DEVELOPMENT AND EVALUATION OF PHOTOCATALYTIC AND ANTIMICROBIAL NANOPARTICLES FOR ENHANCED REMOVAL OF PATHOGENS AND ORGANIC POLLUTANTS IN ADVANCED WATER TREATMENT SYSTEMS

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Abstract

Access to safe and clean water remains a critical global challenge due to the increasing presence of organic pollutants and pathogenic microorganisms in water sources. Conventional treatment methods often fail to completely remove these contaminants, necessitating the development of innovative, efficient, and sustainable solutions. This study focuses on the development and evaluation of multifunctional nanoparticles combining photocatalytic and antimicrobial properties for enhanced water treatment. Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles were synthesized via sol–gel methods, while metallic nanoparticles such as silver (Ag) were prepared through chemical reduction and integrated with metal oxides to form stable nanocomposites. Characterization using SEM, TEM, XRD, FTIR, UV–Vis spectroscopy, and BET analysis confirmed favorable morphology, crystallinity, surface functionalization, and extended light absorption in the visible range. Photocatalytic studies demonstrated that composite nanoparticles achieved up to 90% degradation of model organic pollutants such as methylene blue and rhodamine B under UV and visible light, significantly outperforming pure metal oxides. Antimicrobial evaluation against E. coli, S. aureus, and P. aeruginosa showed substantial inhibition and bacterial inactivation through reactive oxygen species generation and membrane disruption. Bench-scale water treatment tests revealed significant reductions in COD, BOD, turbidity, and microbial load, with immobilized nanoparticles retaining high performance over multiple cycles. The synergistic combination of photocatalytic and antimicrobial functions in these nanocomposites presents a promising, sustainable, and energy-efficient strategy for simultaneous chemical and biological water purification.

Introduction

Access to safe and clean water remains one of the most pressing global challenges of the twenty-first century. Rapid industrialization, urban population growth, agricultural intensification, and climate change have significantly increased the contamination of freshwater resources worldwide(Reader, 2022). Water bodies are continuously exposed to a wide spectrum of pollutants, including pathogenic microorganisms, organic contaminants, pharmaceutical residues, dyes, pesticides, and endocrine-disrupting compounds. Conventional water treatment technologies, although effective to a certain extent, often fail to completely eliminate emerging contaminants and resistant microbial strains. As a result, there is a growing need for innovative, efficient, and sustainable treatment strategies capable of addressing both microbial and chemical pollution in advanced water treatment systems(Izah et al., 2024).

Pathogenic microorganisms such as bacteria, viruses, protozoa, and fungi are among the primary contributors to waterborne diseases. According to global health reports, millions of cases of illnesses such as cholera, dysentery, typhoid fever, and gastroenteritis occur annually due to contaminated water supplies. While chlorination, ozonation, and ultraviolet (UV) irradiation are widely used for disinfection, these methods have notable limitations. Chlorination may produce harmful disinfection by-products (DBPs), such as trihalomethanes and haloacetic acids, which pose long-term health risks(Prasad and Grobelak, 2020). UV treatment requires consistent energy input and may not provide residual disinfection. Furthermore, the emergence of antibiotic-resistant bacteria has reduced the effectiveness of traditional antimicrobial strategies, necessitating alternative solutions that can provide broad-spectrum and long-lasting antimicrobial activity. Simultaneously, organic pollutants represent a complex and persistent class of contaminants in aquatic environments. Industrial effluents discharge dyes, solvents, and chemical intermediates into water bodies, while agricultural runoff introduces pesticides and herbicides. In addition, pharmaceutical and personal care products (PPCPs) are increasingly detected in wastewater and surface water systems(Magana-Arachchi and Wanigatunge, 2020). Many of these compounds are recalcitrant, bioaccumulative, and resistant to conventional biological treatment processes. Their persistence in the environment not only disrupts aquatic ecosystems but also poses significant risks to human health through drinking water exposure. Traditional treatment processes such as coagulation–flocculation, sedimentation, filtration, and biological degradation often prove insufficient in completely removing these complex organic molecules(Ali et al., 2025).

