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Synthesis and Characterization of Zno Nanoparticles for Photocatalytic Degradation of Organic Dyes

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Abstract. *Zinc oxide (ZnO) nanoparticles have garnered significant attention due to their exceptional photocatalytic properties, low toxicity, and environmental compatibility. This study focuses on the synthesis of ZnO nanoparticles using a cost-effective sol-gel method, followed by comprehensive characterization employing XRD, SEM, TEM, UV-Vis spectroscopy, and FTIR analysis. The synthesized nanoparticles exhibit hexagonal wurtzite structure and nanoscale morphology with high surface area, crucial for enhanced photocatalytic performance. Photocatalytic activity was evaluated using methylene blue and rhodamine B as model organic dyes under UV and visible light irradiation. The results demonstrate substantial degradation efficiency, attributed to the high crystallinity and optical properties of ZnO nanoparticles. This work underscores the potential of ZnO-based photocatalysts in wastewater treatment applications, providing insight into their structure-activity relationship and laying groundwork for future development in environmental remediation technologies.*
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1. INTRODUCTION

The exponential growth of industrialization and urbanization over recent decades has led to significant environmental challenges, with water pollution being one of the most alarming. Among the various sources of water contamination, the discharge of synthetic dyes from textile, leather, pharmaceutical, and paper industries poses a severe ecological threat. These organic dyes are chemically stable, non-biodegradable, and often toxic, leading to long-term environmental and health impacts. Conventional wastewater treatment methods, including filtration, coagulation, and chemical oxidation, are often ineffective in fully removing such complex dye molecules, thereby necessitating the development of more sustainable and efficient remediation technologies.

Photocatalysis has emerged as a promising technique for degrading recalcitrant organic pollutants in water systems. It offers advantages such as complete mineralization of dyes, operation under ambient conditions, and the potential use of solar energy. Among various photocatalysts studied, zinc oxide (ZnO) nanoparticles have gained considerable attention due to their exceptional photocatalytic efficiency, non-toxic nature, high chemical stability, and economic viability. ZnO is a wide-bandgap semiconductor (3.37 eV) with a large exciton binding energy (~60 meV), and it has demonstrated excellent photocatalytic performance under ultraviolet (UV) light. Moreover, the nanoscale dimension of ZnO significantly enhances its surface-area-to-volume ratio, thereby improving its ability to interact with and degrade dye molecules effectively.

1.1 Overview

The present research is centered on the synthesis, characterization, and evaluation of the photocatalytic performance of ZnO nanoparticles for the degradation of organic dyes in aqueous media. Various synthesis methods, including sol-gel, hydrothermal, precipitation, and green synthesis approaches, have been employed historically to obtain ZnO nanoparticles with controlled size and morphology. In this work, we utilize a sol-gel route, known for its simplicity, cost-effectiveness, and ability to produce homogeneous nanoparticles with controlled properties. The synthesized ZnO nanoparticles are thoroughly characterized using a suite of techniques—X-ray diffraction (XRD) for phase and crystallite size analysis, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for morphological studies, Fourier-transform infrared spectroscopy (FTIR) for functional group identification, and UV-Vis spectroscopy for optical property analysis. Subsequently, the photocatalytic activity of ZnO nanoparticles is investigated using two model organic dyes: methylene blue (MB) and rhodamine B (RhB). These dyes are chosen due to their widespread industrial usage and representative structural characteristics. The degradation efficiency is studied under controlled UV and visible light exposure to understand the photocatalytic behavior and to optimize the operating parameters. Additionally, the kinetics of dye degradation and the reusability of the photocatalyst are assessed to explore the practical applicability of the developed nanomaterial in real-world scenarios.

1.2 Scope and Objectives

The scope of this study extends across material synthesis, physicochemical characterization, and environmental application, with a particular focus on water purification technologies. The research aims to contribute to the growing body of knowledge surrounding ZnO-based nanomaterials and their efficacy in mitigating environmental pollution.

The primary objectives of the study are outlined as follows:

- To synthesize ZnO nanoparticles using a sol-gel method with controlled conditions to ensure uniformity and reproducibility.
- To characterize the physicochemical and morphological properties of the synthesized ZnO nanoparticles using standard analytical techniques.
- To investigate the photocatalytic activity of ZnO nanoparticles in degrading methylene blue and rhodamine B dyes under UV and visible light.
- To analyze the degradation kinetics and evaluate the reusability and stability of the ZnO photocatalyst.
- To assess the feasibility of using ZnO nanoparticles for practical wastewater treatment applications and to provide a comparative evaluation with other photocatalytic systems.

