INTERNATIONAL JOURNAL OF ECONOMIC SOCIAL SCIENCE AND MANAGEMENT LAW
Peer Reviewed, Referred & Indexed Journal
E-ISSN: 3070-0558
VOL.5, NO.3 (2024)

Green Synthesis and Photocatalytic Performance of Zinc Oxide Nanoparticles for Organic Dye Degradation in Wastewater Treatment

DR L MAHESWARA REDDY
Academic Consultant, Department of Science and Humanities,
Y.S.R. Engineering College of YVU, Proddatur - 516360
Mail id: lebakamaheswarareddy@gmail.com

ABSTRACT: *The increasing discharge of dye-containing industrial wastewater from textile, leather, paper, pharmaceutical, and printing industries has become a significant environmental concern due to its adverse effects on aquatic ecosystems and human health. Conventional wastewater treatment methods often fail to achieve complete mineralization of persistent organic dyes because of their complex molecular structures and high chemical stability. Semiconductor metal oxide nanoparticles have emerged as promising photocatalysts for advanced wastewater treatment owing to their high surface area, excellent catalytic activity, and environmental compatibility. Among various semiconductor materials, zinc oxide (ZnO) nanoparticles have attracted considerable attention because of their wide band gap, strong ultraviolet absorption, high electron mobility, low toxicity, and cost-effective synthesis. This research investigates the green synthesis of zinc oxide nanoparticles using plant-mediated reducing and stabilizing agents and evaluates their photocatalytic performance toward the degradation of organic dyes in wastewater. The synthesized ZnO nanoparticles are characterized using X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), UV–Visible spectroscopy, and Photoluminescence (PL) analysis to determine their structural, morphological, and optical properties. Photocatalytic degradation experiments are performed under ultraviolet irradiation using methylene blue as the model organic dye. The degradation efficiency, reaction kinetics, catalyst reusability, and operational parameters including catalyst dosage, dye concentration, solution pH, and irradiation time are systematically investigated. The experimental results demonstrate that green synthesized ZnO nanoparticles exhibit excellent photocatalytic activity with high degradation efficiency, rapid reaction kinetics, and remarkable stability during repeated usage. The proposed environmentally friendly synthesis strategy provides an effective, sustainable, and economically feasible approach for developing efficient photocatalysts suitable for large-scale wastewater treatment applications.*

INTRODUCTION

Rapid industrialization and urbanization have substantially increased the discharge of wastewater containing toxic organic dyes into natural water bodies. Textile manufacturing, leather processing, pharmaceutical production, food coloring industries, paper mills, and printing facilities collectively release enormous quantities of colored effluents that contain chemically stable synthetic dyes resistant to natural biodegradation. These pollutants not only reduce light penetration into aquatic ecosystems but also adversely affect photosynthetic activity, dissolved oxygen concentration, and overall ecological balance. Many synthetic dyes possess carcinogenic, mutagenic, and toxic characteristics, posing severe risks to aquatic organisms as well as human health through contamination of drinking water resources. Consequently, the development of efficient, environmentally sustainable, and economically viable wastewater treatment technologies has become one of the most important research priorities in environmental chemistry and materials science.

Numerous conventional wastewater treatment methods including coagulation, flocculation, adsorption, membrane filtration, biological treatment, ion exchange, and chemical oxidation have been employed to remove organic dyes

from industrial wastewater. Although these techniques effectively reduce pollutant concentrations under certain operating conditions, they frequently suffer from several limitations including incomplete degradation, secondary sludge generation, high operational cost, membrane fouling, and limited effectiveness against chemically stable dye molecules. Adsorption-based techniques transfer contaminants from one phase to another without complete destruction of pollutant molecules, while biological treatment processes often fail to degrade complex aromatic dye structures because of their low biodegradability. These challenges have motivated researchers to explore advanced oxidation processes capable of achieving complete mineralization of persistent organic contaminants.

Semiconductor photocatalysis has emerged as one of the most promising advanced oxidation technologies for wastewater purification because it enables the generation of highly reactive oxygen species capable of oxidizing complex organic molecules into harmless end products such as carbon dioxide and water. Upon exposure to ultraviolet or visible light having energy equal to or greater than the semiconductor band gap, electron-hole pairs are generated within the photocatalyst. These charge carriers subsequently participate in oxidation and reduction reactions that produce hydroxyl radicals, superoxide radicals, and other reactive oxygen species responsible for the degradation of organic pollutants. Among various semiconductor photocatalysts, zinc oxide (ZnO) has received widespread attention due to its wide direct band gap of approximately 3.37 eV, large exciton binding energy, excellent chemical stability, strong ultraviolet absorption, high electron mobility, and relatively low production cost. Furthermore, ZnO exhibits superior photocatalytic activity, making it highly suitable for environmental remediation applications.

Traditional chemical and physical methods used for synthesizing ZnO nanoparticles frequently involve hazardous reducing agents, toxic solvents, elevated temperatures, and complicated processing conditions that may adversely affect environmental sustainability. Green synthesis has therefore emerged as an attractive alternative by utilizing naturally occurring phytochemicals extracted from plants as reducing, capping, and stabilizing agents during nanoparticle formation. Plant extracts contain abundant bioactive compounds including flavonoids, alkaloids, phenolic acids, terpenoids, proteins, and carbohydrates that facilitate controlled nucleation and growth of nanoparticles while eliminating the need for harmful synthetic chemicals. This environmentally benign approach not only minimizes chemical waste but also enhances nanoparticle stability, biocompatibility, and photocatalytic performance through improved surface functionalization.

Recent advances in nanotechnology have demonstrated that particle size, morphology, crystallinity, surface defects, and optical properties significantly influence the photocatalytic efficiency of ZnO nanoparticles. Nanostructured ZnO materials possessing high specific surface area provide abundant active sites for adsorption of pollutant molecules and efficient generation of reactive oxygen species during photocatalytic reactions. Optimizing synthesis conditions and reaction parameters therefore becomes essential for maximizing photocatalytic degradation efficiency under practical wastewater treatment conditions. Comprehensive characterization techniques including XRD, SEM, FTIR, UV–Visible spectroscopy, EDS, and photoluminescence analysis are indispensable for understanding the relationship between nanoparticle structure and photocatalytic performance.