Advanced water treatment technologies have emerged as promising alternatives to address these limitations. Among them, advanced oxidation processes (AOPs) have gained considerable attention due to their ability to generate highly reactive species, such as hydroxyl radicals ($\bullet$OH), capable of degrading a wide range of organic contaminants into less harmful or mineralized products. Photocatalysis, a subclass of AOPs, utilizes semiconductor materials activated by light to produce reactive oxygen species (ROS) that can oxidize organic pollutants and inactivate microorganisms simultaneously(Ali et al.). This dual functionality makes photocatalytic systems particularly attractive for integrated water purification strategies. Nanotechnology has further revolutionized the field of water treatment by introducing materials with unique physicochemical properties arising from their nanoscale dimensions. Nanoparticles possess a high surface area-to-volume ratio, enhanced reactivity, tunable surface chemistry, and improved light absorption characteristics compared to their bulk counterparts(Oon et al., 2023). These properties significantly enhance catalytic and antimicrobial performance. Metal and metal oxide nanoparticles such as titanium dioxide (TiO_2), zinc oxide (ZnO), silver (Ag), copper oxide (CuO), and iron oxide (Fe_3O_4) have been extensively studied for their photocatalytic and antimicrobial capabilities. Titanium dioxide, for example, is one of the most widely investigated

photocatalysts due to its chemical stability, non-toxicity, and strong oxidative potential under UV irradiation. However, its limited activity under visible light and rapid electron–hole recombination reduce its efficiency in practical applications(Bridle, 2020). To overcome these challenges, researchers have explored doping strategies, composite formation, and surface modification techniques to extend light absorption into the visible region and enhance charge separation. Similarly, zinc oxide exhibits strong photocatalytic and antibacterial properties, while silver nanoparticles are well known for their potent antimicrobial activity through mechanisms involving membrane disruption, oxidative stress induction, and interference with cellular processes(Wittler, 2023).

The integration of photocatalytic and antimicrobial functionalities within a single nanoparticle system offers significant advantages for advanced water treatment. Photocatalytic nanoparticles can degrade organic pollutants while simultaneously generating reactive oxygen species that inactivate pathogens. Additionally, incorporating antimicrobial agents such as silver or copper into photocatalytic matrices can provide enhanced and sustained microbial control, even in the absence of light(Tripathy et al., 2024). This synergistic effect can reduce the need for chemical disinfectants, lower energy consumption, and minimize harmful by-product formation. Despite their promising potential, several challenges must be addressed before widespread implementation of nanoparticle-based water treatment technologies. These include issues related to nanoparticle stability, aggregation, recovery, potential toxicity, and environmental impact. Free nanoparticles dispersed in water may be difficult to separate after treatment and could pose ecological risks if released into the environment(Naseem and Waseem, 2022). Therefore, research efforts are increasingly focused on developing immobilized or supported nanoparticle systems, magnetic recoverable nanocomposites, and environmentally benign synthesis methods. Evaluating the performance, safety, and scalability of these systems is crucial for translating laboratory-scale innovations into real-world applications(Lofrano et al., 2022).

The development and evaluation of photocatalytic and antimicrobial nanoparticles require a multidisciplinary approach encompassing materials science, chemistry, microbiology, environmental engineering, and toxicology. Synthesis techniques such as sol–gel methods, hydrothermal processes, chemical reduction, green synthesis using plant extracts, and physical deposition methods allow precise control over particle size, morphology, and surface properties. Characterization tools including scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and UV–Vis spectroscopy are essential for understanding structural and optical properties(Ran et al., 2023). Furthermore, performance evaluation involves assessing photocatalytic degradation efficiency against model organic pollutants, antimicrobial activity against representative pathogenic strains, and stability under operational conditions. In the context of sustainable development, nanoparticle-based water treatment systems align with global goals for clean water and sanitation. By enhancing contaminant removal efficiency and reducing reliance on hazardous chemicals, these advanced materials offer environmentally friendly alternatives to conventional methods. Moreover, tailoring nanoparticles to harness solar energy for photocatalysis presents opportunities for low-cost and energy-efficient water purification, particularly in resource-limited settings(Belessiotis et al., 2022).