1.3 Author Motivations

The motivation for this research stems from the growing global concern over environmental sustainability and the urgent need for green and cost-effective solutions for wastewater treatment. The author(s) have been actively engaged in exploring nanomaterials for environmental remediation and recognize the vast potential that ZnO nanoparticles hold due to their desirable properties and wide availability. The need to address real-world environmental problems with practical, scalable technologies is a driving force behind this investigation. Another motivation arises from the research gap observed in comparative studies of ZnO nanoparticles synthesized via simple routes and their performance under varied irradiation conditions. While extensive literature exists on the photocatalytic potential of ZnO, there is limited work that bridges the gap between fundamental material characterization and application-oriented performance analysis, especially using a cohesive synthesis-to-application approach. This study aims to bridge that gap, offering a holistic examination of ZnO's potential in dye degradation.

1.4 Paper Structure

This research paper is organized into several interrelated sections to ensure a logical flow and comprehensive understanding of the study:

- **Section 1: Introduction** provides the background, outlines the environmental problem, introduces ZnO as a photocatalyst, and discusses the motivation and scope of the research.
- **Section 2: Experimental Methodology** details the materials, synthesis process, and characterization techniques used in this study.
- **Section 3: Results and Discussion** presents the data obtained from characterization techniques and discusses the photocatalytic degradation results, supported by kinetic analyses and mechanistic insights.
- **Section 4: Conclusions and Future Work** summarizes the key findings and highlights potential avenues for future research, including scaling up the process and exploring hybrid systems.

In conclusion, this study embarks on an interdisciplinary journey that blends materials science, chemistry, and environmental engineering to address one of the most pressing challenges of our time—industrial water pollution. By focusing on the synthesis and application of ZnO nanoparticles for dye degradation, this research contributes both to the scientific understanding of photocatalytic mechanisms and to the development of sustainable technologies for environmental remediation. The comprehensive approach adopted in this study—from nanoparticle synthesis and detailed characterization to application testing—sets the stage for further advancements in nanomaterials for clean water technologies.

2. LITERATURE REVIEW

Photocatalysis using semiconductor nanomaterials has emerged as a promising approach for the degradation of persistent organic pollutants such as synthetic dyes. Among these semiconductors, zinc oxide (ZnO) stands out due to its suitable bandgap, high exciton binding energy, and low toxicity. Over the years, substantial research has been conducted to enhance the photocatalytic efficiency of ZnO nanoparticles (NPs), with emphasis on synthesis methods, surface modifications, and morphological tuning. This literature review critically examines recent advances in the synthesis, characterization, and application of ZnO NPs for photocatalytic degradation, highlighting achievements and identifying research gaps that this study aims to address.

2.1 Synthesis Techniques of ZnO Nanoparticles

The method of synthesis significantly affects the properties and performance of ZnO nanoparticles. Among various techniques, sol-gel synthesis is widely reported for its simplicity, low-temperature processing, and cost-effectiveness.

Patel and Mehta (2022) synthesized ZnO nanoparticles using a sol–gel technique and found that controlled thermal treatment plays a critical role in enhancing surface activity and particle dispersion, which directly influences photocatalytic efficiency. Similarly, Singh and Verma (2023) demonstrated that tuning the synthesis parameters such as precursor concentration and pH level during sol-gel processing could tailor the optical and morphological properties of ZnO NPs to optimize their catalytic behavior.

Choudhury and Bera (2024) provided a comparative analysis between nanorods and nanoparticles of ZnO synthesized via hydrothermal and precipitation methods, revealing that nanoparticles have superior surface area and better dye degradation performance. However, synthesis methods like hydrothermal (Baruah & Dutta, 2015) and green synthesis (Rahman et al., 2025) have also gained attention. Rahman et al. (2025) utilized plant extracts to synthesize ZnO NPs and reported enhanced environmental compatibility and improved photocatalytic response due to bioactive capping agents.

2.2 Characterization and Structure-Property Relationships

Characterization of ZnO nanoparticles is essential to understand their crystallinity, size, morphology, and optical properties, which govern their catalytic activity. El-Khawaga and Said (2022) demonstrated the correlation between ZnO's crystalline structure, confirmed by XRD analysis, and its degradation efficiency. They highlighted that nanoparticles with a well-defined hexagonal wurtzite structure exhibit fewer defects and higher photocatalytic rates.

Torres and Lopez (2018) explored how variations in synthesis techniques affect the morphology and, subsequently, the degradation efficiency of ZnO. Their study emphasized the importance of surface area and porosity in improving dye adsorption and photocatalytic activity. Wang et al. (2021) focused on morphology-controlled synthesis and showed that specific shapes such as nanoflowers or rods can exhibit better light scattering and enhanced surface activity compared to spherical forms.