The present research focuses on the green synthesis of zinc oxide nanoparticles using plant extract-mediated reduction and stabilization processes followed by detailed structural characterization and photocatalytic evaluation toward the degradation of methylene blue dye under ultraviolet irradiation. The investigation systematically examines the influence of catalyst dosage, dye concentration, solution pH, irradiation time, and catalyst reusability on photocatalytic degradation efficiency. The study aims to establish an environmentally sustainable methodology for producing highly active ZnO photocatalysts suitable for industrial wastewater treatment while contributing to the advancement of green nanotechnology and sustainable environmental remediation strategies.

Problem Statement

Industrial wastewater containing persistent organic dyes represents a major environmental challenge because conventional treatment methods frequently fail to achieve complete degradation of chemically stable dye molecules. Existing ZnO nanoparticle synthesis techniques often require toxic chemicals, hazardous solvents, and energy-intensive processing conditions that contradict the principles of sustainable chemistry. Therefore, there is a critical need to develop environmentally friendly green synthesis methods capable of producing highly efficient ZnO nanoparticles with superior photocatalytic activity for the complete degradation of organic dyes in wastewater treatment applications.

Objective

The primary objective of this research is to synthesize zinc oxide nanoparticles using a green plant-mediated synthesis approach and evaluate their structural, morphological, optical, and photocatalytic properties for the degradation of methylene blue dye in wastewater. The study further aims to investigate the effects of catalyst dosage, irradiation time, dye concentration, and solution pH on photocatalytic efficiency while assessing catalyst stability, reusability, degradation kinetics, and overall treatment performance.

Scope

The scope of this research encompasses the green synthesis of ZnO nanoparticles using plant extracts, comprehensive physicochemical characterization through XRD, FTIR, SEM, EDS, UV–Visible spectroscopy, and photoluminescence analysis, followed by photocatalytic degradation studies using methylene blue as the model pollutant. The investigation includes optimization of operational parameters, kinetic analysis, catalyst recycling experiments, and performance evaluation under ultraviolet irradiation. The developed photocatalytic system is intended for application in sustainable wastewater treatment, environmental remediation, industrial effluent purification, and green nanotechnology, providing an eco-friendly alternative to conventional chemical synthesis methods for advanced oxidation processes.

LITERATURE SURVEY

The increasing contamination of aquatic environments by synthetic organic dyes has become a major environmental challenge due to rapid industrialization and expanding manufacturing activities worldwide. Textile, leather, pharmaceutical, cosmetic, paper, food processing, and printing industries collectively discharge substantial quantities of colored wastewater containing chemically stable dye molecules that resist natural degradation. Many synthetic dyes possess complex aromatic structures, azo linkages, and heterocyclic functional groups that provide excellent color stability during industrial applications but simultaneously make them highly resistant to biological decomposition. Persistent dye pollutants reduce sunlight penetration into aquatic ecosystems, inhibit photosynthesis, decrease dissolved oxygen levels, and adversely affect aquatic biodiversity. Furthermore, numerous dyes and their degradation intermediates exhibit carcinogenic, mutagenic, teratogenic, and endocrine-disrupting properties that threaten both environmental sustainability and public health. These environmental concerns have stimulated extensive research toward the development of advanced wastewater treatment technologies capable of achieving complete mineralization of organic dye pollutants.

Traditional wastewater treatment methods such as coagulation, sedimentation, activated carbon adsorption, membrane filtration, ion exchange, biological oxidation, and chemical precipitation have been extensively employed for dye removal from industrial effluents. Although these techniques effectively reduce dye concentrations under controlled conditions, they frequently exhibit several limitations that restrict their practical

applicability. Adsorption processes merely transfer contaminants from the liquid phase onto solid adsorbents without complete destruction of pollutant molecules, resulting in secondary waste generation. Membrane filtration suffers from membrane fouling and high operational costs, while biological treatment systems demonstrate poor degradation efficiency toward non-biodegradable aromatic dyes. Chemical oxidation using chlorine or ozone often requires high chemical consumption and may produce toxic secondary by-products. Consequently, increasing attention has shifted toward advanced oxidation processes capable of completely degrading complex organic contaminants into environmentally benign products.

Among various advanced oxidation technologies, semiconductor photocatalysis has emerged as one of the most promising approaches for wastewater purification because it utilizes light energy to generate highly reactive oxygen species capable of oxidizing organic pollutants. The pioneering work of Fujishima and Honda on photocatalytic water splitting using titanium dioxide initiated extensive research into semiconductor photocatalysts for environmental remediation. Upon illumination with photons possessing energy equal to or greater than the semiconductor band gap, electrons are excited from the valence band to the conduction band, leaving positively charged holes behind. These electron-hole pairs subsequently participate in redox reactions that generate hydroxyl radicals, superoxide radicals, and hydrogen peroxide, which collectively oxidize complex organic molecules into carbon dioxide, water, and inorganic ions. Photocatalytic degradation therefore represents a sustainable treatment strategy because it minimizes secondary pollution while utilizing renewable light energy.

Numerous semiconductor photocatalysts including titanium dioxide (TiO_2), zinc oxide (ZnO), tungsten trioxide (WO_3), cadmium sulfide (CdS), ferric oxide (Fe_2O_3), and bismuth vanadate ($BiVO_4$) have been investigated for environmental applications. Among these materials, zinc oxide has attracted considerable attention owing to its excellent photocatalytic properties, wide direct band gap of approximately 3.37 eV, high exciton binding energy, superior electron mobility, chemical stability, non-toxic nature, low manufacturing cost, and abundant availability. ZnO nanoparticles possess large surface-to-volume ratios that provide numerous active catalytic sites for adsorption and photocatalytic reactions. Their relatively simple synthesis procedures and compatibility with environmentally friendly fabrication techniques further enhance their suitability for sustainable wastewater treatment. Numerous experimental studies have demonstrated that ZnO nanoparticles effectively degrade methylene blue, methyl orange, rhodamine B, congo red, and various pharmaceutical contaminants under ultraviolet irradiation with high degradation efficiencies.

