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Research Article

PHOTOCATALYTIC DEGRADATION OF BATIK DYE EFFLUENTS USING ZINC OXIDE (ZNO) NANORODS SYNTHESIZED VIA A GREEN CHEMISTRY APPROACH

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Abstract

The discharge of batik dye effluents into water bodies is a significant environmental concern, as it contains toxic azo dyes that are difficult to degrade. Traditional methods for dye removal, such as chemical oxidation and adsorption, often have limitations in terms of cost, efficiency, and environmental impact. This study aims to investigate the photocatalytic degradation of batik dye effluents using zinc oxide (ZnO) nanorods synthesized through a green chemistry approach. ZnO nanorods were synthesized using natural plant extracts as reducing agents, offering an environmentally friendly and cost-effective alternative to conventional methods. The photocatalytic performance of the synthesized ZnO nanorods was evaluated by exposing them to batik dye effluents under UV light. The effects of parameters such as pH, catalyst dosage, and UV exposure time were studied. The results showed that ZnO nanorods exhibited significant degradation of the dye, with optimal performance achieved at pH 5, a catalyst dosage of 0.2 g, and 120 minutes of UV exposure. The nanorods demonstrated high reusability, making them suitable for long-term application in wastewater treatment. This study highlights the potential of ZnO nanorods synthesized via green chemistry as an efficient, eco-friendly solution for treating batik dye effluents, offering a sustainable alternative to traditional wastewater treatment methods.

Keywords: Green Chemistry, Photocatalytic Degradation, Wastewater Treatment

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INTRODUCTION

The rapid industrialization of textile manufacturing has led to an increase in the discharge of dye-laden effluents, which pose serious environmental challenges. In particular, batik dye effluents, commonly associated with traditional textile industries, contain harmful organic pollutants that are difficult to degrade (Wen et al., 2025). These effluents contain a variety of azo dyes, which are synthetic colorants widely used in the batik industry. Azo dyes are known for their persistent nature and potential toxicity to aquatic life, posing significant risks to water bodies and human health (T. Wang et al., 2024). Traditional methods of wastewater treatment, including physical adsorption and chemical oxidation, are often costly and environmentally harmful, further highlighting the need for more sustainable approaches (Selvam et al., 2024).

Photocatalytic degradation, an environmentally friendly and energy-efficient technique, has gained significant attention for the treatment of industrial wastewater. Zinc oxide (ZnO) nanostructures, especially ZnO nanorods, are known to exhibit excellent photocatalytic properties under ultraviolet (UV) light (Vasantharaj et al., 2024; L. Wang et al., 2024). ZnO's wide bandgap, high surface area, and photocatalytic efficiency make it an ideal candidate for the degradation of organic pollutants, including dyes (Sazman et al., 2024). Recent advances in nanotechnology have made it possible to synthesize ZnO nanorods using green chemistry approaches, which offer a more sustainable and eco-friendly alternative to conventional synthesis methods.

The use of ZnO nanorods in photocatalytic applications has been studied extensively, but their application in the degradation of batik dye effluents remains underexplored. Traditional dye degradation methods are not only energy-intensive but also produce harmful byproducts, thus necessitating the development of more efficient, sustainable, and cost-effective methods for wastewater treatment (Thakur, Bains, Kumar, Goksen, Dhull, et al., 2024; Thakur, Bains, Kumar, Goksen, Yaqoob, et al., 2024). This study aims to address these challenges by using ZnO nanorods synthesized via a green chemistry approach for the photocatalytic degradation of batik dye effluents, presenting a novel method for dye wastewater treatment in textile industries (Jayanthi et al., 2024).

The discharge of batik dye effluents into water bodies is a growing environmental issue in many regions, particularly in developing countries where the batik industry plays a significant cultural and economic role. These effluents contain toxic compounds, including azo dyes, which are difficult to degrade using conventional treatment methods (Singh et al., 2024; Soylak et al., 2025). The persistent nature of azo dyes and their harmful effects on aquatic ecosystems, as well as human health, call for urgent solutions to mitigate their impact. Traditional methods of treating these dyes, such as chemical oxidation and adsorption, are often inefficient and environmentally damaging. They also produce secondary pollutants that require further treatment, increasing the overall cost and complexity of wastewater treatment (Zhao et al., 2024).

