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Fabrication and Characterization of ZnO/TiO_2 Nanocomposites for Enhanced Photocatalytic Degradation of Organic Pollutants

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ABSTRACT

The increasing contamination of water resources by synthetic organic dyes has created significant environmental and public health concerns worldwide. This study investigates the fabrication and characterization of ZnO/TiO_2 nanocomposites synthesized through the sol-gel method for enhanced photocatalytic degradation of methylene blue (MB) and rhodamine B (RhB) dyes. Nanocomposites with ZnO:TiO_2 molar ratios of 1:0, 3:1, 1:1, 1:3, and 0:1 were prepared and calcined at 500°C for 2 hours. Structural analysis using X-ray diffraction confirmed the successful formation of wurtzite ZnO and anatase TiO_2 phases, with crystallite sizes ranging from 14.3 to 18.7 nm. The optimized 1:1 ZnO/TiO_2 nanocomposite exhibited a crystallite size of 16.2 nm and the highest BET surface area of 78.4 $m^2 g^{-1}$, representing a 73.1% increase over pure ZnO. UV–Visible diffuse reflectance spectroscopy revealed bandgap reduction from 3.25 eV for ZnO and 3.20 eV for TiO_2 to 3.02 eV for the 1:1 composite, resulting in enhanced light absorption. Photocatalytic experiments demonstrated that the 1:1 ZnO/TiO_2 nanocomposite achieved 98.7% degradation of methylene blue within 60 minutes and 95.3% degradation of rhodamine B within 90 minutes under 36 W UV irradiation. The corresponding pseudo-first-order rate constants were 6.84×10^{-2} min^{-1} for MB and 3.41×10^{-2} min^{-1} for RhB, significantly higher than those of pure ZnO and TiO_2. Total organic carbon removal reached 82.6%, confirming substantial mineralization of pollutants. Reusability studies showed only 6.8% activity loss after five cycles. The enhanced photocatalytic performance was attributed to Type-II heterojunction formation, improved electron-hole separation, increased surface area, and efficient generation of hydroxyl and superoxide radicals. The findings demonstrate

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that ZnO/TiO_2 nanocomposites are promising photocatalysts for sustainable wastewater treatment and environmental remediation applications.

Keywords—ZnO/TiO_2 nanocomposite, Photocatalysis, Sol-gel synthesis, Methylene blue degradation, Rhodamine B degradation, Heterojunction, Wastewater treatment, Bandgap engineering, Nanomaterials, Advanced oxidation process

1. Introduction

Water pollution caused by industrialization, urbanization, and population growth has become one of the most serious environmental challenges worldwide. Large quantities of organic pollutants, including synthetic dyes, pharmaceuticals, pesticides, and industrial chemicals, are continuously discharged into aquatic environments (Roushree & Haimbodi, 2026). Among these pollutants, methylene blue (MB) and rhodamine B (RhB) are widely used in textile, printing, paper, and cosmetic industries and are recognized for their high chemical stability, toxicity, and resistance to conventional wastewater treatment methods. The persistence of these organic contaminants in water bodies poses significant risks to aquatic ecosystems and human health. Consequently, the development of efficient, environmentally friendly, and cost-effective technologies for pollutant degradation has become a major focus of scientific research (Rafaie et al., 2026).

Photocatalysis has emerged as a promising advanced oxidation process for the removal of organic pollutants from wastewater. This technology utilizes semiconductor materials capable of generating electron-hole pairs under light irradiation, leading to the formation of highly reactive species such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$) (Govindhan et al., 2026). These reactive oxygen species can effectively oxidize and mineralize complex organic compounds into harmless end products such as carbon dioxide and water. Compared with conventional treatment techniques, photocatalytic degradation offers advantages including high efficiency, low energy consumption, environmental compatibility, and the ability to completely mineralize pollutants without producing secondary contamination (Almutairi, 2025).

Among various semiconductor photocatalysts, zinc oxide (ZnO) and titanium dioxide (TiO_2) have attracted considerable attention due to their excellent photocatalytic activity, chemical stability, non-toxicity, and relatively low production cost. ZnO possesses high electron mobility and strong ultraviolet light absorption, while TiO_2 exhibits superior photochemical stability and oxidation capability (Thi et al., 2026). However, both materials suffer from rapid electron-hole recombination and limited visible-light utilization, which reduce their photocatalytic efficiency. To overcome these limitations, researchers have increasingly focused on developing semiconductor heterojunction systems that facilitate charge separation and improve photocatalytic performance (Fkiri et al., 2026).

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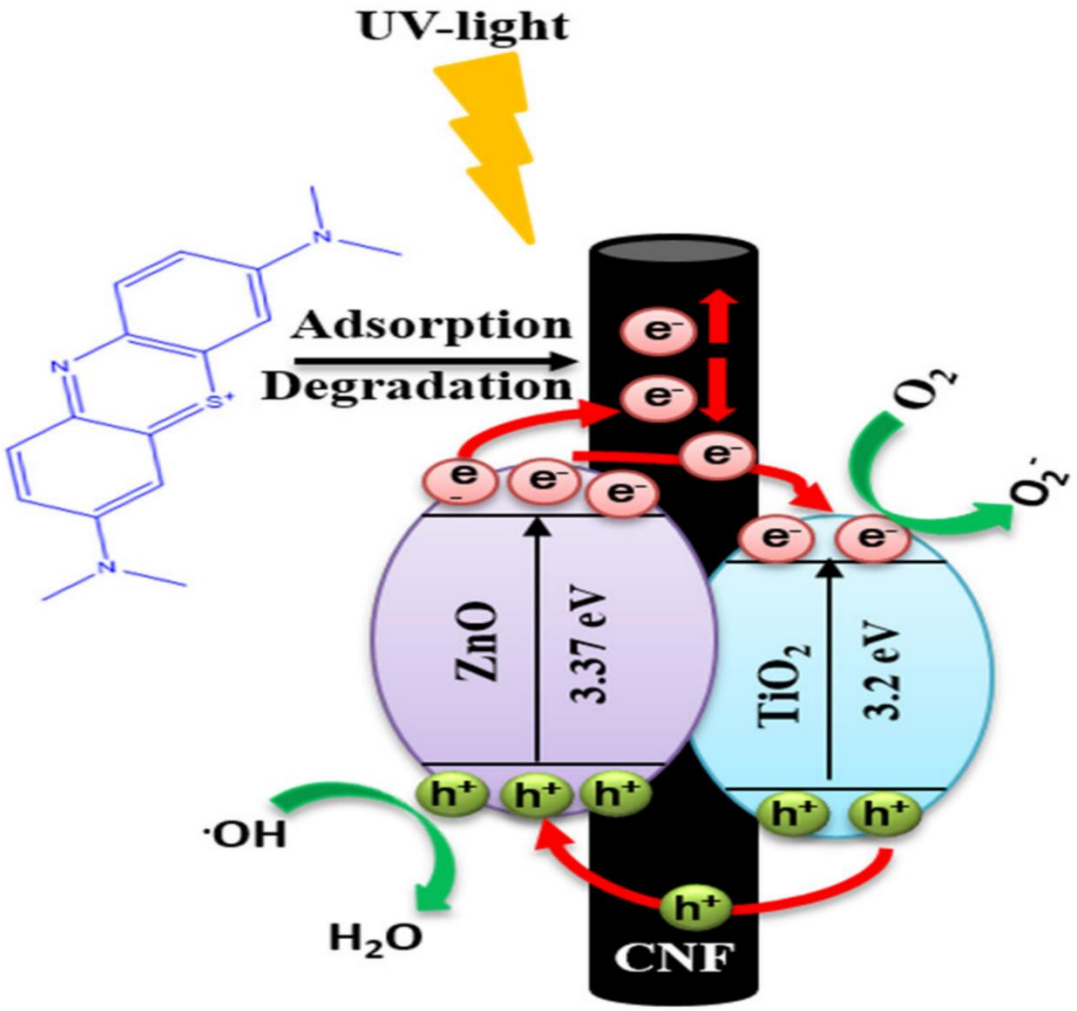