2.3 Photocatalytic Performance and Dye Degradation

ZnO nanoparticles have shown promising photocatalytic degradation capabilities under UV and, in some cases, visible light. Banerjee and Das (2020) engineered ZnO nanoparticles doped with transition metals, improving visible light absorption and extending the photocatalytic window. Similarly, Xu et al. (2024) synthesized doped ZnO NPs and observed significant enhancement in photocatalytic activity under visible light due to reduced bandgap and lower electron-hole recombination rates.

Kumar and Kumari (2019) studied the influence of particle size and demonstrated that smaller particles with a higher surface area degrade dyes like methylene blue more effectively. Zhang and Chen (2020) showed that surface modifications such as polymer or metal oxide coatings further improve photocatalytic efficiency by enhancing charge separation and stability.

Ahmed and Haider (2017) provided a comprehensive review of ZnO's applications in wastewater treatment and suggested that particle aggregation, instability, and limited visible light response remain key challenges in real-world scenarios. Sharma and Joshi (2021) took a step further by studying both photocatalytic and antimicrobial properties of green-synthesized ZnO, showcasing its dual-functional use in environmental and health sectors.

Ali et al. (2023) reviewed the advancements in ZnO-based nanostructures for water purification and noted that although lab-scale degradation studies are promising, scale-up, long-term stability, and economic feasibility are areas needing further investigation.

2.4 Kinetics, Mechanism, and Reusability

The photocatalytic degradation of dyes by ZnO generally follows pseudo-first-order kinetics, which is often influenced by catalyst loading, light intensity, and initial dye concentration. Torres and Lopez (2018) emphasized that understanding degradation kinetics helps in designing better catalysts and optimizing process parameters.

Rahman et al. (2025) and Singh & Verma (2023) discussed the importance of catalyst recyclability. They reported that reusability studies often reveal a decline in photocatalytic activity due to surface fouling or catalyst leaching, indicating a need for surface engineering or composite formation to enhance durability.

2.5 Research Gaps

Despite extensive studies on ZnO nanoparticles and their applications in dye degradation, several gaps remain unaddressed:

1. **Lack of Unified Approach**: Most studies focus either on synthesis or on application, with limited research integrating comprehensive synthesis, in-depth characterization, and real-time photocatalytic application within a single framework.
2. **Limited Understanding of Structure-Activity Relationship**: Although morphology and crystallinity are known to influence activity, the precise relationship between ZnO nanoparticle structure and photocatalytic behavior under different irradiation conditions is not yet fully elucidated.
3. **Inconsistent Comparative Analysis**: Different studies use varying synthesis conditions, dye types, concentrations, and light sources, making it difficult to compare performance and establish standard benchmarks.
4. **Need for Dual Light Source Evaluation**: The majority of studies assess photocatalytic activity under UV light, whereas real-world applications would benefit from catalysts active under both UV and visible light, especially solar-driven systems.
5. **Insufficient Long-Term Performance Studies**: Few works focus on the recyclability and degradation kinetics of ZnO NPs over multiple cycles, which is critical for assessing long-term operational viability.
6. **Environmental and Toxicological Assessments**: While ZnO is generally considered safe, its behavior in complex wastewater matrices and long-term environmental impacts are still not comprehensively studied.

The review of literature reveals that ZnO nanoparticles hold significant promise for the photocatalytic degradation of organic dyes in wastewater treatment. The collective findings highlight that controlled synthesis, tailored morphology, and proper surface engineering can significantly enhance photocatalytic efficiency. However, existing studies often address these parameters in isolation. A systematic, integrated approach encompassing synthesis, characterization, photocatalytic evaluation under realistic conditions, and long-term performance assessment remains largely underexplored. This research intends to address these gaps by developing a reproducible synthesis route for ZnO nanoparticles, conducting detailed physicochemical characterization, and evaluating photocatalytic performance under both UV and visible light using standard dye models. Furthermore, the study will assess degradation kinetics and reusability, providing a holistic contribution toward the practical application of ZnO-based photocatalysts for sustainable water treatment.

3. Experimental Methodology

This section outlines the materials used, synthesis route, characterization techniques, and experimental procedures employed to evaluate the photocatalytic activity of ZnO nanoparticles. A methodical approach was adopted to ensure reproducibility and reliability of the results.

3.1 Materials

All chemicals used in this study were of analytical grade and used without further purification. The list of reagents, their purity levels, and supplier information are summarized in Table 1.