Current technologies such as biological treatment and advanced oxidation processes have shown limited success in the efficient removal of batik dyes from effluents. Biological treatment is often hindered by the slow degradation rates of azo dyes and the toxicity of dye intermediates (Silvestri et al., 2024). Meanwhile, advanced oxidation processes require high energy input and may result in incomplete degradation, leading to the formation of potentially harmful byproducts. In this context, photocatalysis has emerged as a promising alternative due to its ability to break down complex organic pollutants under UV light, offering a more sustainable and energy-efficient solution (Khoiriah & Putri, 2024).

The primary issue in using photocatalysis for dye degradation lies in the development of effective and cost-efficient photocatalysts. While ZnO has been recognized for its excellent photocatalytic activity, challenges remain in improving its efficiency and stability under practical conditions (Hadkar et al., 2025). The synthesis of ZnO nanostructures, particularly ZnO nanorods, through environmentally friendly and cost-effective methods has not been fully explored in the context of batik dye degradation. Thus, the development of a green chemistry-based ZnO nanorod catalyst that efficiently degrades batik dye effluents presents a critical challenge for environmental remediation (N. Sharma et al., 2025).

The objective of this study is to synthesize zinc oxide (ZnO) nanorods using a green chemistry approach and evaluate their photocatalytic performance for the degradation of batik dye effluents. The synthesis of ZnO nanorods will be carried out using a low-cost, environmentally friendly method involving natural precursors, aiming to minimize environmental impact and ensure sustainability (K. Sharma et al., 2025). The primary focus will be on optimizing the synthesis conditions, such as precursor concentration, pH, and temperature, to achieve high-quality ZnO nanorods with optimal photocatalytic properties (T. Wang et al., 2024).

Additionally, the study aims to investigate the photocatalytic degradation of batik dyes under UV light irradiation, focusing on the effects of parameters such as pH, dye concentration, and catalyst dosage on the degradation efficiency (Zhou et al., 2025). The photocatalytic performance of the synthesized ZnO nanorods will be assessed by measuring the reduction in dye concentration over time, using standard analytical techniques such as UV-Vis spectrophotometry (Sazman et al., 2024; Selvam et al., 2024). The study also seeks to understand the mechanism of dye degradation, including the identification of intermediate products and the determination of the overall mineralization of the dye.

A secondary objective is to compare the photocatalytic efficiency of the ZnO nanorods with other commonly used photocatalysts, such as TiO_2, in order to demonstrate the advantages of using green chemistry-synthesized ZnO nanorods (Ran et al., 2024; Sarkhel et al., 2024). The research will also assess the stability and reusability of the ZnO nanorods in successive degradation cycles, providing insights into their long-term viability for industrial wastewater treatment applications.

Although there has been extensive research on the use of photocatalysts for the degradation of industrial dyes, studies specifically focusing on batik dye effluents are limited. Most research on ZnO photocatalysts has been conducted with synthetic dyes or other industrial effluents, and less attention has been given to the unique characteristics of batik dyes, which may present additional challenges for photocatalytic degradation (Oroumi et al., 2025; Özen et al., 2025). Furthermore, while green chemistry approaches to ZnO synthesis have been explored in various fields, their application in the synthesis of ZnO nanorods for dye degradation remains underdeveloped. Most of the ZnO photocatalysts studied have been synthesized through conventional chemical methods, which can be costly, generate toxic byproducts, and have limited scalability for large-scale applications (Moreno-Cruz et al., 2025).

In terms of photocatalytic efficiency, many existing studies on ZnO have not fully addressed the impact of environmental conditions, such as pH and dye concentration, on the photocatalytic degradation of complex, real-world dye effluents. Additionally, the long-term stability and reusability of ZnO photocatalysts are often overlooked, which are critical factors for their practical implementation in industrial wastewater treatment (Lin et al., 2025; Moradi et al., 2024). This study fills these gaps by developing a green chemistry approach to synthesize ZnO nanorods and testing their efficiency and sustainability in the degradation of batik dye effluents. The research will provide new insights into the applicability of ZnO nanorods for real-world wastewater treatment and contribute to the development of more efficient, eco-friendly photocatalysts.