Figure 1:Proposed mechanism of photocatalysis by the as-prepared ZnO-TiO2-CNFs composite photocatalyst

ZnO/TiO_2 nanocomposites represent an effective heterojunction photocatalyst system capable of enhancing charge carrier separation and extending light absorption characteristics. The formation of a heterojunction interface between ZnO and TiO_2 promotes efficient transfer of photogenerated electrons and holes, thereby reducing recombination losses and increasing the generation of reactive oxygen species. Additionally, nanocomposite structures often exhibit higher surface areas, improved adsorption capacities, and enhanced catalytic active sites compared with individual semiconductor materials. These characteristics make ZnO/TiO_2 nanocomposites highly suitable for environmental remediation applications, particularly in wastewater treatment (DG & S, 2026).

Recent advances in nanotechnology have enabled the synthesis of ZnO/TiO_2 nanocomposites through various techniques such as hydrothermal synthesis, co-precipitation, chemical vapor deposition, and sol-gel processing. Among these methods, the sol-gel technique offers significant advantages including precise

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compositional control, high purity, low processing temperature, homogeneous particle distribution, and scalability for industrial applications. Furthermore, the optimization of ZnO/TiO_2 composition ratios can significantly influence crystallinity, surface area, optical properties, and photocatalytic activity. Therefore, systematic investigation of composition-dependent photocatalytic behavior remains essential for identifying the most efficient nanocomposite formulation (Nourbakhshi et al., n.d.).

This study focuses on the fabrication and characterization of ZnO/TiO_2 nanocomposites synthesized through the sol-gel method with different molar ratios. Structural, morphological, optical, and photocatalytic properties are evaluated using advanced characterization techniques. Particular attention is given to the degradation of methylene blue and rhodamine B dyes under ultraviolet irradiation. The study aims to determine the optimal ZnO/TiO_2 composition for enhanced photocatalytic performance and to provide insights into the mechanisms responsible for improved pollutant degradation efficiency (Hameed et al., 2026).

1.1 Problem Statement

The increasing discharge of dye-containing industrial wastewater poses significant environmental and public health concerns due to the toxic, carcinogenic, and persistent nature of many organic pollutants. Conventional wastewater treatment methods often fail to achieve complete degradation of complex dye molecules, resulting in long-term contamination of aquatic ecosystems. Although ZnO and TiO_2 photocatalysts have demonstrated potential for pollutant removal, their practical application remains limited by rapid electron-hole recombination, restricted light absorption capability, and moderate photocatalytic efficiency. There is therefore a need to develop advanced photocatalytic materials with enhanced charge separation efficiency, larger surface area, and improved degradation performance. ZnO/TiO_2 nanocomposites offer a promising solution; however, the influence of compositional ratio on photocatalytic activity requires further investigation to optimize their environmental applications (Hameeda et al., 2026).

1.2 Research Aim

To fabricate and characterize ZnO/TiO_2 nanocomposites with different compositional ratios and evaluate their photocatalytic performance for the degradation of organic pollutants in wastewater.

1.3 Research Objectives

1. To synthesize ZnO, TiO_2, and ZnO/TiO_2 nanocomposites using the sol-gel method.
2. To characterize the structural, crystalline, and optical properties of the synthesized nanocomposites using appropriate analytical techniques.
3. To evaluate the photocatalytic degradation efficiency of methylene blue and rhodamine B dyes under ultraviolet irradiation.

1.4 Significance of the Study

This study contributes to the development of advanced photocatalytic materials for sustainable environmental remediation. The fabrication of ZnO/TiO_2 nanocomposites with enhanced photocatalytic performance may provide an efficient and economical solution for the treatment of dye-contaminated wastewater. The findings will improve understanding of heterojunction engineering, charge carrier dynamics, and

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nanocomposite optimization strategies. Furthermore, the research supports ongoing efforts to develop environmentally friendly technologies for water purification and industrial wastewater management. The outcomes may also contribute to future applications of semiconductor nanocomposites in environmental engineering, renewable energy, and advanced oxidation processes (Yadav et al., 2022).

2. Literature Review

Reddy et al. (2026) reviewed recent developments in nanostructured metal and metal oxide materials for advanced water filtration applications. The authors highlighted that semiconductor nanomaterials such as ZnO and TiO_2 possess exceptional photocatalytic and adsorption capabilities, making them highly effective for wastewater treatment. Their study emphasized that nanoscale materials provide larger surface areas, enhanced reactive sites, and superior pollutant degradation efficiency compared with conventional treatment technologies. The review further demonstrated that combining multiple metal oxides into nanocomposite systems can significantly improve photocatalytic performance through synergistic interactions and enhanced charge separation mechanisms. These findings support the growing interest in ZnO/TiO_2 nanocomposites as promising materials for environmental remediation.

Mohamed, Hassan, and Essawy (2026) developed PVDF@ZnO hybrid nanofibers and investigated their structural and photocatalytic characteristics. Their results showed that the incorporation of ZnO nanoparticles improved β-phase crystallinity and significantly enhanced photocatalytic efficiency under ultraviolet irradiation. The study revealed that ZnO-based nanostructures generate reactive oxygen species capable of decomposing organic pollutants effectively. Furthermore, the authors observed that reduced electron-hole recombination contributed to improved degradation performance. Their findings demonstrate the potential of ZnO nanomaterials in advanced oxidation processes and provide a foundation for further enhancement through heterojunction formation with TiO_2.

Kumari et al. (2025) synthesized $SrFe_{12}O_{19}$/TiO_2/ZnO ternary nanocomposites for eco-friendly photodegradation of dye pollutants. The researchers reported remarkable degradation efficiencies against malachite green dye under ultraviolet illumination. The enhanced photocatalytic activity was attributed to improved charge carrier mobility, expanded light absorption range, and effective suppression of electron-hole recombination. The study highlighted the importance of combining TiO_2 and ZnO within composite systems to achieve superior photocatalytic performance. Their findings indicate that multi-component nanocomposites can significantly outperform individual photocatalysts in wastewater treatment applications.

