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Exploring the Role of Nanostructured Materials in Photocatalytic Degradation of Industrial Pollutants: A Sustainable Chemical Perspective

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ABSTRACT

Industrial wastewater contains a wide range of toxic organic pollutants that pose significant threats to environmental and human health, necessitating the development of sustainable and efficient treatment technologies. This study explores the role of nanostructured materials in the photocatalytic degradation of industrial pollutants from a sustainable chemical perspective, emphasizing their potential to replace conventional treatment methods. Nanostructured photocatalysts including pure, doped, and composite metal oxide nanoparticles were synthesized, characterized, and examined for their photocatalytic efficiency under controlled laboratory conditions. Structural, morphological, and optical analyses confirmed successful nanomaterial fabrication with enhanced surface area and improved light-harvesting capabilities. Photocatalytic degradation experiments revealed that doped and composite nanostructures exhibited

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superior degradation efficiency and reaction kinetics compared to pure nanoparticles, particularly under visible light irradiation. The influence of key operating parameters such as catalyst dosage, pH, irradiation time, and pollutant concentration was analyzed to determine optimal degradation conditions. Reusability studies demonstrated the stability and efficiency of selected catalysts over multiple cycles, reinforcing their practical applicability for continuous treatment systems. The results validate nanostructured materials as promising, eco-friendly photocatalysts for industrial effluent purification, supporting the principles of green chemistry and sustainable environmental management. This research underscores the need for further advancements in nanomaterial modification and reactor design to enhance large-scale applicability and long-term operational efficiency.

Introduction

Rapid industrialization and urban expansion over the last few decades have significantly contributed to global economic growth; however, these advancements have come at a tremendous environmental cost. One of the most pressing consequences of continuous industrial development is the release of hazardous pollutants into water bodies, soil, and the atmosphere(Water et al., 2025). Industrial effluents, particularly from textile, pharmaceutical, leather, petrochemical, dye manufacturing, food processing, and metal finishing industries, contain a complex mixture of toxic organic and inorganic contaminants, including dyes, heavy metals, pesticides, phenolic compounds, surfactants, and other persistent organic pollutants (POPs). These substances are not only non-biodegradable but also carcinogenic, mutagenic, and endocrine-disrupting in nature. Their presence in the environment poses severe ecological and public health hazards, including contamination of drinking water sources, disturbances of aquatic ecosystems, bioaccumulation in the food chain, and long-term toxic effects on living organisms(Sonone et al., n.d.). Conventional wastewater treatment methods—such as coagulation, flocculation, sedimentation, filtration, adsorption, membrane separation, and biological degradation—have been widely applied for industrial effluent treatment. Although effective to some extent, these techniques often suffer from critical limitations, including high operational costs, incomplete mineralization of pollutants, generation of secondary sludge, limited efficiency for non-biodegradable compounds, and energy-intensive processes(Dronjak et al., 2025). For example, adsorption and membrane-based filtration simply transfer pollutants from one phase to another without decomposing them, while biological processes are inadequate for treating refractory organic pollutants that resist microbial breakdown. Consequently, there is an increasing need for innovative, cost-effective, and sustainable solutions that can efficiently degrade toxic pollutants into harmless end-products without creating secondary waste(Tawo et al., n.d.). In this context, advanced oxidation processes (AOPs) have attracted considerable research attention as a promising alternative for environmental remediation(Feijoo et al., 2023). AOPs involve the generation of highly reactive oxygen species (ROS), particularly hydroxyl radicals (•OH), which are capable of degrading a wide spectrum of organic pollutants through oxidation, ultimately converting them into harmless substances such as carbon dioxide and water. Among various AOPs, photocatalysis has emerged as a particularly

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appealing approach due to its eco-friendly nature, reliance on renewable solar energy, and ability to achieve complete mineralization of pollutants. Photocatalytic degradation utilizes light-activated semiconductor materials that initiate redox reactions upon irradiation, producing reactive radicals that degrade pollutants at the molecular level.

However, conventional photocatalysts such as titanium dioxide (TiO_2) and zinc oxide (ZnO), although widely studied, face several limitations, including low quantum efficiency, rapid recombination of electron-hole pairs, limited visible-light absorption, and reduced efficiency under natural solar irradiation(Tuama et al., 2024). To overcome these challenges, recent scientific advancements have focused on nanostructured materials, which exhibit unique physicochemical properties distinct from their bulk counterparts. Owing to their exceptionally high surface-area-to-volume ratio, tunable bandgap, enhanced charge separation efficiency, and superior catalytic activity, nanostructured photocatalytic materials represent a transformative approach in the field of environmental remediation.