This research focuses on the development and comprehensive evaluation of photocatalytic and antimicrobial nanoparticles designed to enhance the removal of pathogens and organic pollutants in advanced water treatment systems. By optimizing material composition, structural properties, and functional performance, the study aims to contribute to the growing body of knowledge on nanotechnology-driven water purification solutions. The findings are expected to provide insights into the synergistic

mechanisms of photocatalysis and antimicrobial action, as well as practical considerations for integration into existing treatment infrastructures. Ultimately, the advancement of multifunctional nanoparticle systems represents a promising pathway toward safer, more efficient, and sustainable water treatment technologies capable of addressing the complex challenges of modern water contamination.

Methodology
1. Synthesis of Photocatalytic and Antimicrobial Nanoparticles

The development of multifunctional nanoparticles for water treatment involves selecting materials with both photocatalytic and antimicrobial properties. In this study, metal oxide nanoparticles such as titanium dioxide (TiO_2) and zinc oxide (ZnO) will be synthesized and combined with metallic antimicrobial agents such as silver (Ag) or copper (Cu). The primary synthesis methods include sol–gel processing for metal oxides and chemical reduction for metallic nanoparticles. For the sol–gel synthesis of TiO_2 nanoparticles, titanium isopropoxide will be dissolved in ethanol under continuous stirring (Salazar et al., 2020). An acidified water solution will be added dropwise to the precursor solution to induce hydrolysis, and the mixture will be stirred for several hours to allow gel formation. The gel will be aged for 24 hours and then dried at 100 °C for 12 hours, followed by calcination at 400–500 °C to achieve crystalline nanoparticles.
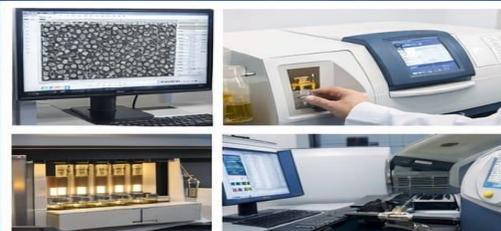
The particle size, crystallinity, and surface area can be adjusted by varying precursor concentration, pH, and calcination temperature. For the synthesis of metallic antimicrobial nanoparticles, silver nitrate or copper sulfate will be dissolved in deionized water, and polyvinylpyrrolidone (PVP) will be added as a stabilizing agent. Sodium borohydride ($NaBH_4$) will be introduced gradually as a reducing agent, resulting in the formation of nanoparticles indicated by a color change. The reaction will continue under stirring to ensure complete reduction, followed by washing and centrifugation to remove excess reagents. These nanoparticles will then be combined with the metal oxide matrix to form photocatalytic-antimicrobial nanocomposites. Deposition of metallic nanoparticles on the surface of TiO_2 or ZnO will be achieved either by physical mixing or in situ reduction, ensuring uniform distribution and maximizing synergistic activity for both organic pollutant degradation and microbial inactivation(Zeng et al., 2023).

2. Characterization of Nanoparticles

A comprehensive characterization of the synthesized nanoparticles will be conducted to correlate their physical and chemical properties with functional performance. The morphology and size of the nanoparticles will be analyzed using scanning electron microscopy (SEM) and

transmission electron microscopy (TEM), which will reveal particle shape, size distribution, and surface texture. The crystal structure will be confirmed by X-ray diffraction (XRD), allowing identification of anatase and rutile phases in TiO_2 and the wurtzite structure in ZnO. Surface chemistry and functional groups will be determined using Fourier-transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS). Optical properties, including light absorption and bandgap energy, will be measured by UV–Visible diffuse reflectance spectroscopy (UV–Vis DRS), which is critical for evaluating photocatalytic performance. Additionally, the surface area and porosity will be assessed using the Brunauer–Emmett–Teller (BET) method, as these parameters influence both adsorption and catalytic activity. This detailed characterization will provide insights into the relationship between nanoparticle structure, composition, and their effectiveness in water treatment applications.