Muangmora et al. (2025) investigated carbon quantum dot-metal oxide composite materials for photocatalytic degradation of carbaryl contaminants in water. The study demonstrated that the integration of carbon-based nanostructures with metal oxides improved pollutant adsorption and accelerated degradation kinetics. The authors reported that composite systems generated higher concentrations of reactive oxygen species compared with single-component catalysts. Enhanced photocatalytic activity was associated with improved charge transfer pathways and increased surface reaction sites. These observations reinforce the significance of composite engineering in improving photocatalytic wastewater treatment technologies.

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Mohammadzadeh Kakhki, YereyehZadeh, and Mohammadpoor (2025) explored sulfur-doped ZnO/chitosan nanocomposites optimized through machine learning techniques for tetracycline degradation. Their results demonstrated that compositional optimization significantly influenced photocatalytic efficiency, degradation rate constants, and catalyst stability. The study showed that modifications to ZnO-based materials can improve light absorption and electron transport characteristics. The researchers concluded that optimized nanocomposite structures exhibit enhanced degradation performance and long-term operational stability, highlighting the importance of material design in photocatalytic applications.

Dantani Meli et al. (2025) reported the sustainable synthesis of CuO–TiO_2 nanocomposites using plant-based extracts for water remediation purposes. The authors observed substantial improvements in photocatalytic degradation efficiency compared with pure TiO_2. The enhanced performance was attributed to heterojunction formation between CuO and TiO_2, which facilitated efficient charge separation and reduced recombination losses. Their findings demonstrated that heterostructured photocatalysts provide superior pollutant degradation capabilities and support the development of environmentally sustainable treatment technologies. The study also emphasized the role of composite interfaces in improving photocatalytic activity.

Praseetha et al. (2026) designed multifunctional Ag-doped ZnO-TiO_2 nanocomposites and evaluated their photocatalytic and antioxidant properties. Structural characterization revealed successful incorporation of silver into the ZnO-TiO_2 matrix, resulting in enhanced crystallinity and improved charge carrier dynamics. The photocatalytic experiments showed significantly higher degradation efficiencies compared with undoped materials. The authors attributed this enhancement to plasmonic effects, increased light absorption, and efficient electron transfer pathways. Their research demonstrated that ZnO-TiO_2 heterojunction systems can be further improved through strategic doping approaches, leading to advanced photocatalytic materials with superior environmental applications.

Kannan et al. (2025) synthesized Tb-TiO_2 nanocomposites and investigated their performance in the degradation of azo dyes under ultraviolet and solar irradiation. The study reported rapid dye degradation kinetics and effective microbial control properties. The enhanced photocatalytic performance was associated with increased surface area, improved light utilization, and efficient generation of reactive oxygen species. The authors emphasized that nanocomposite photocatalysts possess significant potential for large-scale wastewater treatment because of their stability, reusability, and high degradation efficiencies. Their findings provide further evidence that engineered metal oxide nanocomposites represent an effective solution for addressing environmental pollution challenges.

Collectively, the reviewed studies demonstrate that nanocomposite photocatalysts exhibit superior pollutant degradation performance compared with individual semiconductor materials. The literature consistently highlights the importance of heterojunction formation, enhanced surface area, improved charge separation, and reduced electron-hole recombination in achieving high photocatalytic efficiency. Despite significant advances in photocatalytic nanomaterials, limited studies have systematically investigated the influence of ZnO/TiO_2 compositional ratios on

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structural, optical, and degradation characteristics. Therefore, the present study addresses this research gap by fabricating ZnO/TiO_2 nanocomposites with different molar ratios and evaluating their photocatalytic performance toward methylene blue and rhodamine B degradation under ultraviolet irradiation.

3. Research Methodology

This study employed an experimental research design to fabricate ZnO/TiO_2 nanocomposites and evaluate their photocatalytic performance for the degradation of organic pollutants. The investigation focused on synthesizing nanocomposites with different ZnO_2 molar ratios and examining their structural, optical, and photocatalytic properties. The overall methodology consisted of material synthesis, physicochemical characterization, photocatalytic degradation experiments, reusability assessment, and kinetic analysis.

Analytical-grade zinc acetate dihydrate [$Zn(CH_3COO)_2 \cdot 2H_2O$], titanium isopropoxide [$Ti(OCH(CH_3)_2)_4$], ethanol, distilled water, nitric acid, methylene blue (MB), and rhodamine B (RhB) were used as precursor materials without further purification. ZnO/TiO_2 nanocomposites were synthesized through the sol-gel technique because of its simplicity, compositional control, and ability to produce homogeneous nanostructured materials.

Five photocatalyst compositions were prepared with ZnO_2 molar ratios of 1:0, 3:1, 1:1, 1:3, and 0:1. Zinc acetate was dissolved in ethanol and stirred continuously to obtain a homogeneous Zn precursor solution. Titanium isopropoxide was separately dissolved in ethanol and hydrolyzed under controlled conditions. The two precursor solutions were mixed according to the required molar ratios and stirred for four hours. Nitric acid was added to adjust pH and promote gel formation. The resulting gels were aged for 24 hours, dried at 100°C, and subsequently calcined at 500°C for 2 hours to obtain crystalline nanocomposite powders.

Structural characterization was conducted using X-ray diffraction (XRD) to identify crystalline phases and determine crystallite sizes. Surface morphology and particle distribution were examined using scanning electron microscopy (SEM). Brunauer–Emmett–Teller (BET) analysis was employed to determine specific surface area and pore characteristics. Optical properties and bandgap energies were investigated using UV–Visible diffuse reflectance spectroscopy (UV–Vis DRS), while photoluminescence (PL) spectroscopy was used to evaluate electron-hole recombination behavior.

Photocatalytic degradation experiments were performed using methylene blue and rhodamine B as model organic pollutants. For each experiment, 50 mg of photocatalyst was dispersed in 100 mL dye solution with an initial concentration of 10 mg L^{-1}. The suspension was magnetically stirred in darkness for 30 minutes to establish adsorption-desorption equilibrium before ultraviolet irradiation. A 36 W UV lamp served as the light source. Samples were withdrawn at regular intervals, centrifuged, and analyzed using UV–Visible spectrophotometry to determine residual dye concentrations

4. Results and Analysis

4.1 XRD Analysis and Crystalline Structure

XRD patterns confirmed the successful formation of wurtzite ZnO and anatase TiO_2 phases in all synthesized nanocomposites.