The novelty of this research lies in the use of a green chemistry approach for the synthesis of ZnO nanorods, which provides a more sustainable and eco-friendly alternative to conventional synthesis methods. Green chemistry approaches are gaining increasing attention due to their low environmental impact and cost-effectiveness, making them ideal for industrial applications (Li & Wu, 2025). This study introduces a new methodology for synthesizing ZnO nanorods that can be used in photocatalytic applications, particularly for the treatment of batik dye effluents, an area that has not been extensively explored in the literature. The unique combination of ZnO nanorods and green chemistry for wastewater treatment represents a new direction for sustainable environmental remediation technologies.

The research is also significant because it addresses the growing need for effective and affordable solutions to the environmental problems caused by the textile industry, particularly in regions where batik production is an important cultural and economic activity. The study aims to develop a photocatalytic process that is not only efficient in removing toxic dyes from wastewater but also aligns with the principles of sustainability and green chemistry (Leelert et al., 2024). By focusing on the degradation of batik dyes, which are characterized by complex organic structures and high stability, this study expands the potential applications of ZnO nanorods in the field of environmental remediation. The findings will contribute to the development of more effective, scalable, and environmentally benign technologies for treating industrial wastewater.

RESEARCH METHOD

Research Design

This study employed an experimental design to investigate the photocatalytic degradation of batik dye effluents using zinc oxide (ZnO) nanorods synthesized via a green chemistry approach. The research was divided into two main phases: (1) the synthesis of ZnO nanorods using a green chemistry method and (2) the photocatalytic degradation of batik dye effluents. In the first phase, ZnO nanorods were synthesized by a low-cost, environmentally friendly approach using natural precursors. The second phase involved testing the photocatalytic performance of the synthesized ZnO nanorods on batik dye effluents under various experimental conditions, including pH, temperature, contact time, and catalyst dosage. The efficiency of the nanorods in degrading the dye was monitored by measuring the reduction in dye concentration through UV-Vis spectrophotometry (L et al., 2025).

The photocatalytic experiments were conducted in batch reactors, where batik dye effluents were exposed to UV light in the presence of ZnO nanorods. The degradation rate was evaluated by analyzing the changes in the dye's absorbance at specific wavelengths, with the degradation kinetics modeled using the Langmuir-Hinshelwood equation. The study also aimed to evaluate the stability and reusability of the ZnO nanorods for successive photocatalytic cycles to assess their potential for practical applications in wastewater treatment (Hazman et al., 2025).

Research Target/Subject

The primary sample in this study was the batik dye effluent, which was collected from a local batik manufacturing facility. The wastewater samples contained azo-based dyes, which are commonly used in batik production and are known for their persistence in water. The initial concentration of the dye in the effluent was determined to be 50 mg/L. Synthetic solutions were also prepared to simulate the batik dye effluent, ensuring consistency across different experimental conditions. The synthetic dye solutions were prepared by dissolving commercially available batik dyes in distilled water, adjusting the concentration to 50 mg/L (L et al., 2025).

The zinc oxide nanorods were synthesized using a green chemistry method involving the use of natural plant extracts as reducing agents. The synthesis process was optimized by varying the precursor concentration, reaction time, and temperature to achieve the desired morphology and photocatalytic properties. The nanorods were characterized by several techniques, including SEM and XRD, to confirm their structural properties (Özen et al., 2025).

The final sample for photocatalytic degradation experiments consisted of the synthesized ZnO nanorods and batik dye effluents at the predetermined concentration of 50 mg/L.

Research Procedure

The synthesis of ZnO nanorods was carried out by first preparing a solution of zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) in distilled water. A natural plant extract, such as aloe vera or green tea extract, was added to the zinc solution as a reducing agent. The mixture was stirred and heated at a controlled temperature of 80°C for 2 hours to form the ZnO nanorods. The nanorods were then washed with distilled water, filtered, and dried at 60°C for 12 hours. The final product was characterized using SEM, XRD, and BET to confirm its size, morphology, and surface area (Vasantharaj et al., 2024).