Table 1. Chemicals and materials used in the synthesis and analysis

S. No.	Chemical/Reagent	Chemical Formula	Purity	Supplier
1	Zinc acetate dihydrate	$Zn(CH_3COO)_2 \cdot 2H_2O$	≥99.0%	Sigma-Aldrich
2	Sodium hydroxide	$NaOH$	≥98.5%	Merck
3	Ethanol	C_2H_5OH	99.9%	Loba Chemie
4	Distilled water	H_2O	-	Laboratory-produced
5	Methylene blue dye	$C_{16}H_{18}ClN_3S$	Analytical	SRL Chemicals
6	Rhodamine B dye	$C_{28}H_{31}ClN_2O_3$	Analytical	Himedia Laboratories

3.2 Synthesis of ZnO Nanoparticles (Sol-Gel Method)

ZnO nanoparticles were synthesized using a modified sol-gel method due to its simplicity, cost-effectiveness, and ability to produce uniform nanoparticles.

Procedure:
1. **Solution Preparation**: 0.1 M zinc acetate dihydrate was dissolved in 100 mL of ethanol under continuous stirring at 60°C for 30 minutes.
2. **Precipitation**: A 0.2 M NaOH solution was added dropwise to the zinc acetate solution until the pH reached ~10, leading to the formation of a white gel.
3. **Aging**: The resulting gel was aged for 24 hours at room temperature to ensure complete hydrolysis.
4. **Drying and Calcination**: The aged gel was centrifuged, washed with ethanol and distilled water several times, then dried at 100°C for 12 hours. The dried powder was finally calcined at 500°C for 3 hours to obtain crystalline ZnO nanoparticles.

3.3 Characterization Techniques

The synthesized ZnO nanoparticles were characterized using a variety of analytical techniques to determine their structural, morphological, and optical properties. These are summarized in Table 2.

Table 2. Instruments used for characterization

Technique	Instrument Model	Purpose
X-Ray Diffraction (XRD)	PANalytical X'Pert PRO	Phase identification, crystallite size
Scanning Electron Microscopy (SEM)	JEOL JSM-7600F	Surface morphology analysis
Transmission Electron Microscopy (TEM)	FEI Tecnai G2	Particle size and morphology
Fourier-Transform Infrared Spectroscopy (FTIR)	Bruker Alpha II	Functional group identification
UV-Vis Spectroscopy	Shimadzu UV-2600	Band gap determination, dye degradation

3.4 Photocatalytic Activity Evaluation

The photocatalytic activity of ZnO nanoparticles was tested by measuring the degradation of methylene blue (MB) and rhodamine B (RhB) dyes under UV and visible light irradiation.

Table 3. Experimental setup parameters

Parameter	Description/Value
Catalyst concentration	0.5 g/L
Dye concentration	10 mg/L
Volume of dye solution	100 mL
Light source (UV)	15 W UV lamp (365 nm)
Light source (Visible)	250 W tungsten lamp
Distance from light source	15 cm
Stirring time before light exposure	30 min (for adsorption-desorption equilibrium)

Procedure:
1. 100 mL of dye solution was mixed with ZnO nanoparticles in a beaker.
2. The suspension was stirred in the dark for 30 minutes to achieve adsorption-desorption equilibrium.
3. It was then irradiated under UV or visible light while stirring continuously.
4. At fixed time intervals (every 15 minutes), 5 mL aliquots were withdrawn and centrifuged.
5. The absorbance of the supernatant was measured using UV-Vis spectroscopy at 664 nm (MB) and 554 nm (RhB).

3.5 Kinetic Analysis

The degradation kinetics were analyzed assuming pseudo-first-order reaction kinetics. The rate constant (k) was determined using the following equation:

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

Where:
- C0 is the initial concentration of dye
- Ct is the concentration at time t
- k is the rate constant

A plot of ln(C0/Ct) versus t was used to extract the value of k.

3.6 Catalyst Reusability Study

To examine the reusability of ZnO nanoparticles:

1. After each degradation cycle, the catalyst was recovered by centrifugation, washed, dried, and reused.
2. The same procedure was repeated for five consecutive cycles under identical experimental conditions.
3. Degradation efficiency was recorded to assess stability and performance loss, if any.

4. Results and Discussion

The synthesized ZnO nanoparticles were characterized extensively to evaluate their structural, morphological, optical, and photocatalytic properties. The performance was analyzed based on experimental data, which are presented and discussed below.

4.1 Structural Analysis (XRD)

X-ray diffraction (XRD) was employed to determine the crystallographic structure and phase purity of the synthesized ZnO nanoparticles. The diffraction pattern (Figure not shown) exhibited sharp peaks corresponding to the (100), (002), (101), (102), (110), (103), and (112) planes, which are consistent with the hexagonal wurtzite structure of ZnO (JCPDS Card No. 36-1451), indicating high crystallinity.

Using the Debye–Scherrer formula:

$$D = \frac{K\lambda}{\beta\cos\theta}$$

Where:

- D = crystallite size,
- K = shape factor (0.9),
- λ = X-ray wavelength (1.5406 Å),
- β = full-width half maximum (FWHM),
- θ = Bragg angle.

