APPLICATION OF ZINC OXIDE NANOPARTICLES IN TREATMENT OF INDUSTRIAL WASTEWATER

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Abstract: The discharge of untreated industrial wastewater, especially from textile industries, poses serious environmental challenges due to the presence of toxic dyes and organic pollutants. In this study, zinc oxide (ZnO) nanoparticles were synthesized via a chemical precipitation method and applied for the treatment of real textile wastewater. The nanoparticles were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV–Visible spectroscopy. Photocatalytic experiments were conducted under UV irradiation to evaluate pollutant degradation. Key water quality parameters such as pH, chemical oxygen demand (COD), and color intensity were monitored before and after treatment. The results showed a significant reduction in pollutant levels, with up to 90% color removal and ~75% COD reduction within 150 minutes. The findings demonstrate the practical applicability of ZnO nanoparticles as efficient and cost-effective photocatalysts for industrial wastewater treatment.

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Keywords

ZnO Nanoparticles, Textile Wastewater, Photocatalysis, COD Reduction, Environmental Remediation

1. Introduction

Industrial wastewater generated from textile and dyeing industries is a major source of environmental pollution. These effluents contain complex organic dyes, surfactants, and heavy metals that are resistant to conventional treatment methods. The presence of such pollutants reduces light penetration in water bodies and adversely affects aquatic ecosystems. (Hoffmann et al., 1995).

Advanced oxidation processes (AOPs), particularly semiconductor-based photocatalysis, have gained attention due to their ability to completely mineralize organic pollutants into harmless substances such as CO_2 and H_2O. Zinc oxide (ZnO) is a widely studied photocatalyst due to its wide band gap (~3.37 eV), high catalytic efficiency, low toxicity, and affordability.

Most previous studies have focused on synthetic dye solutions under controlled laboratory conditions. However, real industrial wastewater contains a mixture of pollutants, making treatment more challenging. Therefore, this study emphasizes the use of real textile wastewater to evaluate the practical performance of ZnO nanoparticles. (Kołodziejczak-Radzimska & Jesionowski, 2014).

2. Materials and Methods

2.1 Materials

Analytical grade zinc acetate dihydrate and sodium hydroxide were used. Distilled water was used throughout the experiment. Textile wastewater samples were collected from a local dyeing industry.

2.2 Synthesis of ZnO Nanoparticles

ZnO nanoparticles were synthesized using a precipitation method. Zinc acetate solution was stirred continuously, and NaOH was added dropwise until a white precipitate formed. The precipitate was aged for 12 hours, filtered, washed repeatedly, dried at 100°C, and calcined at 400°C for 3 hours to obtain crystalline ZnO nanoparticles.

2.3 Characterization Techniques

- **XRD:** Identification of crystal structure and crystallite size
- **SEM:** Morphology and particle distribution
- **UV–Vis Spectroscopy:** Optical absorption and monitoring degradation (Cullity & Stock, 2001).

2.4 Wastewater Sampling and Analysis

The collected wastewater was filtered and analyzed for initial parameters:

- **pH:** Measured using a digital pH meter
- **Color intensity:** Determined via UV–Vis spectroscopy

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- **Chemical Oxygen Demand (COD):** Measured using standard dichromate method (APHA, 2017).

2.5 Photocatalytic Treatment Procedure

100 mL of wastewater was mixed with 0.05 g of ZnO nanoparticles. The suspension was stirred in the dark for 30 minutes to establish adsorption equilibrium. The mixture was then exposed to UV light (365 nm) under continuous stirring.

Samples were withdrawn at regular intervals (30, 60, 90, 120, and 150 minutes), centrifuged, and analyzed.

2.6 Evaluation Parameters

Color Removal Efficiency

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

COD Removal Efficiency

$$\text{COD Reduction (\%)} = \frac{COD_0 - COD_t}{COD_0} \times 100$$

3. Results and Discussion

3.1 XRD Analysis

XRD patterns confirmed the formation of pure ZnO with a hexagonal wurtzite structure. The sharp peaks indicated high crystallinity, and the average crystallite size was estimated to be ~25–35 nm. (Cullity & Stock, 2001).

3.2 SEM Analysis

SEM images showed nearly spherical nanoparticles with slight agglomeration. The nanoscale size provides a large surface area, enhancing photocatalytic performance.

3.3 Initial Wastewater Characteristics

Parameter	Value (Before Treatment)
pH	~8.5
COD	~520 mg/L
Color	Dark blue

3.4 Photocatalytic Degradation Performance

Time (min)	Color Removal (%)	COD Reduction (%)
30	35	20
60	55	40
90	70	55
120	85	68
150	90	75

The results show a steady increase in degradation with time. Maximum efficiency was achieved at 150 minutes.