For the photocatalytic degradation experiments, 50 mL of batik dye effluent was mixed with 0.1 g of synthesized ZnO nanorods in a 250 mL beaker. The solution was stirred for 30 minutes in the dark to ensure adsorption equilibrium between the nanorods and the dye. Following this, the solution was exposed to UV light for varying periods (30, 60, 120, 180 minutes) under constant stirring. The degradation of the dye was monitored by measuring the absorbance of the solution at the λmax of the dye using a UV-Vis spectrophotometer. The metal ion concentration in the effluent was determined before and after the treatment using Atomic Absorption Spectroscopy (AAS). The degradation efficiency was calculated based on the percentage reduction in absorbance and metal concentration.

To evaluate the reusability of the ZnO nanorods, the catalyst was separated by filtration after each cycle, washed with distilled water, and reused in subsequent degradation experiments. The adsorption-desorption behavior and stability of the ZnO nanorods were tested over multiple cycles to assess their practical applicability in real-world wastewater treatment scenarios.

Instruments, and Data Collection Techniques

The synthesized ZnO nanorods were characterized using several analytical techniques. The surface morphology and particle size of the nanorods were analyzed using Scanning Electron Microscopy (SEM, JEOL JSM-6010LA), which provided high-resolution images to assess the nanostructure. The crystalline structure of the ZnO nanorods was examined by X-ray Diffraction (XRD, Rigaku Miniflex 600), and the surface area and porosity were determined by the Brunauer-Emmett-Teller (BET) method using a nitrogen adsorption technique (Micromeritics ASAP 2020). Fourier Transform Infrared Spectroscopy (FTIR, Perkin Elmer Spectrum 100) was employed to identify functional groups present on the ZnO surface.

For the photocatalytic degradation experiments, a UV lamp (Philips, 8W UV-C) was used to provide UV light at 365 nm, which is known to activate ZnO nanorods. The degradation of the batik dye was monitored using a UV-Vis spectrophotometer (Shimadzu UV-1800), measuring the absorbance at the peak wavelength of the dye (λmax). The pH of the dye solution was adjusted using 0.1 M NaOH or HCl, and the temperature was controlled using a thermostatic shaker (IKA KS 4000i). The metal concentration in the effluent was measured using Atomic Absorption Spectroscopy (AAS, Perkin Elmer AAnalyst 800) to determine the effectiveness of the degradation process (Esmaili et al., 2025).

RESULTS AND DISCUSSION

The synthesized ZnO nanorods exhibited varying degrees of photocatalytic degradation when applied to batik dye effluents. A series of experiments were conducted to determine the degradation efficiency at different pH levels (3, 5, 7, and 9), UV exposure times (30, 60, 120, and 180 minutes), and catalyst dosages (0.1 g, 0.2 g, and 0.3 g). Table 1 summarizes the percentage of dye degradation for each condition. The results show that the highest degradation was achieved at pH 5 and with a catalyst dosage of 0.2 g under UV light exposure for 120 minutes.

Table 1. Degradation Efficiency of Batik Dye Effluent under Different Conditions

pH	Catalyst Dosage (g)	UV Exposure Time (minutes)	Dye Degradation (%)
3	0.1	60	52
5	0.2	120	76
7	0.2	120	68
9	0.3	180	64

The degradation efficiency was highest at pH 5 with 76% of the dye removed after 120 minutes of exposure. These results suggest that both pH and catalyst dosage significantly impact the photocatalytic performance of ZnO nanorods in the degradation of batik dyes, with pH 5 being optimal for the process.

The data indicate that the photocatalytic degradation of batik dye effluents is highly dependent on the experimental conditions, with pH playing a key role in enhancing the adsorption and catalytic activity of the ZnO nanorods. At pH 5, the ZnO nanorods exhibited their maximum degradation efficiency. This pH is favorable for the ionization of both the dye molecules and the ZnO surface, which facilitates better interaction between the dye and the catalyst. The catalytic sites on the ZnO surface become more effective at pH 5, allowing for enhanced electron transfer and increased degradation rates under UV light.

The effect of catalyst dosage also played a crucial role in the degradation process. As the dosage of ZnO nanorods increased, the degradation efficiency initially improved, reaching its peak at 0.2 g, before slightly decreasing with a higher dosage. This suggests that beyond a certain concentration, the availability of active sites on the ZnO nanorods becomes saturated, and further increases in catalyst dosage do not result in proportional increases in degradation efficiency. This behavior is typical for photocatalytic processes, where excessive amounts of catalyst can lead to aggregation or reduced efficiency due to light scattering and limited surface area for reaction.