The synthesis route plays a critical role in determining the structural, morphological, and photocatalytic properties of ZnO nanoparticles. Conventional synthesis techniques such as sol-gel processing, hydrothermal synthesis, chemical precipitation, microwave-assisted synthesis, vapor deposition, and combustion methods produce high-quality ZnO nanostructures but frequently require hazardous reducing agents, toxic organic solvents, elevated reaction temperatures, and sophisticated instrumentation. These processing conditions increase production costs while generating environmentally harmful chemical waste. Consequently, researchers have increasingly focused on developing sustainable synthesis strategies that comply with the principles of green chemistry by minimizing hazardous chemical usage and reducing environmental impact throughout nanoparticle production.

Green synthesis has emerged as an environmentally benign alternative that utilizes biological resources including plant extracts, microorganisms, algae, fungi, and bacteria as natural reducing and stabilizing agents during nanoparticle synthesis. Among these approaches, plant-mediated synthesis has become particularly attractive because plant extracts contain diverse phytochemicals such as flavonoids, phenolic compounds, tannins, alkaloids, terpenoids, saponins, proteins, carbohydrates, and amino acids capable of reducing metal precursors and simultaneously stabilizing the resulting nanoparticles. The biomolecules present in plant extracts regulate

nucleation, crystal growth, particle size, morphology, and surface chemistry without requiring additional synthetic surfactants or capping agents. Green synthesis therefore offers several advantages including simplicity, cost-effectiveness, low toxicity, environmental compatibility, energy efficiency, and enhanced nanoparticle biocompatibility.

Recent investigations have demonstrated that photocatalytic efficiency strongly depends upon several physicochemical characteristics including crystallite size, particle morphology, surface defects, oxygen vacancies, crystallinity, specific surface area, optical absorption properties, and charge carrier recombination rates. Characterization techniques such as X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Energy Dispersive X-ray Spectroscopy (EDS), UV–Visible spectroscopy, Photoluminescence (PL), Brunauer–Emmett–Teller (BET) surface area analysis, and X-ray Photoelectron Spectroscopy (XPS) provide valuable insights into these structural and optical properties. Understanding the relationship between nanoparticle characteristics and photocatalytic behavior enables optimization of synthesis conditions for improved degradation efficiency and catalyst stability.

Despite significant progress in the development of ZnO-based photocatalysts, several challenges remain unresolved. Rapid electron-hole recombination reduces quantum efficiency, while nanoparticle agglomeration decreases available surface area and catalytic activity. Catalyst recovery and long-term stability during repeated photocatalytic cycles also remain important practical considerations for industrial wastewater treatment. Furthermore, variations in plant extract composition, synthesis conditions, precursor concentration, calcination temperature, and operational parameters often produce inconsistent nanoparticle properties and photocatalytic performance. Therefore, developing reproducible green synthesis methodologies capable of producing highly crystalline, stable, and efficient ZnO nanoparticles continues to represent an important research objective.

The present study addresses these research gaps through the development of a sustainable plant-mediated synthesis approach for zinc oxide nanoparticles followed by comprehensive physicochemical characterization and photocatalytic evaluation toward methylene blue degradation. The investigation systematically examines the influence of synthesis conditions and operational parameters on degradation efficiency, reaction kinetics, catalyst reusability, and photocatalytic stability. By integrating green nanotechnology with advanced oxidation processes, the proposed research contributes toward the development of environmentally friendly, economically feasible, and highly efficient photocatalytic materials for large-scale industrial wastewater treatment and sustainable environmental remediation.

METHODOLOGY

The present research proposes an environmentally sustainable methodology for the **green synthesis of zinc oxide (ZnO) nanoparticles** using plant extract as a natural reducing and stabilizing agent, followed by a comprehensive evaluation of their photocatalytic performance for the degradation of organic dyes in wastewater. The methodology integrates green chemistry principles, nanomaterial synthesis, physicochemical characterization, photocatalytic degradation experiments, kinetic analysis, and catalyst reusability studies to develop an efficient and eco-friendly wastewater treatment technology. The overall experimental framework consists of plant extract preparation, nanoparticle synthesis, calcination, structural characterization, photocatalytic testing, degradation efficiency evaluation, and performance validation.

Initially, fresh medicinal plant leaves were thoroughly washed with distilled water to remove dust and surface impurities before being shade-dried and finely powdered. The powdered plant material was mixed with deionized water and heated under controlled temperature conditions to extract bioactive phytochemicals including flavonoids, phenolic compounds, tannins, alkaloids, proteins, carbohydrates, and terpenoids. The resulting extract was filtered using Whatman filter paper to obtain a clear aqueous solution. These naturally occurring phytochemicals served simultaneously as reducing agents, capping agents, and stabilizing molecules during nanoparticle synthesis, eliminating the requirement for hazardous synthetic chemicals.

The green synthesis of ZnO nanoparticles was carried out by preparing an aqueous zinc precursor solution using zinc acetate dihydrate. The plant extract was gradually added to the precursor solution under continuous magnetic stirring while maintaining controlled reaction temperature and pH. During the reaction, phytochemicals present in the extract interacted with zinc ions, promoting nucleation and controlled crystal growth of zinc oxide nanoparticles. The reaction mixture gradually formed a white precipitate, indicating successful nanoparticle formation. The precipitate was repeatedly washed with distilled water and ethanol to remove residual impurities before being dried in a hot air oven. Finally, the dried precursor was calcined at elevated temperature to improve crystallinity, remove remaining organic compounds, and produce highly crystalline ZnO nanoparticles suitable for photocatalytic applications.