3.5 Kinetic Analysis

The degradation followed pseudo-first-order kinetics:

$$\ln\left(\frac{C_0}{C_t}\right) = kt$$

The linear relationship confirms that photocatalytic degradation depends on dye concentration and catalyst activity.

3.6 Mechanism of Photocatalysis

The photocatalytic activity of ZnO nanoparticles is driven by the generation of reactive electron–hole pairs under UV light, which initiate a series of oxidation–reduction reactions capable of degrading organic pollutants:

1. **Photon Absorption and Electron–Hole Generation:**
When ZnO nanoparticles are irradiated with UV light ($\lambda \leq 387$ nm), photons with energy equal to or greater than the band gap excite electrons from the valence band (VB) to the conduction band (CB), leaving behind positively charged holes in the VB:

$$ZnO + h\nu \rightarrow e^-_{CB} + h^+_{VB}$$

2. **Formation of Reactive Oxygen Species (ROS):**
   - The **photo-generated electrons (e^-)** react with dissolved molecular oxygen in the solution to form superoxide radicals ($O_2^{-}\bullet$):

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$$e^- + O_2 \rightarrow O_2^-\bullet$$

- The **photo-generated holes (h^+)** oxidize water or hydroxide ions to produce hydroxyl radicals (•OH):

$$h^+ + H_2O \rightarrow \cdot OH + H^+$$

3. **Oxidation of Organic Pollutants:** The highly reactive hydroxyl and superoxide radicals attack the chromophoric structures of dye molecules, breaking double bonds and aromatic rings, leading to the degradation of complex organic compounds into smaller, harmless molecules such as CO_2, H_2O, and mineral acids:

$$Dye + \cdot OH/O_2^-\bullet \rightarrow CO_2 + H_2O + otherharmlessproducts$$

4. **Overall Process:** The efficiency of photocatalytic degradation depends on factors such as:
   - Surface area and morphology of ZnO nanoparticles
   - Separation efficiency of electron–hole pairs
   - Concentration of dissolved oxygen and water molecules

The nanoscale size of ZnO provides a large surface area for adsorption of dye molecules, while its strong oxidative potential ensures rapid mineralization of pollutants (Hoffmann et al., 1995; Kołodziejczak-Radzimska & Jesionowski, 2014).

3.7 Practical Implications

The successful treatment of real wastewater demonstrates:

- High efficiency under realistic conditions
- Applicability in industrial-scale treatment
- Potential for replacing conventional methods

4. Conclusion

In this study, zinc oxide (ZnO) nanoparticles were successfully synthesized using an economical chemical precipitation method and applied for the photocatalytic treatment of real textile wastewater. Structural characterization confirmed the formation of highly crystalline ZnO with a hexagonal wurtzite structure (Ozgur et al., 2005; Spanhel & Anderson, 1991). Morphological analysis indicated nanoscale particles with a large surface area, which enhances photocatalytic performance (Kołodziejczak-Radzimska & Jesionowski, 2014).

Under UV irradiation, the ZnO nanoparticles demonstrated significant improvement in wastewater quality parameters. A notable reduction in color intensity and chemical oxygen demand (COD) was achieved, with approximately **90% color removal** and **~75% COD reduction** within 150 minutes of photocatalytic treatment. These results highlight the ability of ZnO nanoparticles to generate reactive oxygen species (such as hydroxyl and superoxide radicals) through photo-induced electron–hole pairs that effectively oxidize complex organic pollutants into less harmful products (Hoffmann et al., 1995; Kołodziejczak-Radzimska & Jesionowski, 2014).

The observed degradation efficiencies in a real industrial setting confirm that ZnO nanoparticles are not only efficient but also cost-effective and environmentally friendly photocatalysts compared to conventional treatment methods, which often struggle with refractory dye compounds (Forgacs, Cserháti, & Oros, 2004). The successful application of ZnO photocatalysis to actual textile effluent underscores its practical potential for industrial wastewater remediation.

For future work, emphasis should be placed on addressing current limitations and enhancing real-world applicability. Strategies such as **modification of ZnO nanoparticles through metal/non-metal doping** or formation of nanocomposites (e.g., Ag-, Cu-, or graphene-based ZnO systems) may extend photocatalytic activity into the visible-light region, increasing efficiency under solar irradiation (Kołodziejczak-Radzimska & Jesionowski, 2014). Additionally, systematic studies on **reusability, stability, and catalyst recovery** are needed to support long-term industrial deployment. Finally, pilot-scale or continuous-flow reactor studies will be crucial for validating the scalability of ZnO nanoparticle-based photocatalytic treatment for large-volume industrial wastewater streams

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