



**Comparative Evaluation of Plant-Mediated Zinc Oxide and Titanium Dioxide Nanoparticles for Photocatalytic Degradation of Industrial Dyes in Wastewater**

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**ABSTRACT**

Water pollution caused by industrial dyes has become a significant environmental challenge due to the persistence, toxicity, and non-biodegradable nature of synthetic colorants. Conventional wastewater treatment methods often fail to completely degrade such pollutants, leading to the accumulation of hazardous compounds in aquatic ecosystems. In this context, nanotechnology-based approaches, particularly metal oxide nanoparticles, have emerged as efficient alternatives for dye removal. The present study focuses on the comparative evaluation of plant-mediated zinc oxide (ZnO) and titanium dioxide (TiO<sub>2</sub>) nanoparticles for the photocatalytic degradation of industrial dyes in wastewater.

The nanoparticles were synthesized using environmentally friendly green synthesis techniques involving plant extracts rich in phytochemicals such as flavonoids, phenolics, and alkaloids. These biomolecules act as reducing and stabilizing agents, eliminating the need for toxic chemicals in nanoparticle fabrication. The synthesized ZnO and TiO<sub>2</sub> nanoparticles were characterized using UV-Visible spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) to determine their optical properties, crystalline structure, morphology, and functional groups.

The photocatalytic activity of the nanoparticles was evaluated using model dye pollutants such as methylene blue and congo red under controlled laboratory conditions. Experimental parameters including pH, catalyst dosage, contact time, and initial dye concentration were optimized to assess degradation efficiency. The comparative analysis revealed that both ZnO and TiO<sub>2</sub> nanoparticles exhibit significant photocatalytic performance, with degradation efficiencies exceeding 85% under optimal conditions. However, variations in efficiency were observed depending on operational parameters and light exposure conditions.

**KEYWORDS**

Green synthesis, Zinc oxide nanoparticles, Titanium dioxide nanoparticles, Photocatalysis, Industrial dyes, Wastewater treatment, Nanotechnology, Environmental remediation

**1. INTRODUCTION**

Water pollution is one of the most critical environmental issues of the twenty-first century. Rapid industrialization and urban expansion have significantly increased the release of untreated wastewater into natural water bodies. Among various pollutants, synthetic dyes



represent a major category due to their extensive use in textile, paper, leather, pharmaceutical, and food industries. These dyes are chemically stable, resistant to biodegradation, and often toxic, posing serious threats to aquatic ecosystems and human health.

Industrial dyes such as methylene blue, congo red, rhodamine B, and crystal violet are widely detected in wastewater streams. Their presence in water reduces light penetration, disrupts photosynthetic activity, and leads to oxygen depletion. Moreover, many dyes and their degradation products are carcinogenic, mutagenic, and toxic to living organisms. Conventional wastewater treatment techniques, including coagulation, flocculation, adsorption, and biological treatment, have limitations in completely removing these contaminants.

In recent years, nanotechnology has emerged as a promising field for addressing environmental challenges. Metal oxide nanoparticles, particularly zinc oxide (ZnO) and titanium dioxide (TiO<sub>2</sub>), have gained considerable attention due to their excellent photocatalytic properties. These nanoparticles can degrade organic pollutants into harmless end products such as carbon dioxide and water through oxidation-reduction reactions under light irradiation.

However, traditional synthesis methods of nanoparticles often involve toxic chemicals and energy-intensive processes, raising environmental concerns. To overcome these limitations, green synthesis approaches using plant extracts have been developed. These methods utilize natural biomolecules to synthesize nanoparticles in an eco-friendly and sustainable manner.

The present study aims to compare the photocatalytic efficiency of plant-mediated ZnO and TiO<sub>2</sub> nanoparticles in degrading industrial dyes. By evaluating their performance under different experimental conditions, this research seeks to identify the most effective nanoparticle system for wastewater treatment applications.

## **2. AIMS AND OBJECTIVES**

### **2.1 Aim**

To comparatively evaluate the photocatalytic efficiency of plant-mediated zinc oxide and titanium dioxide nanoparticles for the degradation of industrial dyes in wastewater.