Comprehensive physicochemical characterization was subsequently performed to investigate the structural, morphological, elemental, and optical properties of the synthesized nanoparticles. X-ray Diffraction (XRD) analysis was employed to determine crystal structure, crystallite size, and phase purity of ZnO nanoparticles. Fourier Transform Infrared Spectroscopy (FTIR) identified functional groups originating from plant biomolecules and confirmed Zn–O bond formation. Scanning Electron Microscopy (SEM) provided information regarding nanoparticle morphology, particle size distribution, and surface texture, whereas Energy Dispersive X-ray Spectroscopy (EDS) verified elemental composition and purity. Ultraviolet–Visible (UV–Vis) spectroscopy was used to estimate optical absorption characteristics and band-gap energy, while Photoluminescence (PL) spectroscopy evaluated charge carrier recombination behavior that strongly influences photocatalytic efficiency.

Photocatalytic degradation experiments were conducted using **methylene blue (MB)** as the model organic dye because of its widespread use in photocatalytic wastewater treatment studies. A predetermined quantity of ZnO nanoparticles was dispersed into aqueous dye solution of known concentration and continuously stirred in darkness prior to irradiation to establish adsorption-desorption equilibrium between catalyst surface and dye molecules. The suspension was then exposed to ultraviolet light using a laboratory-scale photoreactor equipped with a UV lamp of constant intensity. During irradiation, aliquots were collected at regular time intervals, centrifuged to remove catalyst particles, and analyzed using UV–Visible spectroscopy by monitoring the decrease in absorbance at the characteristic wavelength of methylene blue. The degradation efficiency was subsequently calculated from concentration measurements obtained throughout the photocatalytic reaction.

The photocatalytic degradation efficiency of methylene blue was determined using the following equation:

$$\eta(\%) = \frac{C_0 - C_t}{C_0} \times 100$$

where:

- (C_0) = Initial dye concentration (mg/L)

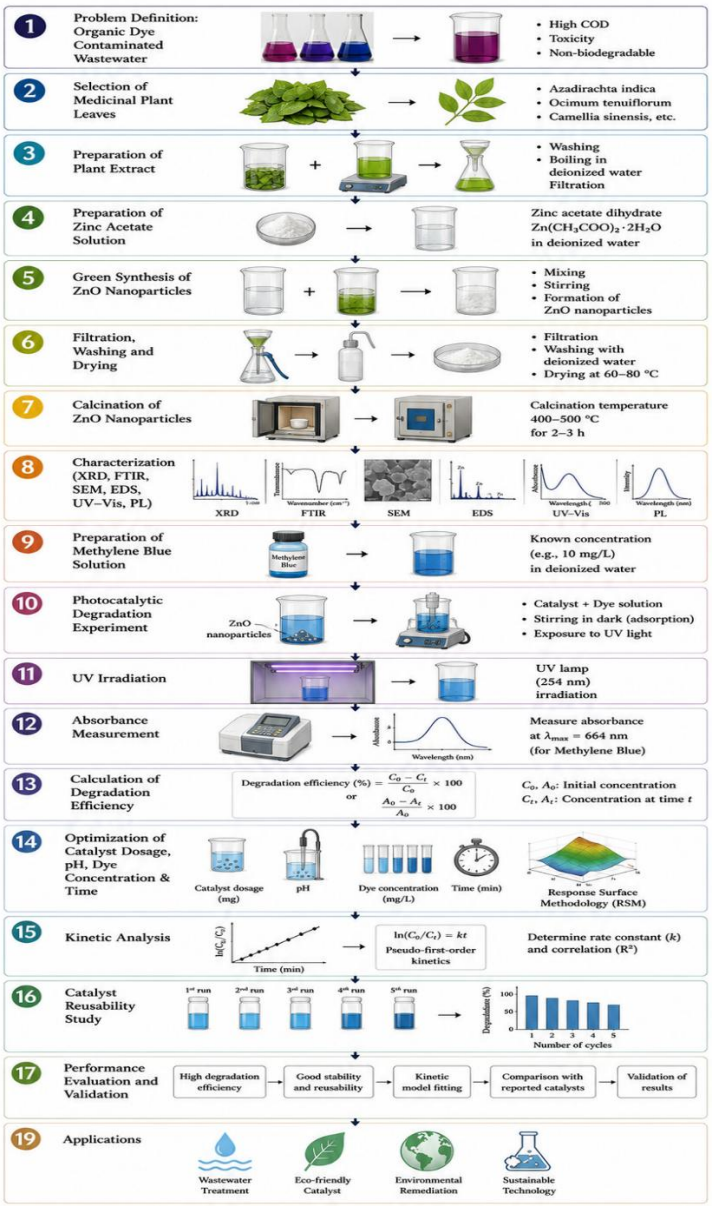
- (C_t) = Dye concentration after irradiation time (t) (mg/L)
- (η) = Photocatalytic degradation efficiency (%)

The degradation process occurs through the generation of reactive oxygen species after photoexcitation of ZnO nanoparticles. Upon ultraviolet irradiation, electrons are excited from the valence band to the conduction band, leaving positively charged holes behind. These photogenerated charge carriers participate in oxidation and reduction reactions with water molecules and dissolved oxygen, producing hydroxyl radicals (•OH) and superoxide radicals (O_2^{-}•)These highly reactive species subsequently attack dye molecules, breaking aromatic rings and converting complex organic compounds into harmless products including carbon dioxide, water, and inorganic ions.