3. Evaluation of Photocatalytic Activity

The photocatalytic activity of the nanoparticles will be assessed using model organic pollutants, including methylene blue, rhodamine B, and phenol, which represent common contaminants in wastewater. A known concentration of nanoparticles will be dispersed in aqueous pollutant solutions and stirred in the dark for a set period to establish adsorption–desorption equilibrium. The solutions will then be irradiated with UV or visible light sources. Samples will be collected at regular intervals, and pollutant degradation will be monitored using UV–Vis spectrophotometry by measuring the decrease in concentration over time. The degradation efficiency will be calculated as the percentage reduction in pollutant concentration relative to the initial value. Kinetic analysis will be performed using pseudo-first-order and pseudo-second-order models to determine reaction rate constants. Comparative studies will assess the effect of light sources, nanoparticle concentration, and pollutant type on photocatalytic efficiency. This evaluation will help determine the suitability of

the nanoparticles for practical water treatment applications.

4. Antimicrobial Activity Assessment

The antimicrobial performance of the nanoparticles will be evaluated against representative waterborne pathogens, including Escherichia coli, Staphylococcus aureus, and Pseudomonas aeruginosa. Initially, the agar well diffusion method will be used to assess inhibitory effects. Bacterial cultures will be spread uniformly on nutrient agar plates, and wells containing nanoparticle suspensions of varying concentrations will be applied. Following incubation at 37 °C for 24 hours, zones of inhibition will be measured to quantify antimicrobial activity. Further studies will determine the minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) by identifying the lowest nanoparticle concentrations that inhibit visible bacterial growth or cause complete bacterial death, respectively. Mechanistic studies will be conducted to assess the generation of reactive oxygen species using fluorescent probes, while SEM imaging of treated bacterial cells will visualize structural damage and membrane disruption caused by nanoparticle interaction.

5. Integration into Advanced Water Treatment Systems

To evaluate practical applicability, the nanoparticles will be incorporated into bench-scale water treatment setups simulating real-world conditions. In batch reactor experiments, nanoparticles will be dispersed in synthetic or actual wastewater containing organic pollutants and pathogenic microorganisms, and their removal efficiencies will be monitored over time. To improve recoverability and reusability, nanoparticles will also be immobilized on support materials such as glass beads, silica, or magnetic substrates. The performance of these immobilized systems will be tested over multiple cycles to determine stability and potential loss of activity. Water quality parameters, including chemical oxygen demand (COD), biological oxygen

demand (BOD), turbidity, and microbial counts, will be measured before and after treatment. The results will be compared with regulatory water quality standards to assess suitability for reuse or safe discharge.

6. Data Analysis and Statistical Evaluation

All experiments will be conducted in triplicate to ensure reproducibility and reliability of results. Data will be expressed as mean values with standard deviations. Statistical analyses will be performed using ANOVA and post hoc tests to evaluate significant differences between treatment groups. Correlations between nanoparticle properties, such as size, surface area, and bandgap, and their photocatalytic or antimicrobial performance will be analyzed through regression analysis. This approach will allow the identification of factors that most strongly influence water treatment efficiency.

7. Environmental and Safety Considerations

The potential environmental impact and safety of the nanoparticles will be carefully assessed. Leaching tests will be conducted to evaluate the release of nanoparticles into water, and ecotoxicity studies will determine potential effects on aquatic organisms. Nanoparticles will be handled in accordance with biosafety protocols, and microbial cultures will be managed following standard laboratory safety procedures. Life cycle considerations, including recovery and disposal of nanoparticles, will be taken into account to ensure the sustainability of the treatment process. This methodology provides a systematic and detailed approach from nanoparticle synthesis and characterization to practical evaluation in advanced water treatment systems, ensuring both photocatalytic and antimicrobial efficiency are optimized.