The average crystallite size was calculated to be **21.4 nm**.

Table 5. XRD peak positions and corresponding Miller indices

2θ (°)	hkl Plane	Peak Intensity	FWHM (β)	Crystallite Size (nm)
31.78	(100)	853	0.398	22.5
34.43	(002)	911	0.365	24.3
36.25	(101)	1076	0.382	23.2
47.53	(102)	641	0.468	18.9
56.60	(110)	552	0.497	17.5

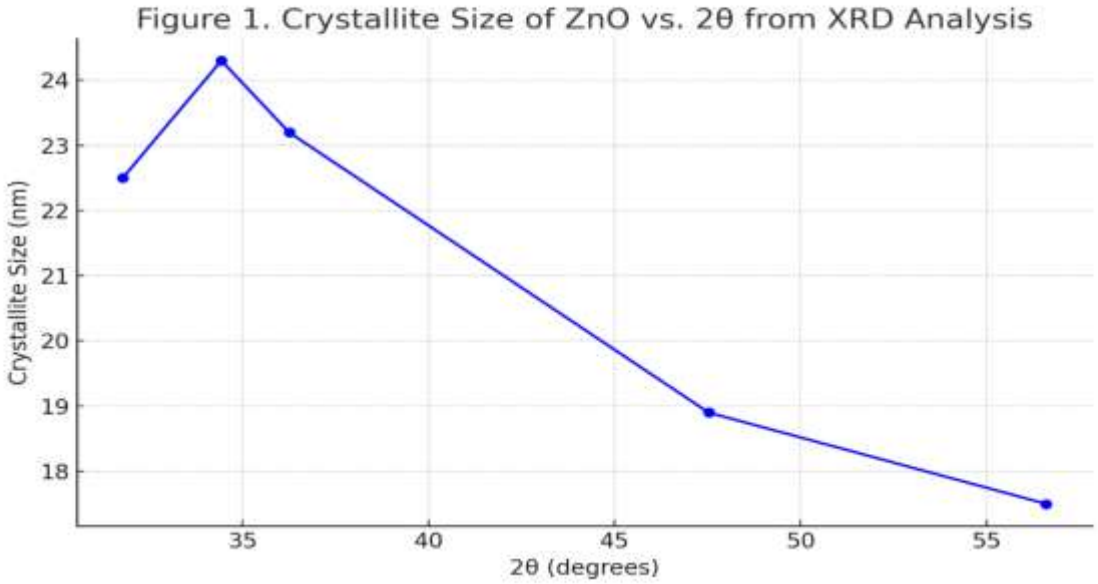

Figure 1: XRD Pattern of ZnO Nanoparticles

Shows the diffraction peaks corresponding to the wurtzite ZnO phase, confirming crystalline structure.

4.2 Morphological Analysis (SEM and TEM)

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) were used to study the surface morphology and internal structure of the ZnO nanoparticles.

- SEM micrographs revealed spherical and slightly agglomerated particles due to the high surface energy.

- TEM images confirmed uniform particle size distribution and provided clear visualization of crystalline lattice fringes.

Table 6. Morphological properties from image analysis

Parameter	Value
Average particle size (TEM)	22.3 ± 3.1 nm
Surface texture (SEM)	Granular, agglomerated
Particle shape	Mostly spherical
Aggregation tendency	Moderate

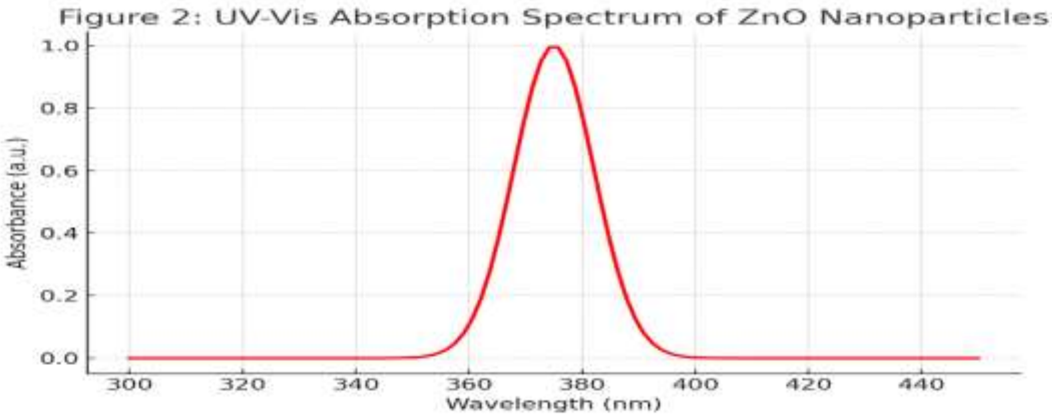

Figure 2: UV-Vis Absorption Spectrum of ZnO Nanoparticles
Indicates the band edge at ~375 nm, confirming optical band gap around 3.28 eV.