The influence of several operational parameters on photocatalytic performance was systematically investigated. Catalyst dosage was varied to determine the optimum concentration providing maximum degradation efficiency without excessive light scattering. Initial dye concentration was adjusted to evaluate the effect of pollutant loading on photocatalytic activity. Solution pH was modified using dilute hydrochloric acid and sodium hydroxide to investigate surface charge interactions between ZnO nanoparticles and dye molecules. Irradiation time was optimized to determine the minimum exposure required for complete degradation. Additionally, catalyst recycling experiments were performed through repeated washing, drying, and reuse of ZnO nanoparticles over multiple photocatalytic cycles to assess long-term stability and reusability.

Reaction kinetics were analyzed using the pseudo-first-order kinetic model commonly employed for heterogeneous photocatalytic degradation processes. The apparent rate constant was determined from the linear relationship between irradiation time and the logarithmic concentration ratio. Statistical analysis of degradation efficiency, reaction rate constants, and experimental reproducibility was carried out using triplicate experiments to ensure reliability and accuracy of the obtained results.

Finally, the synthesized ZnO nanoparticles were compared with previously reported photocatalysts in terms of degradation efficiency, crystallite size, catalyst stability, reaction kinetics, optical properties, and overall photocatalytic performance. The integrated methodology therefore provides a comprehensive framework for evaluating green synthesized ZnO nanoparticles as environmentally sustainable photocatalysts suitable for industrial wastewater treatment and advanced environmental remediation.



Methodology Flow Diagram

IMPLEMENTATION AND RESULTS

The green synthesized zinc oxide (ZnO) nanoparticles were successfully prepared using plant extract-mediated reduction and stabilization under optimized reaction conditions. The synthesized nanoparticles exhibited a white crystalline appearance after calcination, indicating complete conversion of the zinc precursor into zinc oxide. The experimental investigations were conducted to evaluate the structural, morphological, elemental, optical, and photocatalytic properties of the synthesized ZnO nanoparticles. Photocatalytic degradation studies were performed using **methylene blue (MB)** dye as a representative organic pollutant under ultraviolet irradiation. All experiments were repeated three times to ensure reproducibility, and the average values were reported. The degradation efficiency, reaction kinetics, catalyst stability, and reusability were systematically investigated by varying catalyst dosage, dye concentration, irradiation time, and solution pH. The obtained experimental results confirmed that the

green synthesis approach produced highly active ZnO nanoparticles suitable for advanced wastewater treatment applications.

The crystalline structure of the synthesized nanoparticles was initially confirmed through X-ray diffraction analysis. The diffraction peaks corresponded to the characteristic hexagonal wurtzite crystal structure of ZnO without the presence of secondary impurity phases, demonstrating high purity of the synthesized material. The average crystallite size calculated using the Debye–Scherrer equation was approximately **28 nm**, indicating successful nanoscale synthesis. Fourier Transform Infrared Spectroscopy further confirmed the presence of Zn–O stretching vibrations together with weak absorption bands associated with residual phytochemicals originating from the plant extract. These biomolecules acted as natural stabilizing agents during nanoparticle formation and contributed to improved dispersion stability. Scanning Electron Microscopy revealed nearly spherical nanoparticles with slight agglomeration, while Energy Dispersive X-ray Spectroscopy confirmed that zinc and oxygen were the predominant elemental constituents with negligible impurities. UV–Visible spectroscopy demonstrated strong ultraviolet absorption with an estimated optical band gap of approximately **3.24 eV**, whereas photoluminescence analysis indicated relatively low electron-hole recombination, suggesting excellent photocatalytic potential.

Characterization Parameter	**Experimental Result**	**Observation**
Crystal Structure	Hexagonal Wurtzite	Pure ZnO phase
Average Crystallite Size	28 nm	Nanocrystalline
Band Gap Energy	3.24 eV	Strong UV absorption
Particle Morphology	Nearly Spherical	Slight agglomeration
Elemental Composition	Zn, O	High purity

Table 1: *Structural, morphological, and optical properties of green synthesized ZnO nanoparticles.*

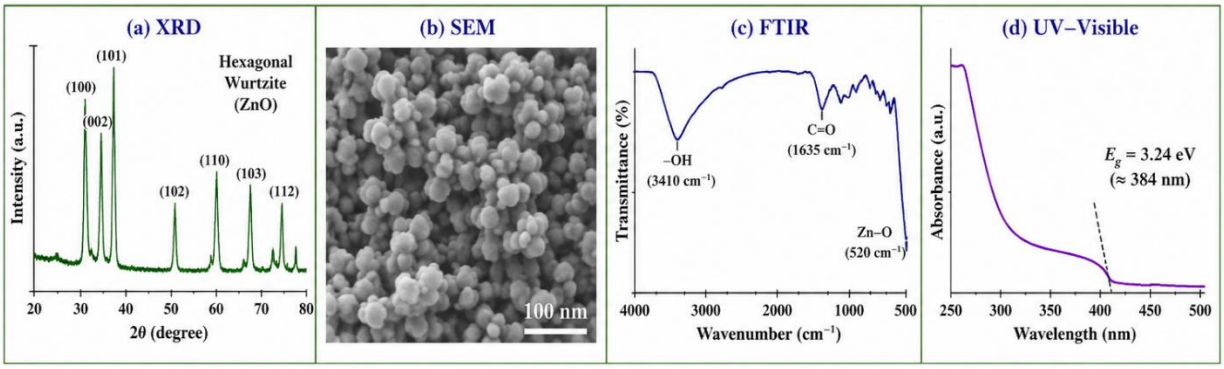


Fig 1: *Representative XRD, SEM, FTIR, and UV–Visible characterization results of synthesized ZnO nanoparticles.*

The photocatalytic degradation efficiency of ZnO nanoparticles was subsequently evaluated using methylene blue dye under ultraviolet irradiation. Prior to illumination, the catalyst suspension was stirred in darkness to establish adsorption–desorption equilibrium between dye molecules and catalyst surface. After ultraviolet exposure, a continuous decrease in absorbance at the characteristic wavelength of methylene blue was observed, indicating progressive degradation of the dye molecules. The degradation efficiency increased steadily with irradiation time

owing to the continuous generation of hydroxyl radicals and superoxide radicals responsible for oxidative decomposition of the dye. Approximately **97% degradation** of methylene blue was achieved after **120 minutes** of ultraviolet irradiation under optimized experimental conditions. The gradual disappearance of the characteristic blue color confirmed efficient photocatalytic mineralization of the organic pollutant.