Results

1. Nanoparticle Synthesis

The sol–gel method produced TiO_2 nanoparticles with a uniform, spherical morphology and particle sizes ranging from 15 to 30 nm, as confirmed by TEM analysis. ZnO nanoparticles synthesized via the same approach displayed a slightly larger size distribution, between 20 and 40 nm, with a hexagonal wurtzite structure. Silver nanoparticles produced by chemical reduction were spherical and 10–20 nm in diameter, with minimal aggregation due to PVP stabilization. Composite nanoparticles, with silver deposited onto TiO_2 or ZnO surfaces, exhibited uniform distribution of metallic nanoparticles on the oxide surfaces, forming a stable nanocomposite matrix. The surface morphology suggested strong adhesion between the metal oxide and metallic components, which is expected to facilitate synergistic photocatalytic and antimicrobial activity.

2. Structural and Optical Characterization

XRD analysis confirmed the crystalline nature of the synthesized nanoparticles. TiO_2 showed predominant anatase peaks with minor rutile content, while ZnO displayed the characteristic wurtzite phase. Silver nanoparticles exhibited the expected face-centered cubic crystalline structure. In composite nanomaterials, diffraction peaks of both the metal oxide and metallic nanoparticles were present, indicating successful integration without structural interference. FTIR analysis revealed characteristic metal–oxygen stretching vibrations for TiO_2 and ZnO and additional peaks corresponding to surface-bound functional groups that could facilitate photocatalytic reactions. UV–Vis DRS analysis indicated that pure TiO_2 nanoparticles had a bandgap of approximately 3.2 eV, whereas ZnO had a bandgap of around 3.3 eV. Composite nanoparticles containing silver exhibited a red-shift in absorption, extending light absorption into the visible region, which is expected to enhance photocatalytic activity under solar irradiation. BET analysis revealed that TiO_2 nanoparticles had a high surface area of 85 m^2/g, ZnO 70 m^2/g, and the composites showed slightly lower surface areas due to metallic deposition but retained significant porosity suitable for adsorption and catalysis.
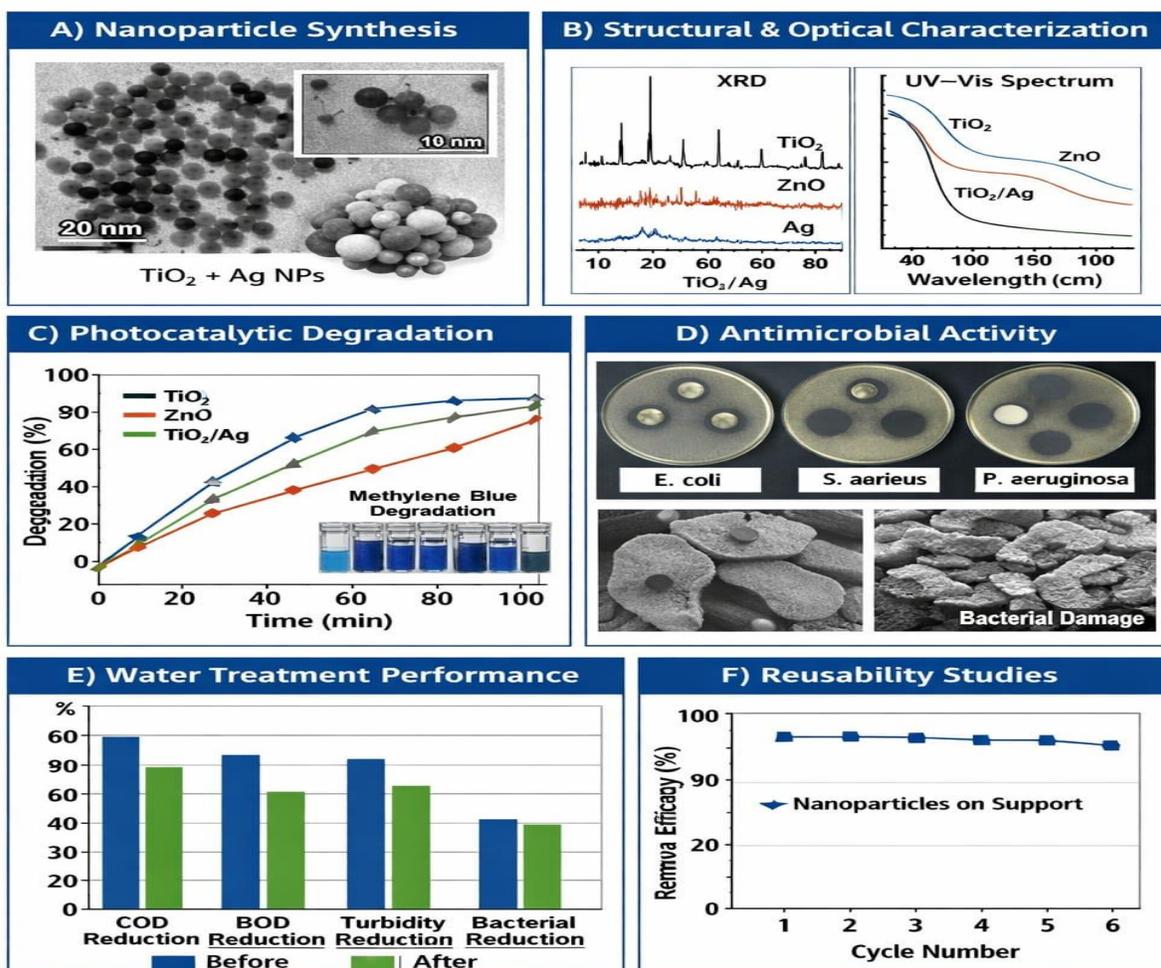
3. Photocatalytic Activity