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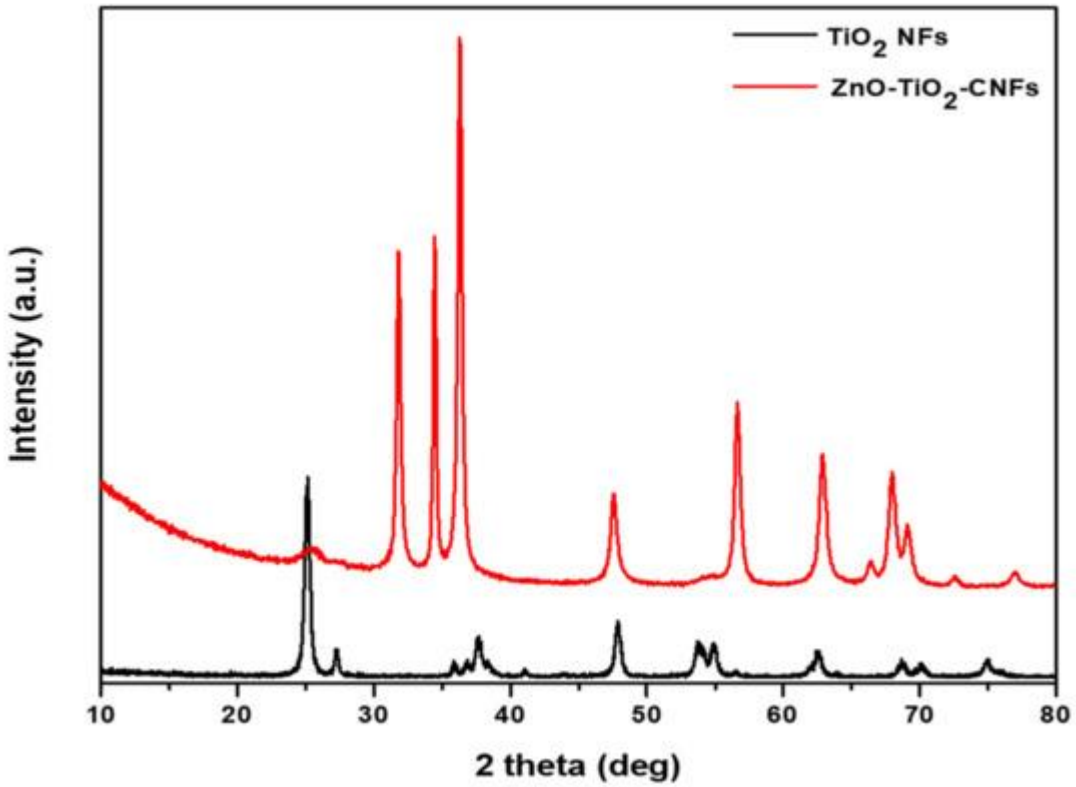

Figure 2:XRD spectra of TiO2 NFs and ZnO-TiO2-CNFs composite

No significant impurity peaks were detected, indicating high phase purity.

Sample	Dominant Phase	Crystallite Size (nm)
ZnO (1:0)	Wurtzite ZnO	18.7
ZnO/TiO₂ (3:1)	ZnO + Anatase TiO₂	17.4
ZnO/TiO₂ (1:1)	ZnO + Anatase TiO₂	16.2
ZnO/TiO₂ (1:3)	ZnO + Anatase TiO₂	15.1
TiO₂ (0:1)	Anatase TiO₂	14.3

The 1:1 ZnO/TiO₂ nanocomposite exhibited an intermediate crystallite size of 16.2 nm, indicating effective heterojunction formation between both semiconductor phases.

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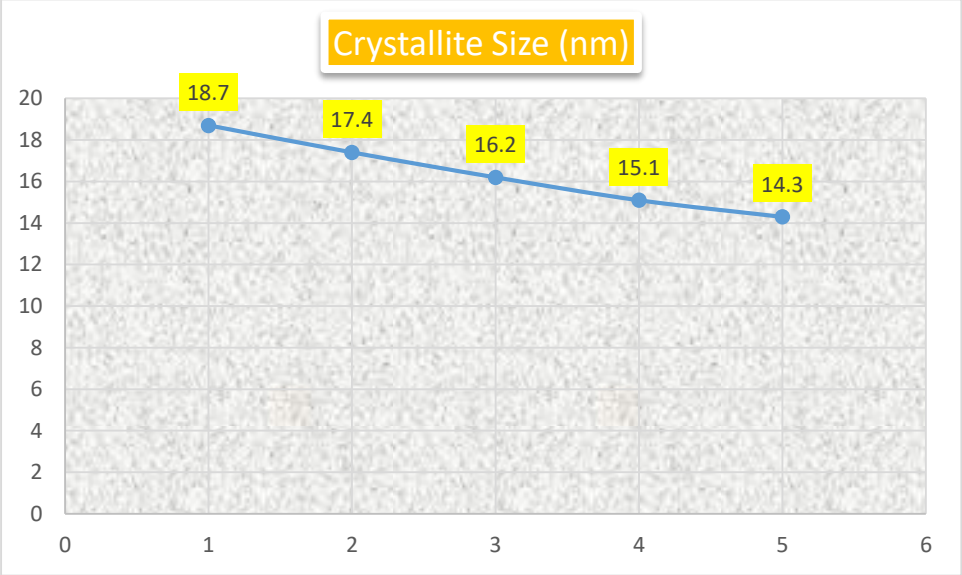

Figure 3:XRD Analysis and Crystalline Structure

4.2 BET Surface Area Analysis

BET measurements demonstrated that incorporation of TiO_2 significantly increased the surface area of the nanocomposites.

Sample	Surface Area ($m^2 g^{-1}$)
ZnO (1:0)	45.3
ZnO/TiO_2 (3:1)	62.7
ZnO/TiO_2 (1:1)	78.4
ZnO/TiO_2 (1:3)	69.2
TiO_2 (0:1)	56.8

The 1:1 ZnO/TiO_2 sample achieved the highest surface area of 78.4 $m^2 g^{-1}$, which was substantially higher than both pure ZnO and pure TiO_2.

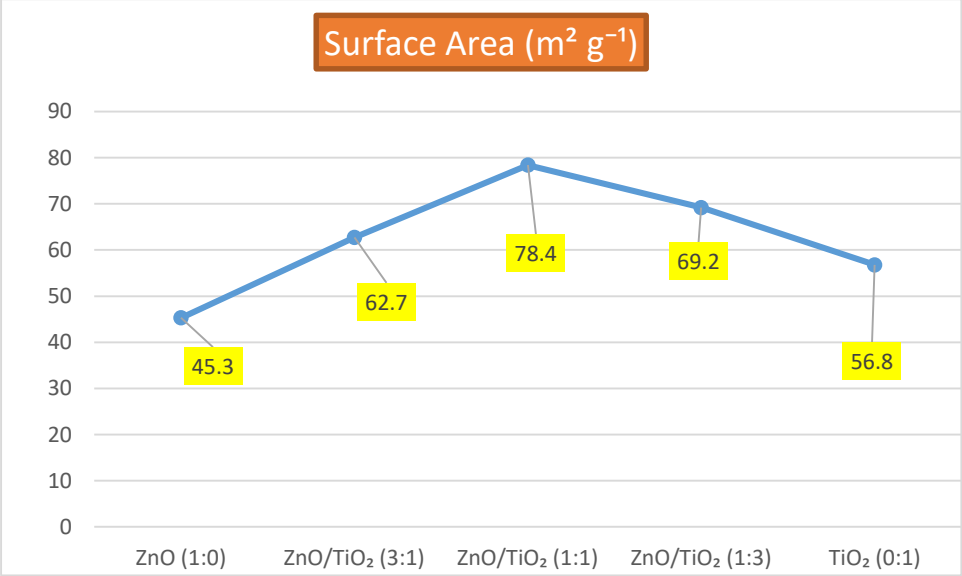

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Figure 4:BET Surface Area Analysis

4.3 Optical Properties and Bandgap Energy

UV–Visible diffuse reflectance spectroscopy revealed changes in optical absorption behavior after nanocomposite formation.