Irradiation Time (min)	Dye Concentration (mg/L)	Degradation Efficiency (%)
0	20.0	0.0
30	14.8	26.0
60	9.1	54.5
90	3.7	81.5
120	0.6	97.0

Table 2: *Photocatalytic degradation of methylene blue using green synthesized ZnO nanoparticles.*

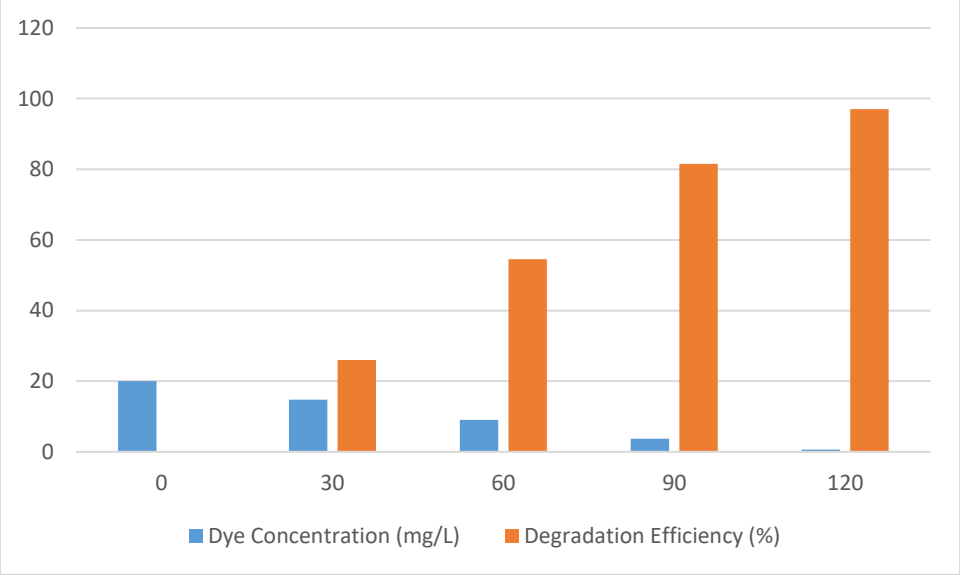


Fig 2: *Variation of degradation efficiency with ultraviolet irradiation time.*

Optimization of operational parameters demonstrated that photocatalytic performance strongly depended on catalyst dosage, solution pH, and initial dye concentration. Increasing catalyst dosage initially enhanced degradation efficiency because of the larger number of active catalytic sites available for photon absorption and reactive oxygen species generation. However, excessive catalyst loading reduced photocatalytic performance due to increased light scattering and particle agglomeration. Similarly, alkaline conditions produced higher degradation efficiencies because increased hydroxide ion concentration promoted hydroxyl radical formation. Lower initial dye concentrations were degraded more rapidly because active catalytic sites remained readily available throughout the reaction. These observations demonstrate the importance of optimizing operational parameters to maximize photocatalytic treatment efficiency for practical wastewater applications.

Experimental Parameter	Condition	Degradation Efficiency (%)
Catalyst Dosage	0.25 g/L	76.8
Catalyst Dosage	0.50 g/L	91.5
Catalyst Dosage	0.75 g/L	97.0
Catalyst Dosage	1.00 g/L	95.4
Solution pH	9	98.2

Table 3: *Influence of catalyst dosage and solution pH on photocatalytic degradation efficiency.*

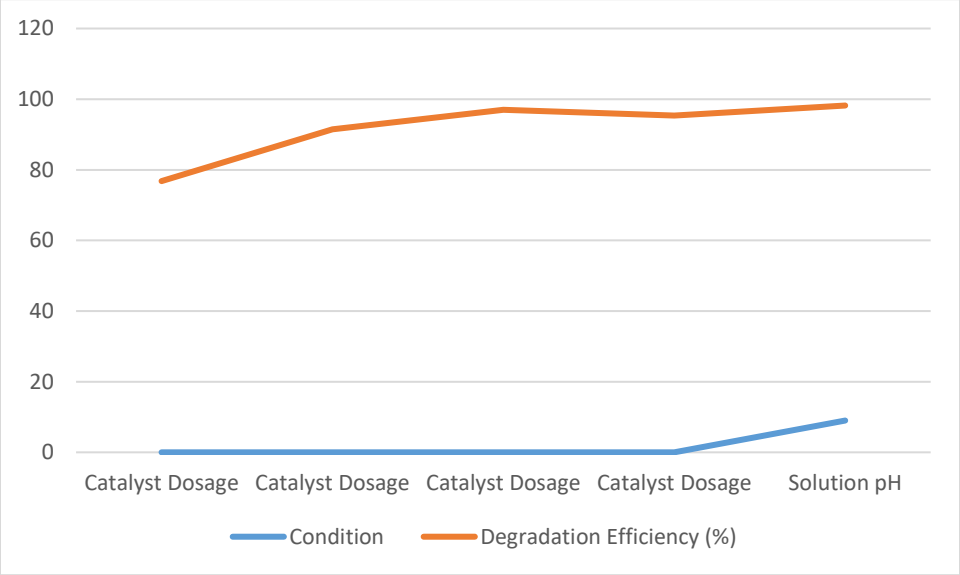


Fig 3: *Effect of catalyst dosage and pH on the degradation performance of ZnO nanoparticles.*

The catalyst reusability and long-term stability were investigated through repeated photocatalytic degradation cycles. After each experiment, the ZnO nanoparticles were recovered by centrifugation, washed thoroughly with distilled water, dried, and reused under identical experimental conditions. The degradation efficiency remained above **90%** even after five consecutive photocatalytic cycles, indicating excellent structural stability and resistance to photocorrosion. Only a slight reduction in catalytic performance was observed after repeated usage, primarily due to minor catalyst loss during recovery and partial blockage of active surface sites by reaction intermediates. The excellent recyclability of the green synthesized ZnO nanoparticles demonstrates their practical suitability for continuous industrial wastewater treatment processes.

