Research Paper

Photocatalytic Effect of Zinc Oxide on The Degradation of Crystal Violet Dye Waste Water under Visible Light

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Abstract
The textile industry is a major contributor to water pollution. Crystal Violet (CV) is a widely used cationic dye; however, it is toxic, difficult to degrade, and potentially carcinogenic, posing a significant threat to both aquatic ecosystems and human health. Zinc oxide (ZnO) is a semiconductor with a wide band gap, high chemical stability, and the ability to generate oxidative radicals capable of degrading complex organic compounds. This study aimed to examine the photocatalytic effect of ZnO on the photodegradation of Crystal Violet in a visible light-based reactor system. ZnO was synthesized using the sol-gel precipitation method, characterized using BET and a Particle Size Analyzer (PSA), and then tested for its photocatalytic activity. The test results showed that ZnO synthesized by a simple process has the potential to be an effective photocatalyst for sustainable textile wastewater treatment. Degradation CV using ZnO under 6 hours of visible light conditions could reach up to 70%.

Keywords: *Zinc oxide, Photocatalytic, Crystal Violet, Textile Waste Water*

INTRODUCTION

The textile industry contributes approximately 80% of total water pollution. Wastewater discharged from this industry comes from textile dyes and other additives used during the dyeing and finishing processes. Dye waste from the textile industry is often discharged directly into the environment without adequate treatment, resulting in pollution of rivers and waterways. As much as 10-15% of the textile dyes used in the dyeing process are disposed of with wastewater (Pratistita et al., 2024).

Commonly used dyes include crystal violet, malachite green, rhodamine B, Congo red, and others. Some compounds in dye waste, such as azo dyes, can decompose into mutagenic (causing gene mutations) and carcinogenic (causing cancer) compounds. This pollution damages water quality, disrupts aquatic life, and negatively impacts humans who depend on these water sources (Yang et al., 2025).

Methods for dealing with textile waste include adsorption, catalytic ozonation, osmosis, and coagulation. However, these methods only transfer pollutants from one phase to another without actually breaking them down. A more promising approach is to utilize photocatalysts composed of semiconductor materials, such as zinc oxide (ZnO) and titanium dioxide (TiO2), as well as doped semiconductor materials. Semiconductor materials can decompose dye molecules through redox transformations.

Physical, chemical, and green methods are used to synthesize ZnO particles. Common chemical routes, such as sol-gel and precipitation, involve reacting zinc precursors (such as zinc acetate) with bases (such as sodium hydroxide) to form ZnO. Precipitation is a cost-effective, scalable, repeatable, and highly controllable method that has been used to synthesize a wide variety

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of ZnO.

This study aims to analyze the photocatalytic activity of ZnO on the degradation of textile wastewater containing Crystal Violet. Crystal violet is commonly used as a textile dye, giving a purple colour. The ZnO was synthesized using the sol-gel precipitation method. The resulting ZnO was characterized using BET, and the ZnO dispersion in water was analyzed using a particle size analyzer, PSA. The photodegradation activity of the wastewater was tested under a visible light photoreactor.

LITERATURE REVIEW

Crystal violet is a triphenylmethane dye that produces a purple color. This dye is a type of cationic dye that has high stability, making fabric durable and fade-resistant. However, this high stability makes the dye difficult to degrade in aquatic ecosystems, as it can reduce the intensity of light entering the water. Therefore, wastewater produced from the dyeing process using this dye must be treated before being discharged into the environment to prevent pollution that is detrimental to the community (Supriyanto et al., 2021).

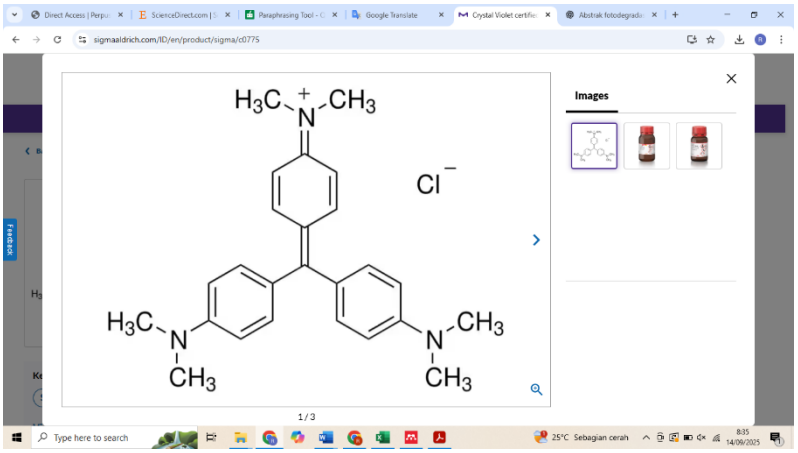

Figure 1. Chemical structure of Crystal violet (Sigma Aldrich, 2025)