### **2.2 Objectives**

1. To synthesize ZnO and TiO<sub>2</sub> nanoparticles using plant extracts.
2. To characterize the synthesized nanoparticles using standard analytical techniques.
3. To evaluate the photocatalytic degradation efficiency of both nanoparticles.
4. To compare the performance of ZnO and TiO<sub>2</sub> under varying experimental conditions.
5. To assess the environmental sustainability and applicability of green-synthesized nanoparticles.

## **3. REVIEW OF LITERATURE**

Green nanotechnology integrates biological systems with material science to develop environmentally friendly nanomaterials. Numerous studies have reported the successful synthesis of metal oxide nanoparticles using plant extracts. Phytochemicals present in plants

act as reducing agents and stabilizers, enabling the formation of nanoparticles under mild conditions.

ZnO nanoparticles are widely studied for their photocatalytic and antimicrobial properties. They exhibit strong absorption in the UV region and can generate reactive oxygen species (ROS) that degrade organic pollutants. TiO<sub>2</sub> nanoparticles, on the other hand, are known for their chemical stability, non-toxicity, and high photocatalytic efficiency, especially under UV light.

**Table 1: Comparative Properties of ZnO and TiO<sub>2</sub> Nanoparticles**

Property	ZnO	TiO <sub>2</sub>
Band Gap	~3.37 eV	~3.2 eV
Light Activity	UV & Visible	Mainly UV
Stability	Moderate	High
Cost	Low	Moderate
Photocatalytic Efficiency	High	Very High

Several researchers have demonstrated dye degradation efficiencies above 85–95% using these nanoparticles. However, differences in synthesis methods, operational conditions, and environmental factors influence their performance.

Despite significant advancements, research gaps still exist in comparative analysis, large-scale applications, and long-term environmental impacts of nanoparticles.

#### 4. RESEARCH METHODOLOGY

##### 4.1 Research Design

The study follows an experimental laboratory-based design focusing on synthesis, characterization, and application of nanoparticles.

##### 4.2 Materials Used

- Plant extracts (Neem, Tulsi, Aloe vera)
- Metal precursors:
  - Zinc nitrate (Zn(NO<sub>3</sub>)<sub>2</sub>)
  - Titanium tetrachloride (TiCl<sub>4</sub>)
- Model dyes (Methylene blue, Congo red)

**Table 2: Methodological Framework**

Stage	Technique
Extraction	Aqueous plant extraction
Synthesis	Green reduction method
Characterization	UV–Vis, XRD, SEM, FTIR
Application	Photocatalytic degradation
Analysis	Spectrophotometric analysis

##### 4.3 Synthesis Procedure

Plant extracts were prepared by boiling plant materials in distilled water and filtering the solution. The extract was mixed with metal salt solutions under controlled conditions. The formation of nanoparticles was indicated by a visible color change.

**4.4 Characterization Techniques**

- **UV–Vis Spectroscopy:** Determines optical properties.
- **XRD:** Identifies crystalline structure.
- **SEM:** Examines morphology and particle size.
- **FTIR:** Detects functional groups.

**4.5 Photocatalytic Experiment**

Synthetic dye solutions were treated with nanoparticles under light irradiation. Samples were collected at regular intervals to measure dye degradation using spectrophotometric methods.

**Table 3: Experimental Parameters**

Parameter	Range
pH	4–10
Catalyst Dose	0.1–1 g/L
Time	0–120 min
Dye Concentration	10–50 mg/L

**5. RESULTS AND INTERPRETATION**

**5.1 Introduction**

The results obtained from the experimental study provide a comprehensive understanding of the photocatalytic efficiency of plant-mediated zinc oxide (ZnO) and titanium dioxide (TiO<sub>2</sub>) nanoparticles. The performance evaluation was carried out based on dye degradation efficiency, influence of operational parameters, and comparative effectiveness of both nanomaterials.

**5.2 Preliminary Observations**

During synthesis, the formation of nanoparticles was indicated by a distinct color change in the reaction mixture. ZnO nanoparticles exhibited a pale white suspension, whereas TiO<sub>2</sub> nanoparticles showed a milky white appearance. These observations confirmed successful nanoparticle formation through green synthesis.

**5.3 Photocatalytic Degradation Efficiency**

The degradation efficiency of both nanoparticles was evaluated using methylene blue and congo red dyes under optimized laboratory conditions.

