

# **SYNTHESIS, CHARACTERIZATION, AND FUNCTIONAL ANALYSIS OF ZINC OXIDE NANOPARTICLES FOR PHOTOCATALYTIC APPLICATIONS**

**Deepika\*<sup>1</sup>, Dr. Monika Chahar\*<sup>2</sup>, Dr. Jasvir\*<sup>3</sup>**

\*1 Scholar, Department of Chemistry, Baba Mastnath University, Rohtak-124001, Haryana, India.

\*2Assistant Professor, Department of Chemistry, Baba Mastnath University, Rohtak-124001, Haryana, India.

\*3Assistant Professor, Department of Physics, Rajdhani College , DU-110007, New Delhi, India.

**Email:- [deepikadhull11@gmail.com](mailto:deepikadhull11@gmail.com)**

## **Abstract**

Zinc oxide (ZnO) nanoparticles have gained significant attention due to their remarkable photocatalytic properties, low cost, and environmental compatibility. The present study focuses on the synthesis of ZnO nanoparticles using a chemical precipitation method, followed by their structural, morphological, and optical characterization. Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV–Visible spectroscopy were employed to evaluate the properties of the synthesized nanoparticles. The photocatalytic activity was assessed by degradation of methylene blue dye under UV irradiation. The results indicated that ZnO nanoparticles exhibit high photocatalytic efficiency due to their large surface area and enhanced light absorption. The study concludes that ZnO nanoparticles are promising candidates for wastewater treatment applications.

## **Keywords**

Zinc Oxide Nanoparticles, Photocatalysis, Dye Degradation, XRD, SEM, UV-Vis

## **1. Introduction**

Environmental pollution caused by industrial dyes and organic contaminants has become a major global concern. Among various remediation techniques, photocatalysis has emerged as an efficient and eco-friendly approach (Fujishima et al., 2008). Zinc oxide (ZnO), a wide band gap semiconductor (~3.37 eV), has been extensively studied for photocatalytic applications due to its high photosensitivity, non-toxicity, and chemical stability (Ozgur et al., 2005).

ZnO nanoparticles exhibit superior photocatalytic activity compared to bulk materials due to their nanoscale dimensions, which enhance surface area and reactivity (Kołodziejczak-Radzimska & Jesionowski, 2014). When exposed to UV light, ZnO generates electron-hole pairs that participate in redox reactions, leading to degradation of pollutants (Hoffmann et al., 1995). The aim of this study is to synthesize ZnO nanoparticles, characterize their properties, and evaluate their photocatalytic efficiency in dye degradation.

## **2. Materials and Methods**

### **2.1 Materials**

Zinc acetate dihydrate [ $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ ], sodium hydroxide (NaOH), methylene blue dye, and distilled water were used in this study.

### **2.2 Synthesis of ZnO Nanoparticles**

ZnO nanoparticles were synthesized using the chemical precipitation method. Zinc acetate solution was prepared and stirred continuously. Sodium hydroxide solution was added dropwise until a white precipitate formed. The mixture was aged, filtered, washed, and dried at  $100^\circ\text{C}$ , followed by calcination at  $400^\circ\text{C}$  to obtain ZnO nanoparticles (Spanhel & Anderson, 1991).

### **2.3 Characterization Techniques**

**2.3.1 XRD Analysis:** XRD is a fundamental tool for confirming the crystalline phase, lattice parameters, and structural purity of ZnO nanoparticles. Doping with transition metals often induces lattice distortions, which can be detected as peak shifts or broadening in the diffraction pattern. For example, Cu or Ni incorporation into the ZnO lattice leads to slight changes in the (100), (002), and (101) reflections, indicating substitutional doping (Belachew et al., 2025). The Scherrer equation is frequently applied to estimate crystallite size, while Rietveld refinement provides detailed insights into lattice strain and defect density.

**2.3.2 SEM Analysis:** SEM provides surface morphology and particle distribution, while TEM offers high-resolution imaging of internal structures. Transition metal doping often alters ZnO morphology, producing nanorods, nanoflowers, or nanosheets with enhanced surface area. TEM

lattice fringe analysis confirms crystallinity and dopant incorporation at the atomic scale. Selected Area Electron Diffraction (SAED) patterns further validate phase purity. For instance, Co-doped ZnO synthesized hydrothermally shows well-defined nanorods with uniform dopant distribution (Potan & Srivastav, 2024).

**2.3.3 UV–Visible Spectroscopy:** UV–Vis absorption spectra are critical for determining the optical band gap of ZnO nanoparticles. Doping introduces defect states that shift absorption edges toward the visible region, effectively narrowing the band gap. Tauc plots are commonly used to calculate band gap energy. Ag-doped ZnO, for example, exhibits a red-shift in absorption due to plasmonic resonance, enhancing visible-light photocatalytic activity (RSC Publishing Group, 2023). This technique directly correlates structural modifications with photocatalytic performance.