Photodegradation is the process of decomposing compounds using photocatalysts, which are activated by photons to facilitate the decomposition of these compounds. Photocatalysts are materials that can increase the rate of photon-induced oxidation and reduction degradation. The basic principle of photodegradation is that when a semiconductor metal is exposed to photons, electrons jump from the valence band to the conduction band, creating electron holes that can interact with the solvent. Thus, photocatalysts can activate the catalyst and increase the rate of oxidation degradation (Diantariani et al., 2019).

The photodegradation of Crystal Violet has been investigated using various catalytic agents. Recently, photodegradation of CV using NiAg2O-infused chitosan nanocomposites has been studied by Shabnum et al. (2025). Eddy et al. (2024) investigated the photolytic and photocatalytic degradations of CV in water using oyster shell-derived CaO nanoparticles (CaO–NP).

ZnO is an efficient photocatalyst material for wastewater detoxification because it produces H2O2 more efficiently than other photocatalysts. ZnO is widely used due to its cost-effectiveness, high oxidation capacity, and wide availability. Furthermore, ZnO semiconductors have the advantage of absorbing the solar UV spectrum and light quanta more readily than TiO2 (Agustina et al., 2020).

The photocatalytic degradation of wastewater using ZnO in various forms has been investigated. Hamdan et al. (2023) used 1 g/L ZnO to treat car wash wastewater, achieving approximately 93% removal of turbidity. The photodegradation of Crystal Violet dye using p-n NiO-ZnO has been investigated by Saeed et al. (2023). The degradation could reach above 90%; however, more cost-effective and straightforward routes still need to be studied, as wastewater treatment costs should be considered.

RESEARCH METHOD

Production of ZnO

The preparation of ZnO particles was based on the research development by Reningtyas et al. (2022). A total of 0.05 M Zn(NO3)2.4H2O was degraded with 0.1 M NaOH (volume ratio 1:1). Sodium hydroxide solution was added dropwise (2mL/min) to the zinc nitrate solution under constant stirring. The solution was sonicated at room temperature. Zn(OH)2 precipitate was produced, then washed with Aquadest, and then dried at 100°C for 30 minutes to reduce the water content in the Zn(OH)2 precipitate. After that, the powder was placed in a furnace at 500°C for 3 hours to undergo the calcination process. The ZnO powder was ground using a mortar and then stored in an air-tight container.

Fotodegradation of Crystal Violet

Crystal Violet (CV) solution was prepared by dissolving 0.5 mg of CV in a 100 mL volumetric flask. ZnO in various weight (0; 0.275; 0.55; and 0.825 grams) were each dispersed in 100 mL 50 ppm CV solution. Each glass is stirred using a magnetic stirrer first for 2-3 minutes, then irradiated in a photoreactor (ML250 Watt Philips 220 230 V mfg 12/2020). The lamp and sample were around 50 cm apart. The catalyst was separated from the solution through centrifugation for each experiment. The resulting filtrate, after a specific time, will be diluted 10 times and its absorbance measured using UV-Vis spectrophotometry at the optimum wavelength. The degradation effect was analyzed for CV and CR at the 589 nm and 499 nm absorption peaks using the HALO DB-20R UV-vis double-beam spectrophotometer. The percentage of dye degradation was determined using Eq. [1]. Where C0 is the initial concentration of dyes and Ct is the concentration at a specific time.

% Degradation= C0-CtC0 …… [1]

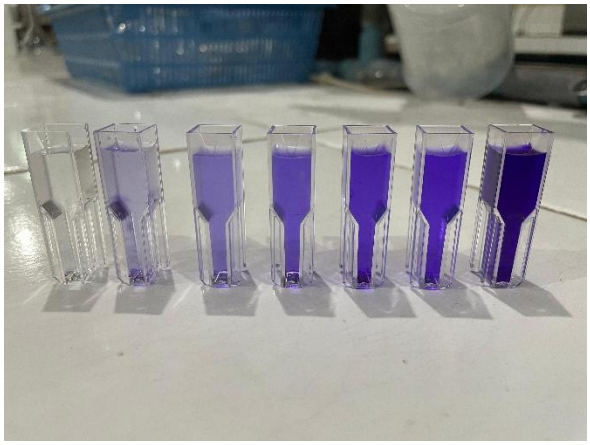

Figure 2. Crystal Violet Standard Solution (1,3,5,7,9 ppm)

FINDINGS AND DISCUSSION

Surface area of the synthesized ZnO was analyzed using the Brunauer–Emmett–Teller (BET) method (nitrogen gas at a temperature of 77 K). The surface area of ZnO is approximately 3.479

m^2/g, with a BET constant value (C constant) of around 1239 and a correlation coefficient of r = 0.9998, indicating excellent data fitting results. The synthesis conditions and sample treatment have been shown to play a significant role in determining the physical characteristics of ZnO, particularly the surface area, which is closely related to their photocatalytic activity.