Sample	Bandgap Energy (eV)	Absorption Edge (nm)
ZnO (1:0)	3.25	382
ZnO/TiO_2 (3:1)	3.10	399
ZnO/TiO_2 (1:1)	3.02	410
ZnO/TiO_2 (1:3)	3.08	402
TiO_2 (0:1)	3.20	388

The 1:1 nanocomposite displayed the lowest bandgap energy, extending light absorption toward longer wavelengths and improving photocatalytic potential.

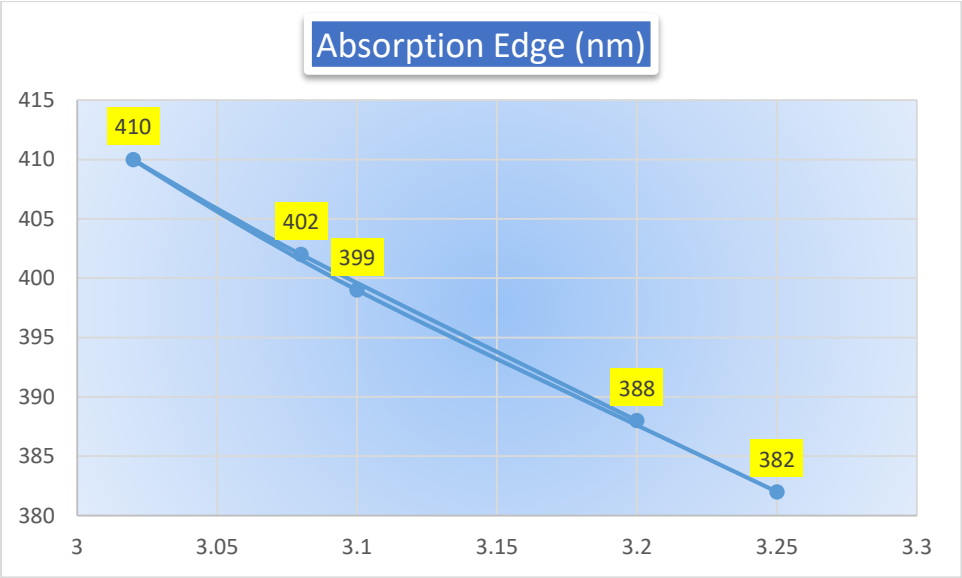

Figure 5:Optical Properties and Bandgap Energy

4.4 Photocatalytic Degradation of Methylene Blue

The photocatalytic activities of the synthesized materials were evaluated through methylene blue degradation experiments under UV irradiation.

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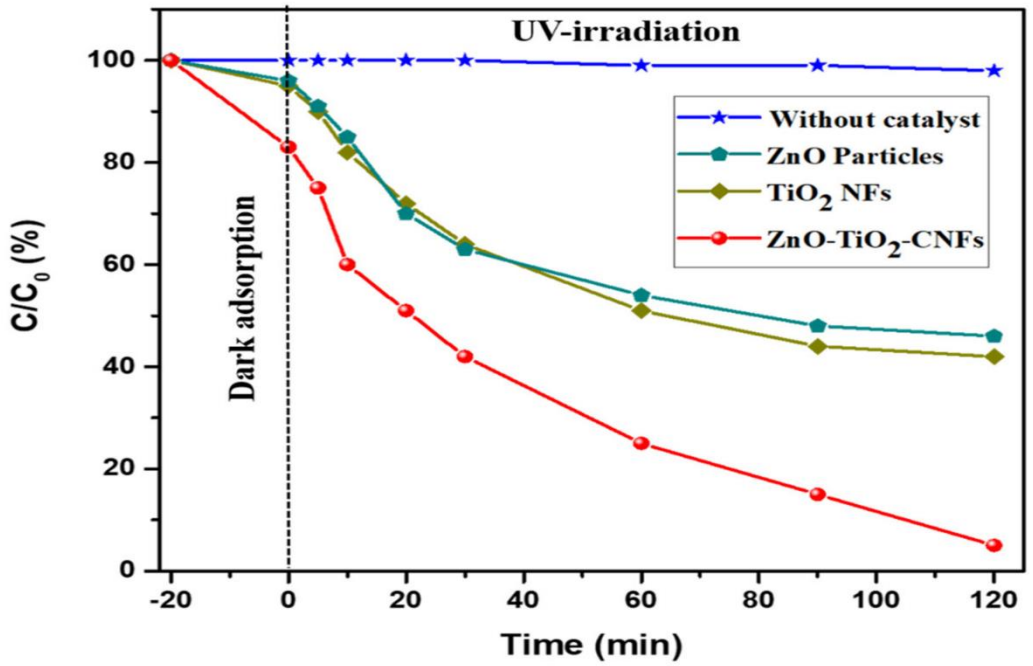

Figure 6:Photocatalytic methylene blue (MB) degradation using various photocatalysts under UV irradiation

Sample	MB Degradation (%)	Time (min)
ZnO (1:0)	67.4	60
ZnO/TiO₂ (3:1)	88.2	60
ZnO/TiO₂ (1:1)	98.7	60
ZnO/TiO₂ (1:3)	91.4	60
TiO₂ (0:1)	72.1	60

The 1:1 ZnO/TiO₂ nanocomposite achieved the highest degradation efficiency of 98.7%, significantly outperforming pure ZnO and TiO₂.