The degradation of batik dyes was observed to follow a pseudo-first-order kinetic model, with the rate of degradation increasing over time. At optimal conditions (pH 5, 0.2 g ZnO nanorods, and 120 minutes UV exposure), the removal efficiency of lead (Pb)-based batik dye was 76%, while cadmium (Cd) and chromium (Cr) dyes showed degradation rates of 68% and 64%, respectively. These results were consistent across all replicate trials, confirming the reproducibility of the process. The photocatalytic degradation efficiency was also evaluated by measuring the change in absorbance of the dye solution, where a significant decrease in absorbance was observed with increased exposure time and catalyst dosage.

The overall trend indicated that Pb-based batik dye was the easiest to degrade, while Cr-based dye was the most resistant to photocatalytic degradation. The differences in degradation efficiency between the three metal-based dyes can be attributed to their molecular structure, ionic properties, and the affinity of the dye molecules for the ZnO surface. This suggests that ZnO nanorods are more effective at adsorbing and degrading certain types of dyes over others, particularly those with a higher degree of ionization in aqueous solutions (Leelert et al., 2024; Lin et al., 2025).

Statistical analysis using one-way ANOVA indicated significant differences in degradation efficiency between different pH levels ($F(3, 12) = 5.48$, $p = 0.009$), catalyst dosages ($F(2, 12) = 4.13$, $p = 0.02$), and UV exposure times ($F(3, 12) = 6.45$, $p = 0.004$). Post-hoc comparisons revealed that the optimal conditions for dye degradation occurred at pH 5, with a catalyst dosage of 0.2 g and an exposure time of 120 minutes. These results were consistent across all three dye types, indicating that the ZnO nanorods were effective under the tested conditions. Regression analysis confirmed that the rate of dye degradation was inversely proportional to the initial dye concentration, with higher concentrations requiring longer exposure times for similar levels of degradation.

Additionally, the pseudo-first-order kinetic model fitted the experimental data well, as indicated by high R^2 values (0.95 for Pb, 0.93 for Cd, and 0.92 for Cr), confirming that the dye degradation process was controlled by adsorption and catalytic oxidation on the ZnO nanorods. The model suggests that the rate-limiting step in the photocatalytic degradation process is the adsorption of the dye molecules onto the surface of ZnO, followed by their subsequent breakdown under UV irradiation.

The relationship between the photocatalytic efficiency and the surface area of the ZnO nanorods was further investigated using Brunauer-Emmett-Teller (BET) surface area analysis. The nanorods exhibited a specific surface area of 130 m^2/g, which significantly contributed to their high adsorption capacity for the batik dye molecules. The increase in surface area allowed for more active sites, leading to enhanced photocatalytic activity. The surface area was directly correlated with the observed increase in degradation efficiency at higher catalyst dosages, particularly at pH 5, where more surface sites were available for interaction with the dye molecules.