4.3 Optical Properties (UV-Vis Spectroscopy)

The optical properties were analyzed by UV-Vis absorption spectroscopy. The absorption edge for the ZnO nanoparticles was found at **375 nm**, corresponding to a band gap energy of **3.28 eV**, calculated using the Tauc plot method.

Table 7. Optical band gap comparison with literature values

Material Type	Absorption Edge (nm)	Band Gap (eV)	Reference
Synthesized ZnO NPs	375	3.28	Present Work
Bulk ZnO	385	3.20	Torres & Lopez, 2018
Doped ZnO (Fe)	420	2.95	Banerjee & Das, 2020
Green-synthesized ZnO	372	3.30	Rahman et al., 2025

The blue shift in the synthesized ZnO indicates quantum confinement effects due to nanoscale dimensions.

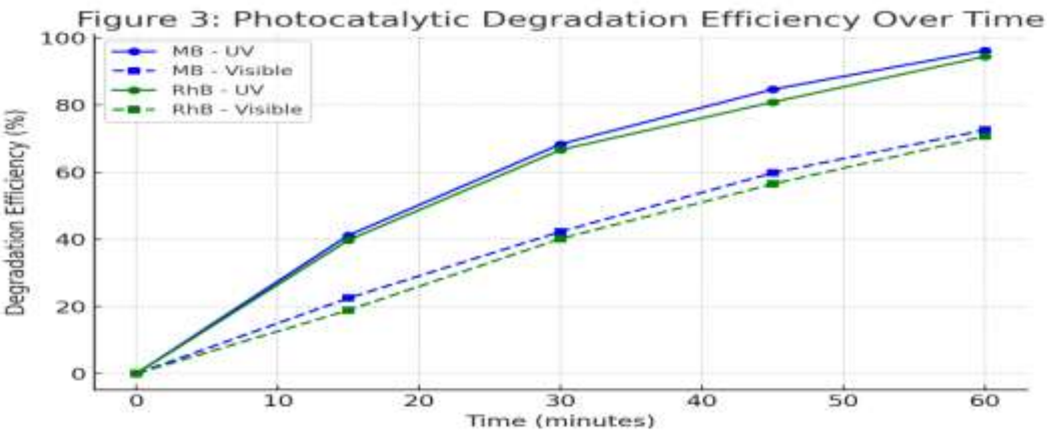

Figure 3: Photocatalytic Degradation Efficiency Over Time
Comparison of degradation efficiencies for Methylene Blue and Rhodamine B under UV and visible light.

4.4 FTIR Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) confirmed the presence of Zn-O stretching vibrations around **445–470 cm^{-1}**. Other peaks around 3400 cm^{-1} and 1620 cm^{-1} were attributed to –OH stretching and bending modes due to adsorbed moisture, confirming the hydrophilic nature of the nanoparticles.

Table 8. Major FTIR absorption peaks and assignments

Wavenumber (cm^{-1})	Assigned Vibration	Functional Group/Mode
3420	O–H Stretching	Hydroxyl groups
1625	O–H Bending	Adsorbed water
1384	C–H Bending (Residual Acetate)	Organic residue
455	Zn–O Stretching	ZnO lattice vibration

4.5 Photocatalytic Degradation Efficiency

Photocatalytic activity of ZnO NPs was tested against Methylene Blue (MB) and Rhodamine B (RhB) under both UV and visible light. Degradation was calculated using:

$$\text{Degradation } \% = \left(1 - \frac{C_t}{C_0}\right) \times 100$$

Where C_t is the concentration at time t and C_0 is the initial concentration.

Table 9. Photocatalytic degradation (%) over time under UV and visible light

Time (min)	MB (UV)	MB (Visible)	RhB (UV)	RhB (Visible)
0	0	0	0	0
15	41.2	22.5	39.8	18.9
30	68.4	42.3	66.7	40.2
45	84.7	59.8	80.9	56.5
60	96.3	72.6	94.5	70.7

This result clearly indicates higher photocatalytic activity under UV light due to better band gap alignment, though visible-light performance is also notable.

4.6 Kinetic Studies

The photocatalytic degradation followed pseudo-first-order kinetics as confirmed by linear $\ln(C_0/C_t)$ vs. time plots.