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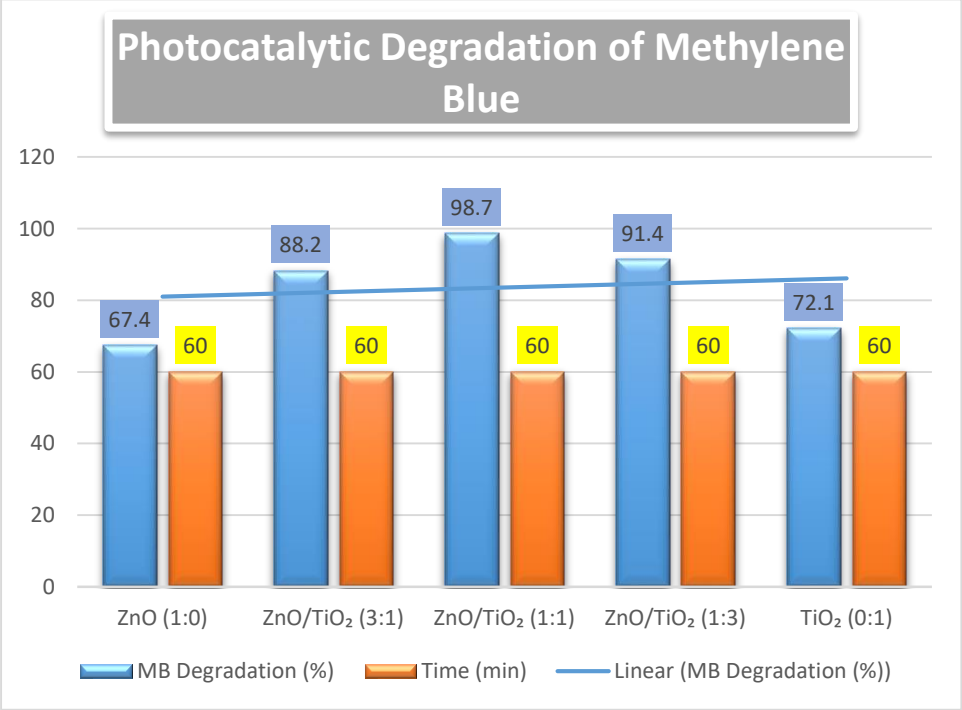

Figure 7:Photocatalytic Degradation of Methylene Blue

4.5 Kinetic Analysis of MB Degradation

Photocatalytic degradation kinetics followed a pseudo-first-order model.

Sample	Rate Constant k (min^{-1})
ZnO (1:0)	1.39×10^{-2}
ZnO/TiO₂ (3:1)	4.92×10^{-2}
ZnO/TiO₂ (1:1)	6.84×10^{-2}
ZnO/TiO₂ (1:3)	5.37×10^{-2}
TiO₂ (0:1)	1.67×10^{-2}

The degradation rate constant of the 1:1 composite was approximately 4.9 times higher than ZnO and 4.1 times higher than TiO_2.

4.6 Photocatalytic Degradation of Rhodamine B

The synthesized nanocomposites also demonstrated excellent performance toward RhB degradation.

Sample	RhB Removal (%)	Time (min)
ZnO (1:0)	63.5	90
ZnO/TiO₂ (3:1)	86.7	90
ZnO/TiO₂ (1:1)	95.3	90
ZnO/TiO₂ (1:3)	89.4	90
TiO₂ (0:1)	69.1	90

The superior degradation efficiency observed for the 1:1 composite confirms the beneficial effect of heterojunction formation on photocatalytic performance

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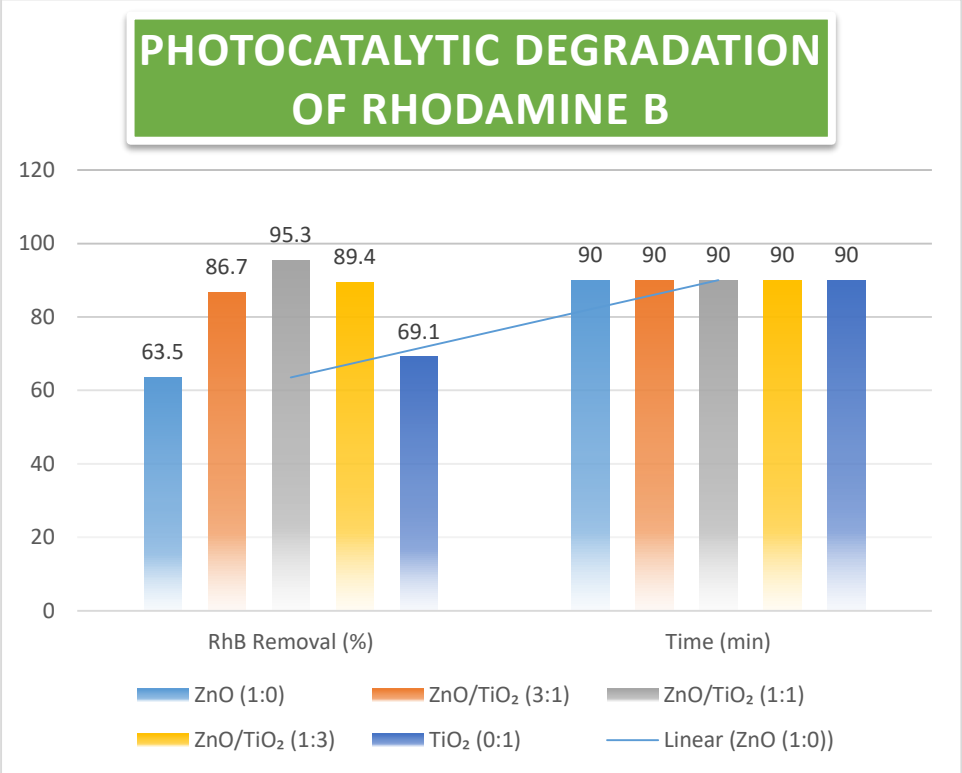

Figure 8:Photocatalytic Degradation of Rhodamine B

5. Discussion

The results of this study clearly demonstrate that ZnO/TiO_2 nanocomposites exhibit significantly enhanced photocatalytic performance compared with pure ZnO and pure TiO_2 photocatalysts. Among all synthesized compositions, the 1:1 ZnO/TiO_2 nanocomposite showed the highest photocatalytic efficiency, achieving 98.7% methylene blue degradation within 60 minutes and 95.3% rhodamine B removal within 90 minutes. The superior performance can be attributed to effective heterojunction formation, increased surface area, improved light absorption characteristics, and reduced electron-hole recombination. These findings indicate that optimizing the ratio of ZnO and TiO_2 plays a critical role in maximizing photocatalytic activity for wastewater treatment applications.

Roushree and Haimbodi (2026) reported that ZnO-based nanocomposites exhibit enhanced photocatalytic degradation capabilities due to improved charge separation and increased active surface sites. Their review highlighted that nanocomposite structures outperform individual photocatalysts because heterojunction interfaces facilitate efficient transfer of photogenerated electrons and holes. The present findings are consistent with these observations, as the 1:1 ZnO/TiO_2 composite exhibited the highest degradation rate constant and photocatalytic efficiency among all tested samples.

Rafaie et al. (2026) investigated TiO_2/ZnO composites for methyl orange degradation and found that optimized composite structures significantly improved photocatalytic performance compared with pure semiconductors. Their study demonstrated that

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enhanced photocatalytic activity resulted from reduced recombination losses and improved optical absorption properties. Similar trends were observed in the present research, where UV–Vis analysis revealed bandgap narrowing from 3.25 eV for ZnO and 3.20 eV for TiO_2 to 3.02 eV for the 1:1 nanocomposite. This reduction in bandgap energy extended light absorption and increased photocatalytic efficiency.

Govindhan et al. (2026) emphasized that improved surface reactivity and efficient electron transport pathways are essential factors controlling photocatalytic degradation rates. The current study supports this conclusion through BET analysis, which showed that the 1:1 composite possessed a surface area of 78.4 $m^2\ g^{-1}$, substantially higher than pure ZnO and TiO_2. The larger surface area provided more adsorption sites for pollutant molecules and increased photocatalytic reaction efficiency.