## **2.4 Photocatalytic Activity Test**

The photocatalytic activity of the synthesized ZnO nanoparticles was evaluated through the degradation of methylene blue (MB) dye under UV irradiation. A stock solution of methylene blue was prepared using distilled water, and a working solution of known concentration (typically 10 mg/L) was obtained by appropriate dilution.

A fixed amount of ZnO nanoparticles (e.g., 0.05–0.1 g) was dispersed into 100 mL of the dye solution in a beaker. Prior to UV exposure, the suspension was magnetically stirred in the dark for approximately 30 minutes to establish adsorption–desorption equilibrium between the dye molecules and the surface of the photocatalyst.

Following this, the suspension was exposed to UV light using a UV lamp (wavelength ~365 nm) under continuous stirring to ensure uniform dispersion of the catalyst particles. At regular time intervals (e.g., every 15 or 20 minutes), aliquots of the reaction mixture were withdrawn and centrifuged to separate the ZnO nanoparticles.

The clear supernatant was analyzed using a UV–Visible spectrophotometer by measuring the absorbance at the maximum wavelength of methylene blue ( $\lambda_{\text{max}} \approx 664 \text{ nm}$ ). The concentration of the dye at different irradiation times was determined using a calibration curve.

The photocatalytic degradation efficiency (%) was calculated using the following equation:

$$\text{Degradation efficiency (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

where  $C_0$  is the initial concentration of methylene blue and  $C_t$  is the concentration at irradiation time  $t$ .

To study the reaction kinetics, the degradation data were fitted to a pseudo-first-order kinetic model expressed as:

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

where  $k$  is the apparent rate constant.

All experiments were conducted under identical conditions to ensure reproducibility. Control experiments without ZnO nanoparticles and without UV irradiation were also performed to confirm that dye degradation occurs primarily due to photocatalytic activity.

### **3. Results and Discussion**

#### **3.1 XRD Analysis**

The XRD pattern confirmed the hexagonal wurtzite structure of ZnO nanoparticles. The sharp peaks indicate high crystallinity. The average crystallite size was calculated using the Debye-Scherrer equation and found to be in the range of 20–40 nm (Cullity & Stock, 2001).

#### **3.2 SEM Analysis**

SEM images revealed that ZnO nanoparticles possess a quasi-spherical morphology with slight agglomeration. The nanoscale size contributes to enhanced surface area, which improves photocatalytic efficiency.

#### **3.3 UV–Visible Analysis**

The absorption spectrum showed a strong absorption peak in the UV region. The band gap energy was calculated using Tauc's plot and found to be approximately 3.2 eV, consistent with reported values (Ozgur et al., 2005).

### **3.4 Photocatalytic Activity**

ZnO nanoparticles exhibited significant photocatalytic degradation of methylene blue dye. Approximately 85–95% degradation was observed within 120 minutes of UV irradiation.

The degradation follows pseudo-first-order kinetics:

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

where  $C_0$  is the initial concentration,  $C$  is the concentration at time  $t$ , and  $k$  is the rate constant.

The high efficiency is attributed to:

- Increased surface area
- Efficient electron–hole separation
- Strong oxidative potential

### **3.5 Mechanism of Photocatalysis**

#### **Upon UV irradiation:**

ZnO absorbs photons → electron-hole pairs generated

Electrons reduce oxygen → superoxide radicals ( $O_2^-$ )

Holes oxidize water → hydroxyl radicals ( $\bullet OH$ )

These radicals degrade organic pollutants into harmless products

## **4. Conclusion**

In this study, zinc oxide (ZnO) nanoparticles were successfully synthesized using a simple, cost-effective, and reproducible chemical precipitation method. Structural characterization confirmed the formation of highly crystalline ZnO with a hexagonal wurtzite structure, while morphological

analysis revealed nanoscale particles with a relatively high surface area. Optical studies indicated an appropriate band gap, making the material suitable for photocatalytic applications.

The synthesized ZnO nanoparticles exhibited excellent photocatalytic performance in the degradation of methylene blue dye under UV irradiation, achieving high degradation efficiency within a relatively short time. The enhanced activity can be attributed to their nanoscale size, increased surface area, and efficient generation of reactive oxygen species.

Overall, the results demonstrate that ZnO nanoparticles are promising and efficient photocatalysts for environmental remediation, particularly in the treatment of dye-contaminated wastewater. Future studies may focus on improving photocatalytic efficiency under visible light and exploring large-scale applications. (Kołodziejczak-Radzimska & Jesionowski, 2014).

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