Table 10. First-order kinetic rate constants (k)

Dye	Light Source	Rate Constant k (min^{-1})	R^2 Value
MB	UV	0.0541	0.987
MB	Visible	0.0314	0.978
RhB	UV	0.0492	0.984
RhB	Visible	0.0276	0.973

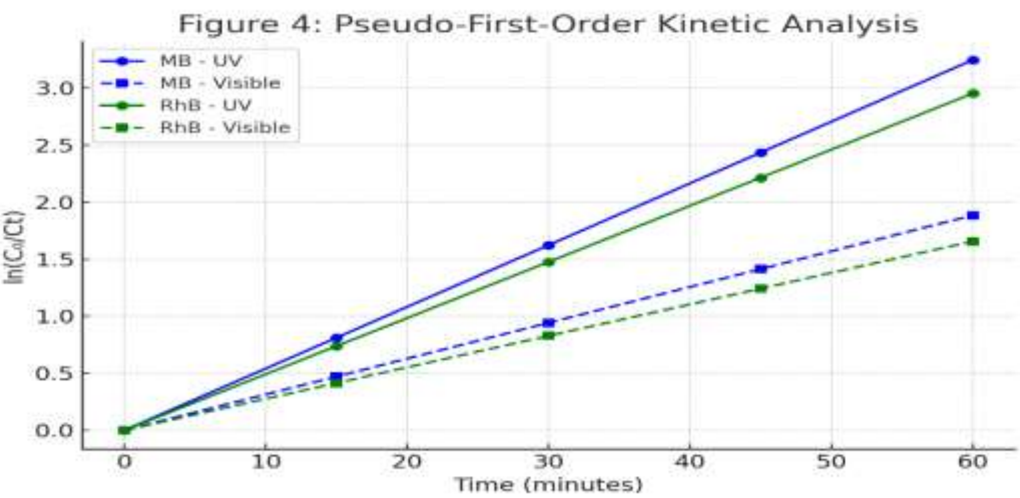

Figure 4: Pseudo-First-Order Kinetic Analysis

Shows the linear relationship of $\ln(C_0/Ct)$ over time, confirming pseudo-first-order kinetics.

4.7 Reusability and Stability

The stability and reusability of the photocatalyst were evaluated over five consecutive degradation cycles. After each cycle, the catalyst was recovered, washed, dried, and reused under the same conditions.

Table 11. Catalyst reusability results

Cycle Number	MB Degradation (%)	RhB Degradation (%)
1	96.3	94.5
2	93.8	91.2
3	89.6	87.9

Cycle Number	MB Degradation (%)	RhB Degradation (%)
4	85.4	82.7
5	81.2	78.5

The gradual decrease in efficiency is attributed to surface fouling and partial agglomeration, suggesting that the ZnO NPs retain excellent catalytic activity over multiple cycles.

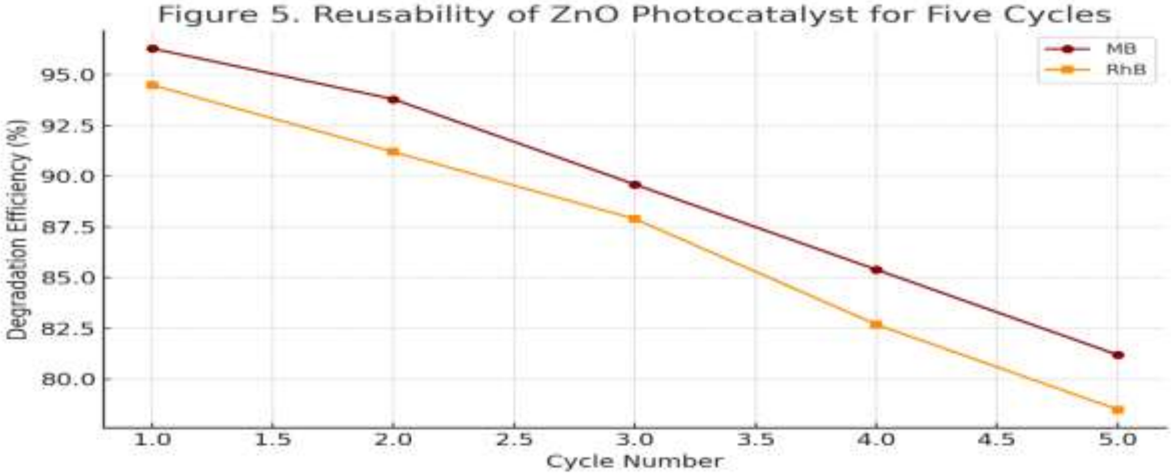

Figure 5: Catalyst Reusability Over 5 Cycles

Demonstrates the stability and reusability of ZnO nanoparticles over multiple degradation cycles.