The synthesized ZnO was then dispersed in the solution of dyes. The size distribution of ZnO in water was tested using a Particle Size Analyzer (PSA). As shown in Fig. 3, the ZnO particles exhibited a polydisperse size distribution with two prominent peaks. The first distribution had an average particle size of ±382.3 nm, with a mode of 376.4 nm, while the second distribution spanned a larger range of ±1431.1 nm, with a mode of 1441.9 nm.

PSA_ZnONP_2300.nsz

Measurement Results

Date	: 04 August 2025 14:49:17
Measurement Type	: Particle Size
Sample Name	: PSA_ZnONP
Scattering Angle	: 90
Temperature of the Holder	: 25.1 °C
Dispersion Medium Viscosity	: 0.893 mPa·s
Transmission Intensity before Meas.	: 30945
Distribution Form	: Standard
Distribution Form(Dispersity)	: Polydisperse
Representation of Result	: Scattering Light Intensity
Count Rate	: 35 kCPS

Calculation Results

Peak No.	S.P.Area Ratio	Mean	S. D.	Mode
1	0.25	382.3 nm	51.2 nm	376.4 nm
2	0.75	1431.1 nm	362.6 nm	1441.9 nm
3	---	--- nm	--- nm	--- nm
Total	1.00	1168.9 nm	552.7 nm	1441.9 nm

Cumulant Operations

Z-Average	: 680.6 nm
PI	: 0.853

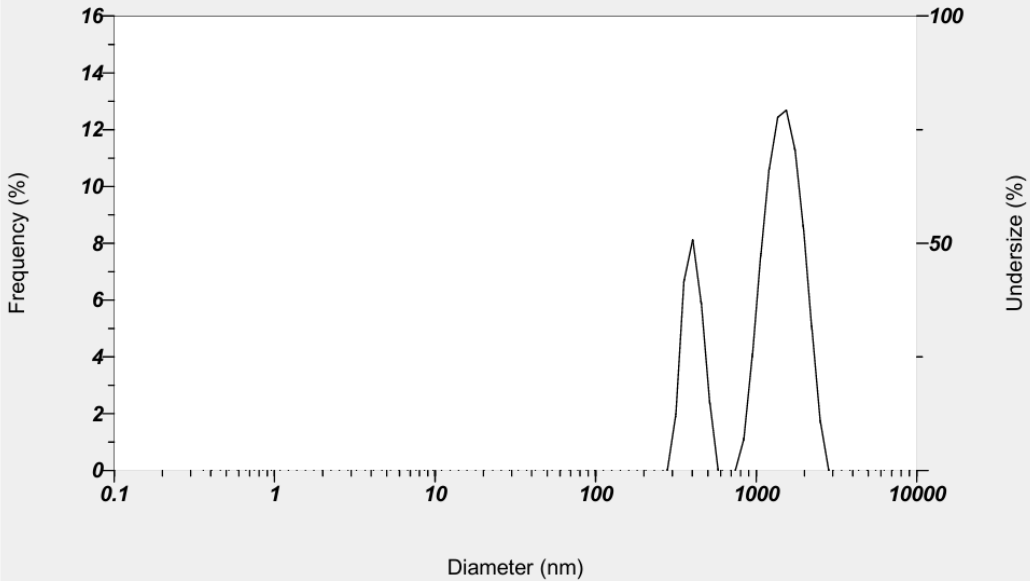

Figure 3. Size Distribution Profile of ZnO Dispersion

The particle Z-average value was 680.6 nm, with a polydispersity index (PI) of 0.853, indicating that the sample consisted of particles with quite varied sizes and a tendency to

agglomerate. This is in accordance with the general nature of ZnO, which is easy to aggregate, so that the measured particle size is larger than the size of a single crystallite. Thus, the PSA results indicate that the resulting ZnO samples were more dominant in sub-micron to micron sizes due to particle agglomeration.