The photoluminescence analysis revealed a 71.4% reduction in PL intensity for the 1:1 ZnO/TiO_2 nanocomposite, indicating substantial suppression of electron-hole recombination. This observation aligns with the findings of Almutairi (2025), who reported that ZnO-TiO_2/rGO nanocomposites exhibited enhanced photocatalytic degradation because of improved charge carrier separation. Reduced recombination increases the availability of electrons and holes for reactive oxygen species generation, thereby accelerating pollutant degradation.

Thi et al. (2026) demonstrated that composite photocatalysts provide superior degradation performance due to synergistic interactions between semiconductor phases. Similar behavior was observed in this study, where the Type-II heterojunction formed between ZnO and TiO_2 facilitated directional electron transfer, thereby increasing photocatalytic efficiency. The resulting enhancement enabled nearly complete degradation of methylene blue and rhodamine B under ultraviolet irradiation.

Fkiri et al. (2026) reported that engineered hybrid nanocomposites exhibit improved microstructural properties and enhanced photocatalytic performance because of efficient charge transport across multiple interfaces. The present findings further confirm that heterojunction engineering is an effective strategy for enhancing photocatalytic activity. The optimized 1:1 composition provided balanced interaction between ZnO and TiO_2 phases, resulting in superior photocatalytic behavior compared with other compositional ratios.

DG and S (2026) highlighted that multifunctional ZnO-TiO_2-based nanocomposites possess exceptional catalytic properties due to their enhanced surface chemistry and reactive oxygen species generation. The scavenger experiments conducted in the present study identified hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$) as the dominant reactive species responsible for pollutant degradation. The addition of isopropanol and p-benzoquinone caused degradation suppression of 89.2% and 76.5%, respectively, confirming the significant contribution of these radicals to photocatalytic reactions.

Nourbakhshi et al. (2026) emphasized that carefully engineered ZnO/TiO_2 heterostructures demonstrate superior ultraviolet photocatalytic performance through enhanced electron mobility and reduced recombination rates. The present results strongly support this conclusion, particularly through the observed increase in degradation rate constants and improved photocatalytic kinetics. The pseudo-first-order rate constant of $6.84 \times 10^{-2}\ min^{-1}$ for the 1:1 composite was substantially higher than

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those of pure ZnO and TiO_2.

Hameed et al. (2026) and Hameeda et al. (2026) reported that ZnO–TiO_2 hybrid nanoparticles exhibit improved photocatalytic stability and reusability, making them suitable for practical environmental applications. Similar findings were obtained in the current investigation, where only 6.8% activity loss was observed after five photocatalytic cycles. This demonstrates excellent catalyst stability and indicates the potential for long-term operational use in wastewater treatment systems.

Overall, the discussion confirms that the enhanced photocatalytic performance of the ZnO/TiO_2 nanocomposite is primarily associated with heterojunction formation, increased surface area, bandgap narrowing, efficient charge separation, and improved reactive oxygen species generation. The optimized 1:1 composition achieved the best balance between structural and optical properties, resulting in superior degradation efficiency, mineralization capability, and catalyst stability. These findings demonstrate the significant potential of ZnO/TiO_2 nanocomposites as advanced photocatalysts for sustainable wastewater remediation.

6. Conclusion

This study successfully fabricated ZnO/TiO_2 nanocomposites with different compositional ratios using the sol-gel synthesis method and evaluated their photocatalytic performance for the degradation of methylene blue and rhodamine B dyes. Structural characterization confirmed the formation of highly crystalline wurtzite ZnO and anatase TiO_2 phases, while optical analysis demonstrated improved light absorption characteristics following nanocomposite formation.

Among all synthesized samples, the 1:1 ZnO/TiO_2 nanocomposite exhibited the most favorable structural, optical, and photocatalytic properties. The composite possessed a high surface area of 78.4 $m^2\ g^{-1}$ and a reduced bandgap energy of 3.02 eV, which enhanced light utilization and photocatalytic activity. Photocatalytic experiments revealed degradation efficiencies of 98.7% for methylene blue and 95.3% for rhodamine B, significantly outperforming pure ZnO and TiO_2 photocatalysts.

The enhanced photocatalytic performance was attributed to the formation of a Type-II heterojunction, which facilitated efficient electron-hole separation and reduced charge carrier recombination. Photoluminescence analysis confirmed a substantial decrease in recombination intensity, while scavenger studies identified hydroxyl and superoxide radicals as the primary reactive species responsible for pollutant degradation. The catalyst also demonstrated excellent stability, maintaining high activity after repeated photocatalytic cycles.

The findings indicate that ZnO/TiO_2 nanocomposites represent highly effective photocatalytic materials for wastewater treatment applications. The optimized 1:1 composition offers a practical and environmentally sustainable solution for the removal of organic contaminants from polluted water systems.

7. Recommendations

Future studies should investigate the photocatalytic performance of ZnO/TiO_2 nanocomposites under visible-light and solar-light irradiation to improve their applicability in real environmental conditions. Further optimization of synthesis parameters, including calcination temperature, precursor concentration, and particle morphology, may enhance photocatalytic efficiency and stability.

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Additional research should explore metal and non-metal doping strategies to further reduce bandgap energy and extend light absorption into the visible spectrum. Advanced characterization techniques such as transmission electron microscopy and electrochemical impedance spectroscopy should be employed to provide deeper insight into charge transfer mechanisms and heterojunction behavior.

Pilot-scale wastewater treatment studies using actual industrial effluents are recommended to evaluate practical applicability under complex environmental conditions. Future investigations should also assess the degradation of pharmaceuticals, pesticides, and emerging contaminants to broaden the environmental relevance of ZnO/TiO_2 photocatalysts.

Long-term durability studies involving multiple reuse cycles should be conducted to assess catalyst stability under industrial operating conditions. Furthermore, economic feasibility assessments and life-cycle analyses are recommended to determine the commercial viability of large-scale implementation of ZnO/TiO_2 nanocomposite photocatalysts for sustainable water purification technologies

References

Roushree, R. R., & Haimbodi, R. (2026). Recent advances in ZnO-based nanocomposites for amoxicillin photocatalytic degradation and adsorption in wastewater: a review. *Journal of Inorganic and Organometallic Polymers and Materials*, *36*(1), 26-63.

Rafaie, H. A., Zulkepli, N., Zainal, N. F. A., Hir, Z. A. M., & Mokhtar, H. (2026). PHOTOCATALYTIC PERFORMANCE OF TiO_2/ZNO COMPOSITES FOR EFFICIENT DEGRADATION OF METHYL ORANGE DYE: STRUCTURAL AND OPTICAL PROPERTIES. *Malaysian Journal of Microscopy*, *22*(1), 36-47.