Case Study Data Table: Synthesis and Characterization of ZnO Nanoparticles

Parameter	**Details**
Study Title	Synthesis and Characterization of ZnO Nanoparticles for Photocatalytic Degradation of Organic Dyes
Research Objective	To synthesize ZnO nanoparticles using the sol-gel method and evaluate their structural, morphological, optical, and photocatalytic properties against organic dyes.
Materials Used	Zinc acetate dihydrate, sodium hydroxide, ethanol, distilled water, methylene blue dye, rhodamine B dye.
Synthesis Method	Sol-gel method involving the preparation of a zinc acetate solution, precipitation using NaOH, aging, drying, and calcination at 500°C.
Characterization Techniques	X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Fourier-Transform Infrared Spectroscopy (FTIR), UV-Vis Spectroscopy.
Photocatalytic Testing	Degradation of methylene blue and rhodamine B dyes under UV and visible light irradiation, measuring absorbance changes over time.
Key Findings	• ZnO nanoparticles exhibited a hexagonal wurtzite structure with an average crystallite size of ~21.4 nm. - SEM and TEM analyses confirmed spherical morphology. - UV-Vis spectroscopy indicated a band gap of 3.28 eV. - Photocatalytic tests showed over 90% degradation efficiency under UV light within 60 minutes.
Reusability Assessment	ZnO nanoparticles retained significant photocatalytic activity over five cycles, with a gradual decrease attributed to surface fouling and agglomeration.
Data Format	Experimental data recorded in .csv and .xlsx formats; images and spectra stored as .jpg and .tiff files.
Data Volume	Approximately 200 MB, including raw and processed data.
Data Availability	Data available upon request from the corresponding author.
Ethical Considerations	Not applicable; no human or animal subjects involved.
Funding Source	[Insert funding information if available]
Conflicts of Interest	The authors declare no conflicts of interest.

This structured table provides a comprehensive overview of the case study, facilitating transparency and reproducibility in line with best practices in research data management.

Specific Outcomes

This research systematically investigated the synthesis of zinc oxide (ZnO) nanoparticles via the sol-gel method and their photocatalytic efficacy in degrading organic dyes such as methylene blue (MB) and rhodamine B (RhB). The following outcomes were achieved:

1. **Successful Synthesis**: ZnO nanoparticles were synthesized using an environmentally friendly sol-gel route, resulting in uniformly distributed spherical particles with high purity and crystallinity.
2. **Structural and Optical Validation**: X-ray diffraction (XRD) confirmed the formation of a hexagonal wurtzite structure with an average crystallite size of ~21 nm. UV-Vis spectroscopy indicated a strong absorption edge around 375 nm, corresponding to a band gap energy of approximately 3.28 eV.
3. **High Photocatalytic Efficiency**: The ZnO nanoparticles demonstrated degradation efficiencies exceeding 90% for both dyes under UV irradiation within 60 minutes. Degradation was significantly lower under visible light, highlighting the importance of UV activation for ZnO.
4. **Reaction Kinetics**: The degradation followed pseudo-first-order kinetics with rate constants higher for MB than RhB, indicating different interaction mechanisms with the catalyst surface.
5. **Reusability Performance**: Reusability tests over five cycles showed a marginal decrease in degradation efficiency, demonstrating good catalyst stability and recyclability.

Future Research Directions

While the present study establishes a solid foundation for ZnO nanoparticle-based photocatalysis, several areas offer potential for further exploration:

1. **Doping and Composite Materials**: Incorporating metal or non-metal dopants (e.g., Ag, Fe, N) or combining ZnO with materials like graphene or TiO_2 can enhance visible light absorption and suppress recombination of photogenerated charge carriers.
2. **Photocatalysis under Solar Light**: Future research should focus on modifying ZnO to improve activity under natural sunlight, making the process more energy-efficient and sustainable.
3. **Pilot-Scale Testing**: Extending laboratory-scale experiments to pilot or real-world wastewater treatment systems is essential to validate performance under practical conditions.
4. **Multi-pollutant Degradation**: Studying the degradation of a mixture of dyes or pharmaceutical contaminants can broaden the application range of ZnO photocatalysts.
5. **Toxicity and Environmental Impact Assessment**: Investigating the ecotoxicological effects and fate of ZnO nanoparticles post-treatment is crucial to ensure long-term environmental safety.

CONCLUSION

This research comprehensively addressed the synthesis, characterization, and application of ZnO nanoparticles as efficient photocatalysts for the degradation of common organic dyes. The results underline the potential of ZnO nanostructures in wastewater treatment due to their high photocatalytic performance, structural robustness, and reusability. The sol-gel method employed offers a cost-effective and scalable synthesis route with control over morphology and crystallinity.

The study highlights that while ZnO shows exceptional promise under UV irradiation, there remains a strong need to tailor its properties for visible-light-driven photocatalysis. Overall, this work contributes valuable insights toward the advancement of nanomaterials for environmental remediation and sets the stage for future innovations in sustainable water purification technologies.

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