**Table 4: Dye Degradation Efficiency**

Dye	Initial Conc. (mg/L)	Final Conc. (mg/L) ZnO	Removal % ZnO	Final Conc. (mg/L) TiO <sub>2</sub>	Removal % TiO <sub>2</sub>
Methylene Blue	30	2.1	93.0	1.5	95.0

Congo Red	30	3.0	90.0	2.2	92.7
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**Interpretation**

The results indicate that both ZnO and TiO<sub>2</sub> nanoparticles demonstrate high photocatalytic efficiency. However, TiO<sub>2</sub> showed slightly higher degradation efficiency compared to ZnO under similar conditions. This can be attributed to its superior stability and strong oxidative potential.

**5.4 Effect of Contact Time**

The degradation efficiency increased with an increase in contact time due to prolonged interaction between dye molecules and catalyst surface.

**Table 5: Effect of Contact Time on Dye Removal**

Time (min)	Removal % ZnO	Removal % TiO <sub>2</sub>
20	45	50
40	65	70
60	80	85
90	90	93
120	93	95

**Interpretation**

The data show that degradation efficiency increases rapidly in the initial phase and then gradually reaches equilibrium. TiO<sub>2</sub> consistently exhibited higher removal percentages.

**5.5 Effect of Catalyst Dose**

Increasing catalyst dosage enhances the number of active sites available for degradation.

**Table 6: Effect of Catalyst Dose**

Dose (g/L)	Removal % ZnO	Removal % TiO <sub>2</sub>
0.1	60	65
0.3	75	80
0.5	85	90
1.0	93	95

**Interpretation**

Higher catalyst dosage improves degradation efficiency up to an optimal limit, beyond which aggregation may reduce effectiveness.

**5.6 Effect of pH**

pH plays a crucial role in photocatalytic reactions by influencing surface charge and dye ionization.

**Table 7: Effect of pH on Dye Removal**

pH	Removal % ZnO	Removal % TiO <sub>2</sub>
4	70	75
6	85	88
7	90	92



9	93	95
10	92	94

### **Interpretation**

Maximum efficiency was observed under slightly alkaline conditions. Both nanoparticles showed improved performance at higher pH values.

### **5.7 Characterization Results**

#### **UV–Vis Analysis**

Absorption peaks confirmed nanoparticle formation and optical properties.

#### **XRD Analysis**

XRD patterns revealed crystalline nature of both ZnO and TiO<sub>2</sub> nanoparticles.

#### **SEM Analysis**

SEM images showed spherical morphology with nanoscale particle size.

#### **FTIR Analysis**

Functional groups confirmed the role of plant biomolecules in stabilization.

### **6. DISCUSSION**

The comparative analysis clearly demonstrates that both ZnO and TiO<sub>2</sub> nanoparticles synthesized through green methods are highly effective in degrading industrial dyes. The enhanced performance is primarily due to the nanoscale size, increased surface area, and presence of active catalytic sites.

TiO<sub>2</sub> nanoparticles exhibited slightly higher efficiency due to their strong oxidative potential and chemical stability. However, ZnO nanoparticles showed better performance under visible light conditions, making them suitable for solar-driven applications.

The role of plant extracts in nanoparticle synthesis is significant, as they provide eco-friendly stabilization and enhance catalytic activity. The presence of phytochemicals improves adsorption capacity and facilitates electron transfer processes during photocatalysis.

The study also highlights the importance of optimizing experimental parameters such as pH, catalyst dose, and contact time to achieve maximum efficiency. The results align with previous studies but provide a clearer comparative understanding between ZnO and TiO<sub>2</sub> nanoparticles.

### **7. CONCLUSION**

The present study successfully demonstrates the effectiveness of plant-mediated zinc oxide and titanium dioxide nanoparticles for the photocatalytic degradation of industrial dyes in wastewater. Both nanoparticles exhibited high removal efficiencies, exceeding 90% under optimized conditions.

TiO<sub>2</sub> nanoparticles showed superior stability and slightly higher degradation efficiency, while ZnO nanoparticles offered advantages in visible light activity and cost-effectiveness. The green synthesis approach proved to be environmentally friendly, economical, and sustainable.



The findings suggest that these nanoparticles can serve as promising alternatives to conventional wastewater treatment methods. However, further research is required for large-scale implementation and evaluation of long-term environmental impacts.

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