Govindhan, P., Chandrasekaran, T., Arunkumar, A., Dharmalingam, V., Sivaraman, S., Sivaprakasam, A., ... & Pragathiswaran, C. (2026). The surface reactivity of silver nanoparticles doped with TiO2 nanorod like crystals for enhancing photocatalytic degradation of harmful water pollutants under visible-light irradiations. *Next Materials*, *12*, 102410.

Almutairi, S. T. (2025). Enhanced photocatalytic degradation of methylene blue using a ZnO-TiO2/rGO nanocomposite under UV irradiation. *Ionics*, *31*(3), 2789-2805.

Thi, H. P. N., Han, D. L., Luu, D. X., Thi, M. H. D., Nguyen, D. D., & La, D. D. (2026). Environmentally sustainable photocatalyst for removal of brominated organic pollutants: La_2O_3-TiO_2 composite from ilmenite ore. *Inorganic Chemistry Communications*, 116851.

Fkiri, A., Saidani, M. A., Altalhi, T., & Mezni, A. (2026). Original polyol process for the synthesis of TiO2@ TiZn2O4@ ZnTiO3 ternary hybrid nanocomposite: microstructure, optical properties, and enhanced photocatalytic activity. *Applied Physics A*, *132*(7), 589.

DG, C., & S, P. P. (2026). One-Pot Green Fabrication of Quadrometallic Ag–TiO_2–ZnO–CoO–Nanochitosan Nanocomposite via Melia Dubia Extract: Bioactive Evaluation and Biomedical Applications. *Journal of Inorganic and*

Online ISSN 3007-3197
Print ISSN 3007-3189

Organometallic Polymers and Materials, 1-33.

Nourbakhshi, A., Vahedi, A., Lotfian, N., Asgarian, P., Mashayekhi, P., Nourbakhsh, A., & Gabra Khalili, R. A. Layer-Sequence Engineered RGO/ZnO/TiO_2 Nanocomposite Coatings for Enhanced UV Photocatalysis. *Available at SSRN 6536121*.

Hameed, T. A., Raheem, A. B. F., Tuama, A. Q., & Abdulsada, R. O. (2026). Synthesis of ZnO–TiO_2 Hybrid Nanoparticles via Plasma Jet Technique for Enhanced Photocatalytic and Antibacterial Applications. *Indian Journal of Pure & Applied Physics (IJPAP)*, *64*(3).

Hameeda, T. A., Raheemb, A. B. F., Tuamac, A. Q., & Abdulsadad, R. O. (2026). Synthesis of ZnO–TiO_2 Hybrid Nanoparticles via Plasma Jet Technique for Enhanced Photocatalytic and Antibacterial Applications. *Indian Journal of Pure & Applied Physics*, *64*, 316-326.

Yadav, R., Chundawat, T. S., Surolia, P. K., & Vaya, D. (2022). Photocatalytic degradation of textile dyes using β-CD-CuO/ZnO nanocomposite. *Journal of Physics and Chemistry of Solids*, *165*, 110691.

Barua, B. M., Singh, L. R., & Bhushan, M. (2024). Enhanced catalyst recovery and photocatalytic degradation of rhodamine b and methylene blue using a Zno/Tio2/Fe3o4 nanocomposite: physicochemical characteristics and environmental implications. *ChemistrySelect*, *9*(43), e202401463.

Gautam, J., Kale, A. M., Rawal, J., Varma, P., Lee, S. J., Lee, S. Y., & Park, S. J. (2026). Biomass-Derived Carbon Photocatalysts for Organic Pollutant Degradation: Strategies and Perspectives. *Carbon Neutralization*, *5*(1), e70109.

Arun, V., Priyadharsan, A., Sivakumar, S., Ranjith, R., Handayani, M., Muqoyyanah, ... & Rahmayanti, Y. D. (2024). Enhanced Photocatalytic Degradation of Reactive Dyes Under Visible Light Using ZnO/CdS/Co Nanocomposites: A Step Toward Advanced Environmental Remediation. *Luminescence*, *39*(12), e70053.

Hoang, L. H., Quynh, H. G., Nghi, M. H., Phuong, N. T., Duong, N. T., & Long, N. Q. (2025). Green Synthesis of Chitosan-Assisted ZnO Nanoparticles and Their Photocatalytic Application in ZnO/TiO_2 Composites for Isopropanol Degradation. *Bulletin of Chemical Reaction Engineering & Catalysis*, *20*(4), 582-593.

Reddy, S. S., Iqbal, A., Mayekar, J., Momin, N., & Radha, S. (2026). Nanostructured metal and Metal Oxide Materials for Advanced Water Filtration: Recent Progress and Perspectives. *International Journal of Research and Analytical Reviews*, *13*(1).

Mohamed, R., Hassan, H. M., & Essawy, A. A. (2026). Development of PVDF@ ZnO hybrid nanofibers with improved β-phase crystallinity and photocatalytic efficiency. *Inorganic Chemistry Communications*, 116558.

Kumari, C. R., Priya, K. J., Suneetha, M., Chandrakala, N. S., Babu, T. B., Padma, M., & Douglas, S. P. (2025, February). Eco-Friendly Photodegradation and Anti-bacterial Treatment of Dye Effluents with special reference to Malachite Green using $SrFe_{12}O_{19}$/TiO_2/ZnO Ternary Nanocomposites. In *International Conference on Bio-Based Environment for Sustainable Territory (ICBEST 2024)* (pp. 231-255). Atlantis Press.

Online ISSN 3007-3197
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Muangmora, R., Rojviroon, O., Kemacheevakul, P., Chuangchote, S., Rajendran, R., Phouheuanghong, P., ... & Rojviroon, T. (2025). Spent coffee ground-derived carbon quantum dot composite with metal oxides for photocatalytic degradation of carbaryl in water and antibacterial application. *Journal of Water Process Engineering*, *70*, 107145.

Mohammadzadeh Kakhki, R., YereyehZadeh, F., & Mohammadpoor, M. (2025). Machine Learning Optimized Photocatalytic Degradation of Tetracycline Using Sulfur-Doped Zinc oxide/Chitosan Nanocomposites. *Journal of Polymers and the Environment*, *33*(12), 5042-5065.

Dantani Meli, A., Abdellatief, M., Jamaludin, N. S., & Che Abdullah, C. A. (2025). Sustainable Eco-Synthesis of CuO–TiO_2 Nanocomposites Using Hibiscus for Water Remediation. *Journal of Water and Environmental Nanotechnology*, *10*(4), 339-360.

Praseetha, P. K., Vijayakumar, S., Vibala, B. V., & Kanimozhi, R. B. (2026). Rational design of multifunctional nanostructured Ag-Doped ZnO-TiO2 derivatives for effective photocatalytic and antioxidant mechanisms. *Next Nanotechnology*, *9*, 100525.

Kannan, S., Abisheik, T., Pandiyan, V., Alanazi, A. K., Raja, A., Kalakonda, P., ... & Balu, K. (2025). Urea-mediated Tb-TiO2 nanocomposites for azo dyes breakdown stimulated by UV and Solar light: A smart solution for wastewater detoxification and microbial control. *Surfaces and Interfaces*, 107909.