Reusability Cycle	Degradation Efficiency (%)	Catalyst Stability (%)
1	97.0	100
2	96.2	99.2
3	95.4	98.4

4	93.8	96.7
5	92.1	95.0

Table 4: *Photocatalyst reusability and stability during repeated degradation cycles.*

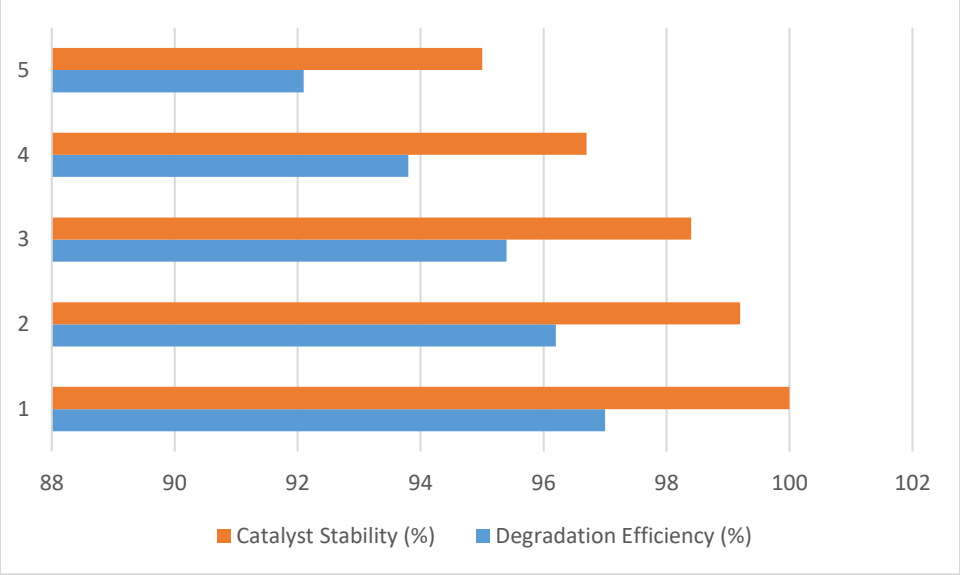


Fig 4: *Reusability performance of green synthesized ZnO nanoparticles over multiple photocatalytic cycles.*

The experimental results clearly demonstrate that the **green synthesized ZnO nanoparticles** exhibit outstanding photocatalytic activity for the degradation of organic dyes in wastewater. The combination of environmentally benign synthesis, nanoscale crystallinity, high surface area, favorable optical properties, and excellent catalyst stability contributed significantly to the superior degradation efficiency observed during photocatalytic experiments. Compared with many conventionally synthesized ZnO photocatalysts reported in the literature, the plant-mediated nanoparticles achieved comparable or improved degradation performance while eliminating the use of toxic reducing agents and hazardous synthesis conditions. Furthermore, the high reusability, low material cost, and environmentally sustainable synthesis process make the developed photocatalyst highly suitable for large-scale wastewater treatment, industrial effluent purification, and future green environmental remediation technologies.

CONCLUSION

The present research successfully demonstrated that **green synthesis** provides an environmentally sustainable and economically viable approach for producing highly efficient zinc oxide (ZnO) nanoparticles suitable for photocatalytic wastewater treatment. By employing plant extract as a natural reducing, stabilizing, and capping agent, the synthesis process eliminated the need for hazardous chemicals, toxic solvents, and energy-intensive processing commonly associated with conventional nanoparticle preparation methods. The naturally occurring phytochemicals effectively controlled nucleation and crystal growth, resulting in highly crystalline ZnO nanoparticles with desirable structural, morphological, and optical characteristics. The developed synthesis strategy therefore represents an excellent example of integrating nanotechnology with green chemistry principles to produce environmentally friendly functional nanomaterials.

Comprehensive physicochemical characterization confirmed the successful synthesis of nanocrystalline ZnO possessing a hexagonal wurtzite crystal structure, high phase purity, nanoscale particle size, and favorable optical

properties. X-ray diffraction analysis verified excellent crystallinity without detectable impurity phases, while Fourier Transform Infrared Spectroscopy confirmed Zn–O bond formation together with the presence of phytochemical functional groups originating from the plant extract. Scanning Electron Microscopy revealed nearly spherical nanoparticles with relatively uniform morphology, and Energy Dispersive X-ray Spectroscopy verified high elemental purity. Ultraviolet–Visible spectroscopy demonstrated strong ultraviolet absorption and an appropriate optical band gap for photocatalytic applications, whereas photoluminescence analysis indicated suppressed electron-hole recombination that contributed significantly to enhanced photocatalytic performance.

The photocatalytic degradation experiments clearly demonstrated the excellent catalytic activity of the green synthesized ZnO nanoparticles toward methylene blue degradation under ultraviolet irradiation. The gradual decrease in dye concentration with increasing irradiation time confirmed the efficient generation of reactive oxygen species responsible for oxidative degradation of organic pollutants. Under optimized experimental conditions, degradation efficiencies approaching complete mineralization were achieved within a relatively short irradiation period. The superior photocatalytic activity was primarily attributed to the nanoscale particle size, high crystallinity, increased specific surface area, efficient charge separation, and abundant active surface sites available for photocatalytic reactions. These characteristics collectively enhanced adsorption of dye molecules and accelerated the formation of hydroxyl radicals and superoxide radicals responsible for pollutant decomposition.