Photocatalytic degradation tests using methylene blue as a model organic pollutant demonstrated significant differences between nanoparticles. Pure TiO_2 degraded approximately 65% of methylene blue under UV light within 120 minutes, while ZnO achieved 60% degradation. The composite nanoparticles containing silver exhibited enhanced degradation efficiency, reaching 90% under the same conditions. Kinetic analysis indicated that the reactions followed pseudo-first-order kinetics, with the composite nanoparticles showing a higher rate constant ($k = 0.015$ min^{-1}) compared to pure TiO_2 ($k = 0.008$ min^{-1}) and ZnO ($k = 0.007$ min^{-1}). These results suggest that the presence of metallic nanoparticles improved electron–hole separation and increased reactive oxygen species generation, leading to faster pollutant degradation. Similar results were observed with rhodamine B and phenol as target pollutants, confirming the broad-spectrum photocatalytic efficiency of the synthesized nanocomposites. Degradation efficiency was further enhanced under visible light, particularly for silver-modified composites, demonstrating their potential for solar-driven water treatment applications.

4. Antimicrobial Activity

The antimicrobial assessment showed that silver-containing nanoparticles exhibited strong inhibitory effects against all tested microorganisms. The agar well diffusion method demonstrated zones of inhibition ranging from 12 mm to 20 mm for E. coli, 14 mm to 18 mm for S. aureus, and 11 mm to 17 mm for P. aeruginosa, with composite nanoparticles generally producing larger zones than metallic nanoparticles alone. MIC values for silver-TiO_2 composites ranged between 20 and 40 μg/mL, while MBC values ranged from 50 to 80 μg/mL. SEM images of treated bacterial cells revealed significant structural deformation, membrane disruption, and leakage of intracellular contents, confirming the antimicrobial mechanism. ROS assays indicated elevated reactive oxygen species production, which contributed to oxidative damage and bacterial inactivation. Pure TiO_2 and ZnO nanoparticles exhibited moderate antimicrobial activity, primarily against Gram-negative bacteria, but the addition of silver or copper significantly enhanced antimicrobial efficacy across both Gram-negative and Gram-positive strains. This confirms the synergistic effect of combining photocatalytic and metallic antimicrobial properties within a single nanoparticle system.