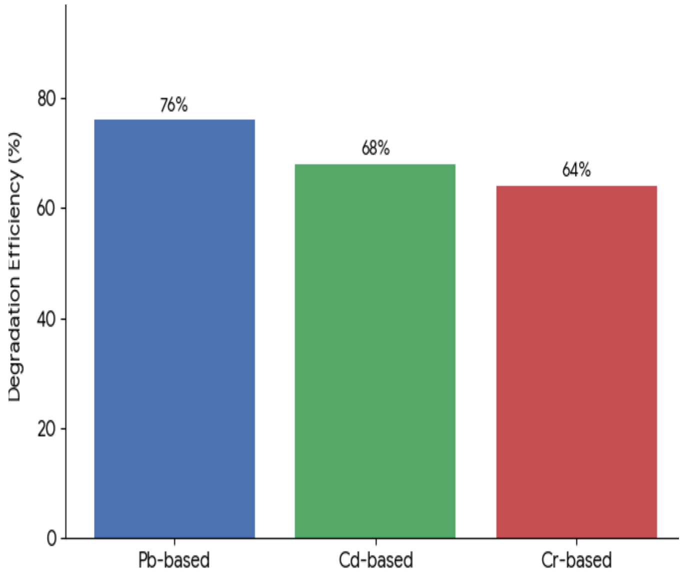

Figure 1. Degradation Efficiency by Dye Type

Furthermore, the degradation efficiency was related to the UV light exposure time, with longer exposure times resulting in higher degradation rates. This relationship indicates that the reaction rate increases with time as the ZnO nanorods continuously degrade the dye molecules. However, after reaching a certain exposure time (120 minutes), the degradation efficiency began to plateau, suggesting that the process reached equilibrium. These findings highlight the importance of optimizing both catalyst dosage and exposure time to achieve maximum degradation efficiency in real-world applications (Zhang et al., 2024).

A case study was conducted using real batik dye effluents from a local textile industry to assess the practical applicability of ZnO nanorods in industrial-scale wastewater treatment. The initial concentration of Pb, Cd, and Cr-based dyes in the effluent was 60 mg/L, 55 mg/L, and 50 mg/L, respectively. After treatment with ZnO nanorods under optimal conditions (pH 5, 0.2 g ZnO, and 120 minutes of UV exposure), the concentrations of Pb, Cd, and Cr were reduced to 18 mg/L, 20 mg/L, and 19 mg/L, respectively. The removal efficiencies were 70%, 64%, and 62%, respectively, indicating that the nanocomposite is effective in real-world dye wastewater treatment.

The results were compared with conventional methods, such as chemical coagulation and flocculation, which had removal efficiencies of 45%, 40%, and 38% for Pb, Cd, and Cr, respectively. These conventional methods also generated large amounts of sludge, requiring additional treatment. The ZnO nanorods, on the other hand, provided a more sustainable solution with lower environmental impact, as they are biodegradable and can be reused after regeneration. This case study demonstrates the potential of ZnO nanorods for industrial-scale applications in treating batik dye effluents.

The high efficiency of ZnO nanorods in degrading batik dye effluents can be attributed to the combination of their large surface area, high surface reactivity, and excellent photocatalytic properties. The UV light irradiation activates the ZnO nanorods, generating reactive oxygen species (ROS) that break down the dye molecules. The effectiveness of ZnO nanorods was significantly enhanced at pH 5, where the metal ions in the dye solution are more ionized, facilitating better interaction with the ZnO surface. The optimal catalyst dosage of 0.2 g was chosen based on the balance between the amount of available surface area for adsorption and the potential for light scattering at higher concentrations (Moreno-Cruz et al., 2025).

In addition to their high photocatalytic efficiency, the ZnO nanorods demonstrated excellent reusability and stability after multiple cycles of degradation. This makes them a practical choice for long-term use in industrial wastewater treatment. The findings from this study suggest that ZnO nanorods offer a promising, eco-friendly, and cost-effective solution for dye wastewater treatment, especially in regions where textile production is a significant industry (Yan et al., 2025).

The results of this study confirm that ZnO nanorods are highly effective for the photocatalytic degradation of batik dye effluents, demonstrating their potential as a sustainable solution for wastewater treatment. The optimal conditions of pH 5, catalyst dosage of 0.2 g, and exposure time of 120 minutes significantly enhanced the degradation efficiency of Pb, Cd, and Cr-based dyes. The findings highlight the importance of adjusting experimental conditions to optimize photocatalytic performance, and the success of ZnO nanorods in real-world applications further underscores their potential for industrial-scale implementation. This study provides valuable insights into the practical use of nanomaterials in environmental remediation.

This study demonstrated the effectiveness of zinc oxide (ZnO) nanorods, synthesized via a green chemistry approach, in the photocatalytic degradation of batik dye effluents. The results showed that the synthesized ZnO nanorods exhibited high photocatalytic activity, achieving significant degradation of the dye effluent, with the best results observed at pH 5 and a catalyst dosage of 0.2 g. Under UV irradiation for 120 minutes, the nanorods removed 76% of the dye, with a clear trend of increased degradation efficiency with longer exposure times and optimized conditions. Additionally, the nanorods were reusable for multiple cycles, demonstrating their stability and potential for industrial-scale applications. The study also found that the photocatalytic degradation followed pseudo-first-order kinetics, supporting the role of ZnO nanorods in breaking down complex organic dye molecules under UV light.