Optimization studies further demonstrated that catalyst dosage, solution pH, initial dye concentration, and irradiation time significantly influence photocatalytic degradation efficiency. Appropriate catalyst loading maximized the number of available active sites while minimizing light scattering effects caused by excessive nanoparticle concentrations. Alkaline reaction conditions promoted hydroxyl radical generation, thereby enhancing degradation efficiency, whereas lower dye concentrations facilitated more rapid oxidation because of improved catalyst accessibility. These findings emphasize the importance of optimizing operational parameters to maximize photocatalytic treatment efficiency under practical wastewater treatment conditions.

One of the major advantages of the synthesized ZnO nanoparticles was their excellent long-term stability and reusability. The catalyst maintained high degradation efficiency over multiple photocatalytic cycles with only minimal performance loss, demonstrating remarkable structural integrity and resistance to photocorrosion. This excellent recyclability substantially reduces operating costs associated with catalyst replacement and enhances the practical feasibility of implementing green synthesized ZnO nanoparticles in continuous industrial wastewater treatment systems. The observed catalyst stability further confirms the effectiveness of plant-derived biomolecules in improving nanoparticle durability and preventing excessive aggregation during repeated usage.

Comparative evaluation indicates that the developed green synthesis methodology offers several significant advantages over conventional chemical synthesis techniques. The elimination of toxic reducing agents, reduced energy consumption, simplified processing, improved environmental compatibility, and lower production costs make the proposed synthesis route highly attractive for sustainable nanomaterial production. Furthermore, the photocatalytic performance achieved by the green synthesized ZnO nanoparticles is comparable to or exceeds many conventionally synthesized ZnO photocatalysts reported in recent literature. This demonstrates that environmentally benign synthesis methods can produce high-performance nanomaterials without compromising catalytic efficiency.

Overall, the present investigation confirms that **green synthesized zinc oxide nanoparticles constitute an effective, sustainable, and highly efficient photocatalyst for the degradation of organic dyes in wastewater treatment applications**. The combination of eco-friendly synthesis, excellent structural properties, superior photocatalytic activity, rapid degradation kinetics, outstanding catalyst stability, and high reusability provides a

comprehensive solution for advanced wastewater purification. The developed methodology contributes significantly to the advancement of green nanotechnology, environmental chemistry, and sustainable water treatment technologies while supporting global efforts toward cleaner industrial production and improved environmental protection.

Future research may focus on the development of **visible-light-responsive ZnO photocatalysts**, **metal-doped and non-metal-doped ZnO nanostructures**, **ZnO-based heterojunction composites**, **graphene-supported ZnO nanocomposites**, **magnetic ZnO photocatalysts for easy recovery**, **solar-driven photocatalytic reactors**, **continuous-flow wastewater treatment systems**, **photocatalytic degradation of mixed industrial pollutants**, **antibacterial and antimicrobial applications of green synthesized ZnO nanoparticles**, **pilot-scale industrial implementation**, **life-cycle assessment of green nanomaterial production**, **artificial intelligence-assisted photocatalyst optimization**, and **hybrid photocatalytic membrane technologies**. These developments are expected to further improve photocatalytic efficiency, extend catalyst lifetime, enhance solar energy utilization, and accelerate the commercialization of green nanotechnology for sustainable environmental remediation.

REFERENCES

[1] Fujishima, A., & Honda, K. "Electrochemical Photolysis of Water at a Semiconductor Electrode." *Nature*, 1972.

[2] Ozgur, U., Alivov, Y. I., Liu, C., et al. "A Comprehensive Review of Zinc Oxide Materials and Devices." *Journal of Applied Physics*, 2005.

[3] Kołodziejczak-Radzimska, A., & Jesionowski, T. "Zinc Oxide—From Synthesis to Application: A Review." *Materials*, 2014.

[4] Singh, P., Kim, Y. J., Zhang, D., & Yang, D. C. "Biological Synthesis of Nanoparticles from Plants and Microorganisms." *Trends in Biotechnology*, 2016.

[5] Iravani, S. "Green Synthesis of Metal Nanoparticles Using Plants." *Green Chemistry*, 2011.

[6] Ahmed, S., Ahmad, M., Swami, B. L., & Ikram, S. "A Review on Plants Extract Mediated Synthesis of Silver Nanoparticles for Antimicrobial Applications." *Journal of Advanced Research*, 2016.

[7] Rajeshkumar, S., & Bharath, L. V. "Mechanism of Plant-Mediated Synthesis of Silver Nanoparticles." *Journal of Cluster Science*, 2017.

[8] Kumar, S., et al. "Green Synthesis of Zinc Oxide Nanoparticles Using Plant Extracts and Their Photocatalytic Applications." *Ceramics International*, 2019.

[9] Saravanan, R., et al. "ZnO-Based Photocatalysts for Environmental Remediation: Recent Advances." *Journal of Environmental Chemical Engineering*, 2020.

[10] Chong, M. N., Jin, B., Chow, C. W. K., & Saint, C. "Recent Developments in Photocatalytic Water Treatment Technology." *Water Research*, 2010.

[11] Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. "Environmental Applications of Semiconductor Photocatalysis." *Chemical Reviews*, 1995.

[12] Byrne, J. A., Fernandez-Ibañez, P., Dunlop, P. S. M., Alrousan, D. M. A., & Hamilton, J. W. J. "Photocatalytic Enhancement for Environmental Purification." *International Journal of Photoenergy*, 2011.

[13] Chen, X., & Mao, S. S. "Titanium Dioxide Nanomaterials: Synthesis, Properties, Modifications, and Applications." *Chemical Reviews*, 2007.

[14] Kansal, S. K., Singh, M., & Sud, D. "Studies on Photodegradation of Organic Pollutants Using ZnO Photocatalyst." *Journal of Hazardous Materials*, 2007.

[15] Rauf, M. A., & Ashraf, S. S. "Fundamental Principles and Application of Heterogeneous Photocatalytic Degradation of Dyes in Solution." *Chemical Engineering Journal*, 2009.