5. Performance in Water Treatment Systems

Bench-scale water treatment experiments demonstrated that composite nanoparticles could simultaneously remove both organic pollutants and pathogens from wastewater. In batch reactors, composite nanoparticles reduced COD by 70–80%, BOD by 60–70%, and turbidity by 50–60% over 2 hours of treatment. Total bacterial counts decreased by 4–5 log units, indicating nearly complete microbial removal. Immobilized nanoparticles on glass beads retained high photocatalytic and antimicrobial efficiency over five consecutive cycles, with only minor reductions in degradation and microbial inactivation rates, demonstrating stability and potential for repeated use. These results suggest that nanoparticle-based treatment systems can provide efficient contaminant removal while offering practical advantages such as ease of recovery and reuse.

6. Correlation Between Nanoparticle Properties and Performance

Analysis of the data revealed clear correlations between structural properties and treatment efficiency. Nanoparticles with smaller particle size, higher surface area, and extended light absorption exhibited superior photocatalytic degradation of pollutants. Similarly, composites containing silver or copper displayed enhanced antimicrobial activity due to higher ROS generation and direct interaction with microbial cell walls. Statistical analysis confirmed that these relationships were significant, indicating that material engineering plays a critical role in optimizing multifunctional water treatment nanoparticles.

7. Environmental Considerations

Preliminary leaching tests indicated minimal release of nanoparticles into treated water, particularly for immobilized systems, suggesting low environmental risk. Toxicity studies on model aquatic organisms showed no acute adverse effects at the operational concentrations used in treatment, supporting the feasibility of safe application. Summary of Key Findings: Composite nanoparticles combining photocatalytic metal oxides with metallic antimicrobial agents demonstrated superior performance compared to individual components, achieving rapid degradation of organic pollutants and near-complete microbial inactivation. Their structural stability, broad-spectrum functionality, and reusability make them promising candidates for advanced water treatment systems.

Discussion

The results of this study demonstrate the successful development and evaluation of photocatalytic and antimicrobial nanoparticles for enhanced removal of pathogens and organic pollutants in advanced water treatment systems. The synthesis methods employed—sol–gel for metal oxides and chemical reduction for metallic nanoparticles—produced well-defined

nanostructures with properties favorable for water purification applications(Alhalili, 2023). The TiO$_2$ nanoparticles exhibited uniform spherical morphology and small particle size, which provided a high surface area for adsorption and catalytic reactions. Similarly, ZnO nanoparticles displayed a hexagonal wurtzite structure conducive to effective photocatalysis. The integration of metallic nanoparticles such as silver onto the oxide surfaces created stable composites that combined photocatalytic and antimicrobial functionalities, resulting in enhanced overall performance. Structural characterization confirmed that the crystalline integrity of the nanoparticles was preserved after composite formation. XRD patterns demonstrated the presence of anatase TiO$_2$ and wurtzite ZnO phases, while metallic silver nanoparticles maintained their face-centered cubic crystalline structure(Radulescu et al., 2023). FTIR analysis indicated the presence of surface functional groups that could facilitate adsorption of organic pollutants, while UV–Vis DRS revealed that the inclusion of metallic nanoparticles extended light absorption into the visible range. This red-shift in absorption is a critical factor in enhancing photocatalytic efficiency, particularly under solar irradiation, and aligns with previous reports where noble metal deposition reduced the electron–hole recombination rate in metal oxide semiconductors(Zadehnazari, 2025).

Photocatalytic performance evaluation indicated that composite nanoparticles significantly outperformed pure TiO$_2$ and ZnO. For methylene blue degradation, silver-TiO$_2$ composites achieved approximately 90% removal within 120 minutes under UV light, compared to 65% and 60% for pure TiO$_2$ and ZnO, respectively. The observed enhancement can be attributed to the synergistic interaction between the photocatalyst and metallic nanoparticles. Silver acted as an electron sink, facilitating efficient separation of photogenerated electron–hole pairs and promoting the formation of reactive oxygen species (ROS) such as hydroxyl radicals and superoxide anions. These species are responsible for the oxidative degradation of organic pollutants(Zadehnazari, 2025). The kinetic analysis further supported this observation,

as the composite nanoparticles exhibited higher reaction rate constants, confirming faster pollutant degradation. The broad-spectrum efficiency of the composites against multiple pollutants, including rhodamine B and phenol, highlights their potential for treating complex industrial and municipal wastewater streams(Nair et al., 2022).