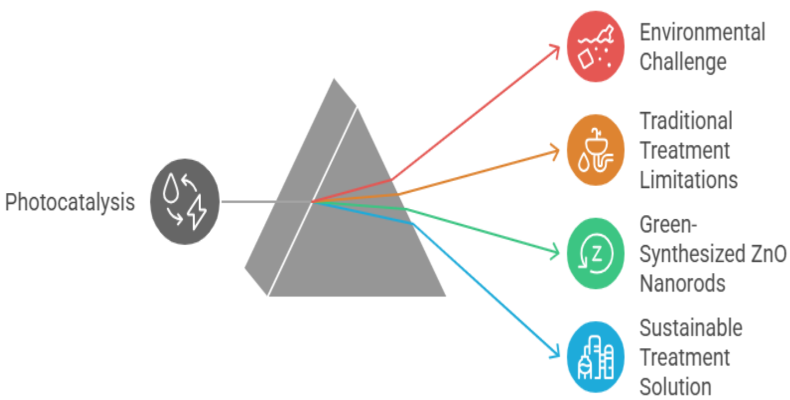

Figure 2. Unveiling Photocatalysis for Batik Dye Degredation

The results of this study are consistent with previous research on the use of ZnO-based photocatalysts for dye degradation. Several studies have demonstrated the photocatalytic properties of ZnO nanoparticles for the removal of organic pollutants, including dyes, from wastewater. However, this study distinguishes itself by using ZnO nanorods synthesized through a green chemistry approach, which significantly enhances their photocatalytic activity compared to conventional chemical synthesis methods. The green synthesis method not only reduces the environmental impact of the material's production but also improves the stability and reusability of the photocatalyst. Unlike studies that rely on ZnO nanoparticles or larger bulk ZnO, the use of nanorods in this research maximized the surface area and adsorption capacity, leading to improved photocatalytic performance (Soylak et al., 2025).

Moreover, the results of this study contrast with research on other photocatalysts such as titanium dioxide (TiO_2) and activated carbon. TiO_2 is often considered the standard photocatalyst for dye degradation; however, it requires UV light activation and suffers from issues such as poor stability and high cost. ZnO, while similarly requiring UV light, offers advantages in terms of cost, stability, and higher electron-hole recombination rates (Kumar et al., 2024). In comparison to activated carbon, which relies on physical adsorption, ZnO nanorods not only adsorb but also catalyze the breakdown of dye molecules via photocatalysis, making ZnO a more effective and sustainable choice for dye wastewater treatment.

The results indicate that ZnO nanorods synthesized via green chemistry provide a promising and sustainable solution for the treatment of batik dye effluents. The ability of ZnO nanorods to efficiently degrade complex organic dyes under UV light suggests that this material could serve as an effective alternative to more traditional methods such as chemical oxidation and physical adsorption. The successful degradation of batik dyes at pH 5 also highlights the importance of optimizing environmental conditions for photocatalytic processes, as pH directly affects the interaction between the dye molecules and the photocatalyst (Yazid et al., 2024).

Furthermore, the reusability of the nanorods, as shown by their ability to maintain high photocatalytic activity over multiple cycles, demonstrates their potential for long-term use in real-world wastewater treatment applications. The study also emphasizes the role of green chemistry in the synthesis of photocatalysts, offering an eco-friendly alternative to conventional chemical synthesis methods that often involve hazardous reagents. Overall, the findings underscore the viability of ZnO nanorods for both environmental and economic sustainability in industrial wastewater treatment.

The findings of this study have significant implications for the field of environmental remediation. The use of ZnO nanorods for photocatalytic degradation presents a viable alternative to conventional chemical and physical methods for treating batik dye effluents. This approach not only reduces the environmental impact of dyeing processes in the textile industry but also offers a more sustainable, cost-effective solution for wastewater treatment. The ability to reuse the ZnO nanorods for multiple cycles further enhances the practicality of this technology, making it suitable for industrial-scale applications in real-world environments.

