toxicology* 1992, *277* (3), 201-220.
35. Monira, S., Ashifuzzaman, M., Islam, M.M., Hossain, M.J., Okitsu, K., Rahman, M.H., Islam, M.S., Uddin, M.H., Effects of additives on sonolytic degradation of Azo dye molecules found in industrial wastewater. *Jurnal Kejuruteraan*. 2022, *34(1),* 41-50.
36. Islam, S., Avick, S.B., Alam, M.S., Uddin, M.H., Investigation ZnO and different additives on ultrasonic degradation of Bisphenol A. *Journal of Chemical Health Risks*, 2024, *14(4),* 867-879.