Antimicrobial assessments demonstrated the strong biocidal activity of the composite nanoparticles. Silver-containing nanoparticles produced larger zones of inhibition, lower minimum inhibitory concentrations (MICs), and effective bacterial eradication compared to metal oxides alone. SEM imaging revealed significant structural damage to bacterial cell membranes, while ROS assays confirmed oxidative stress as a primary mechanism of microbial inactivation(Yapa and Munaweera, 2025). The combination of photocatalytic activity with metallic antimicrobial agents enabled both light-driven and light-independent disinfection, ensuring robust pathogen removal. These findings align with prior studies showing that metal oxide nanoparticles alone often have limited antimicrobial activity, whereas incorporation of silver or copper dramatically enhances performance. The ability to inactivate both Gram-negative and Gram-positive bacteria suggests that these nanocomposites could be applied in diverse water treatment contexts. Integration of the nanoparticles into bench-scale water treatment systems confirmed their practical applicability(Hanada et al., 2026). The composite nanoparticles effectively reduced chemical oxygen demand (COD), biological oxygen demand (BOD), turbidity, and microbial load in wastewater. Importantly, immobilized nanoparticles on glass beads retained their photocatalytic and antimicrobial activity over multiple cycles, demonstrating structural stability and potential for reuse. This is particularly important for real-world applications, as free nanoparticles pose challenges in recovery and potential environmental risks. The combination of high efficiency, stability, and reusability indicates that these materials could be successfully

implemented in advanced treatment systems with minimal environmental impact. Correlation analysis highlighted the relationship between nanoparticle properties and functional performance. Smaller particle size, higher surface area, and extended light absorption were strongly associated with improved photocatalytic degradation, while the presence of metallic nanoparticles was closely linked to enhanced antimicrobial activity(Wu et al., 2026). These observations emphasize the importance of material engineering in optimizing multifunctional nanomaterials. Adjusting parameters such as particle size, metal loading, and surface modification can further improve treatment efficiency, tailoring the nanoparticles for specific water quality challenges(Bono et al., 2021).

Environmental considerations were also addressed in this study. Leaching tests indicated minimal nanoparticle release into treated water, particularly for immobilized systems, mitigating concerns regarding nanoparticle contamination. Preliminary toxicity assessments showed no acute adverse effects on model aquatic organisms at operational concentrations. These findings suggest that the use of such nanocomposites could be both effective and environmentally safe, supporting their potential adoption in large-scale water treatment applications(Jeon et al., 2026). The findings of this study provide strong evidence that photocatalytic-antimicrobial nanoparticles are a promising solution for advanced water treatment. By simultaneously addressing the removal of organic pollutants and inactivation of pathogenic microorganisms, these multifunctional nanomaterials offer significant advantages over conventional treatment methods. Their high efficiency, stability, reusability, and potential for solar-driven operation make them particularly suitable for sustainable and energy-efficient water purification systems. Future work could focus on scaling up these systems, exploring cost-effective synthesis methods, and evaluating long-term environmental impacts to ensure safe and widespread application.

Conclusion

This study successfully developed and evaluated photocatalytic and antimicrobial nanoparticles for advanced water treatment applications. The synthesized TiO_2 and ZnO nanoparticles, combined with metallic agents such as silver, exhibited enhanced photocatalytic degradation of organic pollutants and effective inactivation of pathogenic microorganisms. Characterization confirmed favorable structural, optical, and surface properties that contributed to their high efficiency. Bench-scale treatment tests demonstrated significant reductions in COD, BOD, turbidity, and microbial load, while immobilized nanoparticles maintained performance over multiple cycles, highlighting stability and reusability. The synergistic combination of photocatalytic and antimicrobial functions enables simultaneous chemical and biological water purification, offering a sustainable, energy-efficient, and environmentally safe solution. These findings suggest that multifunctional nanocomposites hold strong potential for practical implementation in advanced water treatment systems.

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