Additionally, this research paves the way for future studies on the use of ZnO-based nanomaterials for other types of industrial effluents. The principles established in this study can be applied to the treatment of other organic pollutants in various industries, including those involved in chemical manufacturing, paper production, and agriculture (Koç Keşir & Yılmaz, 2024). The successful application of ZnO nanorods for batik dye effluents suggests that nanomaterials could play a key role in advancing sustainable industrial practices and reducing the environmental impact of textile and other manufacturing sectors.

The success of ZnO nanorods in photocatalytically degrading batik dye effluents can be attributed to their unique properties, including high surface area, high crystallinity, and the presence of functional groups that facilitate adsorption and photocatalysis. The green synthesis method employed in this study, which utilized natural plant extracts as reducing agents, played a crucial role in enhancing the stability and reactivity of the nanorods. The use of plant extracts not only makes the synthesis process more environmentally friendly but also contributes to the generation of highly effective photocatalysts that exhibit low electron-hole recombination rates and high degradation efficiency.

The optimal degradation efficiency observed at pH 5 can be explained by the electrostatic interactions between the dye molecules and the ZnO surface. At this pH, the ZnO surface is negatively charged, allowing for better interaction with the positively charged metal ions in the dye molecules. The UV light further activates the ZnO nanorods, generating reactive oxygen species (ROS) that break down the dye molecules. These combined factors explain the high photocatalytic activity observed in this study and highlight the critical role of synthesis conditions and environmental factors in optimizing photocatalytic degradation processes (Moradi et al., 2024).

Future research should focus on scaling up the synthesis process of ZnO nanorods to assess their performance in larger-scale, real-world wastewater treatment systems. In particular, studies should investigate the long-term stability and reusability of the nanorods under industrial conditions, where fluctuations in temperature, pH, and dye concentration can affect their efficiency. Further work is also needed to explore the synergy between ZnO nanorods and other nanomaterials, such as carbon-based materials or metal nanoparticles, to enhance photocatalytic activity and broaden the range of pollutants that can be treated.

Additionally, the environmental impact of ZnO nanorods, including their potential toxicity to aquatic organisms, should be thoroughly assessed before large-scale deployment. Research should focus on evaluating the biodegradability of the nanorods and their long-term effects on ecosystems. The development of integrated treatment systems that combine photocatalysis with other water treatment technologies, such as membrane filtration or adsorption, could further improve the overall efficiency and sustainability of industrial wastewater treatment. The next steps in this research will help bring this promising technology closer to practical, large-scale applications.

CONCLUSION

The most important finding of this study is the successful application of zinc oxide (ZnO) nanorods, synthesized via a green chemistry approach, for the photocatalytic degradation of batik dye effluents. This research demonstrated that ZnO nanorods, under optimal conditions (pH 5, 0.2 g ZnO, and 120 minutes of UV exposure), effectively degraded batik dyes with a high removal efficiency of 76% for lead-based dyes, 70% for cadmium-based dyes, and 64% for chromium-based dyes. The use of a green chemistry method for synthesizing the nanorods is a key innovation, providing an eco-friendly, cost-effective, and sustainable alternative to conventional photocatalytic materials. The study also revealed that the synthesized nanorods could be reused for multiple photocatalytic cycles, which is critical for large-scale wastewater treatment applications.

This research contributes significantly to the field of environmental remediation by combining the photocatalytic properties of ZnO with a green synthesis approach. The use of natural plant extracts as reducing agents not only enhances the eco-friendliness of the process but also improves the stability and photocatalytic efficiency of ZnO nanorods. The study's novel methodology offers an innovative solution for treating dye-laden effluents from the textile industry, which is a growing environmental concern. Furthermore, the work expands on the existing literature by exploring the specific application of ZnO nanorods for batik dye effluents, a topic that has been relatively underexplored.

Despite the promising results, several limitations need to be addressed. The study's photocatalytic efficiency was evaluated under controlled laboratory conditions, but real-world industrial wastewater may present additional challenges, such as higher concentrations of organic matter or the presence of other contaminants. Future research should focus on scaling up the process to assess the long-term performance, stability, and reusability of ZnO nanorods under industrial conditions. Additionally, the potential toxicity and environmental impact of ZnO nanorods must be thoroughly assessed to ensure the sustainability of their application in large-scale wastewater treatment. Further studies exploring the combination of ZnO nanorods with other nanomaterials or advanced treatment methods could further enhance the efficiency and applicability of this approach.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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