The effect of ZnO at a concentration of 1 g/L was investigated in the Crystal Violet photodegradation process. The ZnO powder was dispersed in two 100 mL glassware vessels containing a 50 ppm CV solution. One of the glasses was wrapped in aluminum foil, completely covering the entire area with no gaps for light to reach. The sealed sample was placed inside the photoreactor to achieve the same operating conditions as the open sample. The sample with no ZnO addition served as the control. The dispersions were then placed under a photoreactor equipped with a 250W visible light lamp. The photodegradation process was carried out for 6 hours. The concentration of the dye solution at various times was measured using a UV Spectrophotometer. The experimental results were as follows.

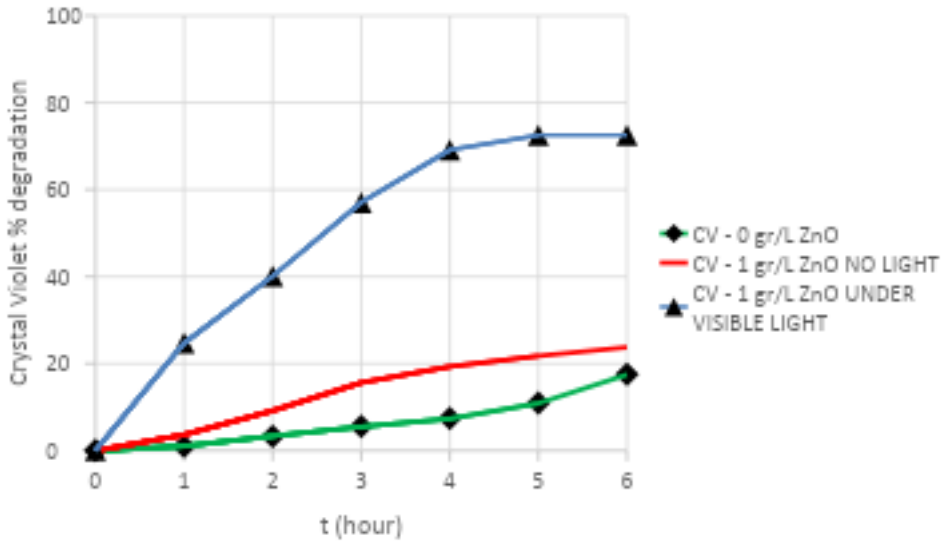

Figure 4. Degradation Crystal Violet Solution

From Figure 4, it can be seen that the degradation of the Crystal Violet solution increased with increasing contact time with ZnO, both in closed and open solution conditions. The sample without ZnO shows the slowest degradation. The degradation rate in the open condition (exposed to photoreactor light) showed a much higher percentage than the closed condition. At the 1st hour, degradation in the open system reached approximately 24.69%, while in the closed system it was only approximately 3.65%. This difference became more pronounced at the 4th hour, where the open system experienced 69.13% degradation, while the closed system reached approximately 19.30%. At the end of the experiment (6 hours), approximately 23.75% of CV degradation was achieved in the closed system. At the same time, the degradation of the open system reached a maximum value of approximately 72.53%, which is three times faster than that of the sample without light treatment. The application of 1 g/L ZnO under visible light resulted in a relatively stable CV degradation percentage after 4 hours of reaction.

The adsorption of CV on the surface of ZnO is the initial stage that allows the dye molecules to be close to the active site of the ZnO, so that when electron-holes are generated by exposure to light, oxidative radicals (•OH, $\bullet O_2^-$) can directly attack the molecules that are already bound to the surface, resulting in degradation.

In no light condition, the addition of ZnO could increase degradation. It indicates that in

addition to functioning as a photocatalytic agent, ZnO also functions as an adsorbent. Thus, it can be concluded that ZnO works in two ways: as an adsorbent that could reduce the concentration of dye through absorption on its surface, and also as a photocatalyst agent that accelerates the degradation process when it receives energy from light. The presence of ZnO and light plays a crucial role in enhancing the degradation of crystal violet.

CONCLUSIONS

This study demonstrates that the presence of ZnO and light has a significant influence on the photodegradation of Crystal Violet. The best results were obtained after 4 hours of irradiation with visible light, with a degradation efficiency exceeding 70%, confirming the potential of ZnO as an effective photocatalyst for treating textile wastewater. The degradation is also attributed to the adsorption properties of the ZnO powder. Thus, ZnO-based photocatalysis technology can be an environmentally friendly alternative that supports the achievement of a sustainable waste management system.

LIMITATIONS & FURTHER RESEARCH

Further research is necessary to characterize and understand the kinetics of ZnO degradation.

ACKNOWLEDGEMENTS

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