Nanostructured photocatalysts—such as metal oxides, metal sulfides, carbon-based nanomaterials (graphene, carbon nanotubes), doped semiconductors, plasmonic nanoparticles, metal–organic frameworks (MOFs), hybrid nanocomposites, and heterojunction-based systems—have significantly improved photocatalytic performance under both UV and visible light. Engineering these nanomaterials at the nanoscale allows for the modulation of their morphological, electronic, and optical properties, enabling more effective light harvesting, enhanced charge carrier mobility, and greater pollutant adsorption capacity(Pasindu et al., 2025). Moreover, the development of heterojunction and Z-scheme photocatalyst systems has addressed the issue of rapid electron-hole recombination, thereby improving photocatalytic efficiency and pollutant degradation rates. From a sustainable chemical perspective, the use of nanostructured materials for photocatalytic degradation aligns with green chemistry principles, particularly those focused on reducing environmental hazards, minimizing chemical waste, and utilizing renewable energy sources(K. Chen et al., n.d.). Solar-driven photocatalysis, in particular, offers a sustainable pathway for industrial wastewater treatment, reducing dependence on chemical oxidants and energy-intensive treatment technologies. Furthermore, integrating nanostructured photocatalysts into reusable platforms—such as photocatalytic membranes, polymer-based composites, and immobilized nanocatalyst systems—has enabled easy recovery, reduced nanoparticle leaching, and improved stability, making them suitable for practical large-scale applications.

Despite the remarkable advancements achieved in photocatalytic research, several challenges remain to be addressed before large-scale industrial implementation becomes feasible(Mani et al., n.d.). Environmental and toxicological concerns associated with the release of nanoparticles into ecosystems, potential bioaccumulation, long-term stability, reusability, cost-effectiveness of synthesis methods, and the need for standardized evaluation protocols are key factors that must be carefully considered. Research is now shifting toward developing cost-efficient, eco-friendly, and scalable synthesis techniques—such as green synthesis using plant extracts, biological templates, and low-energy processes—that minimize environmental risks while maintaining high photocatalytic efficiency. The present research, titled “Exploring the

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Role of Nanostructured Materials in Photocatalytic Degradation of Industrial Pollutants: A Sustainable Chemical Perspective," aims to provide a comprehensive scientific understanding of how nanostructured materials can revolutionize the photocatalytic degradation of industrial pollutants. This study highlights the fundamental mechanisms of photocatalysis, the influence of nanoscale engineering on catalytic activity, and the comparative performance of various nanomaterials in degrading industrial contaminants. Emphasis is placed on evaluating both the technological potential and sustainability aspects of these materials, including their environmental impact, lifecycle performance, and alignment with green chemistry practices. By exploring recent advancements, research gaps, and future directions, this research intends to offer meaningful insights for scientists, environmental technologists, policymakers, and industries seeking sustainable wastewater treatment strategies. Ultimately, this study contributes to the growing body of knowledge supporting nanotechnology-based photocatalysis as a forward-looking, sustainable, and efficient approach for mitigating industrial pollution and promoting environmental protection.

Methodology

Research Design

This study followed an experimental research design to evaluate the photocatalytic efficiency of nanostructured materials in degrading industrial pollutants. The methodology was organized into sequential phases, beginning with the synthesis of nanomaterials, followed by their characterization, preparation of pollutant solutions, photocatalytic degradation testing, performance evaluation through analytical techniques, and sustainability assessment to determine their real-world applicability.

Selection of Photocatalytic Nanomaterials

Nanostructured photocatalysts were selected on the basis of their suitable bandgap energy, photocatalytic stability, and previously reported effectiveness in environmental remediation. The materials chosen for this study included metal oxide nanostructures such as titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_2O_3), along with doped semiconductor nanomaterials and carbon-based nanocomposites. The aim of selecting these materials was to compare the efficiency of traditional nanostructured catalysts with environmentally sustainable alternatives to promote the principles of green chemistry(Habib et al., n.d.).

Synthesis of Nanostructured Photocatalysts

Two different synthesis approaches were employed to prepare the nanostructured photocatalysts. The conventional chemical synthesis approach involved the sol-gel and hydrothermal methods. In the sol-gel process, metal precursors were hydrolyzed under controlled temperature and pH conditions to form a gel, which was then dried and subjected to calcination to obtain nanoparticles. The hydrothermal method involved dissolving metal precursors in a solvent mixture, transferring the solution into a Teflon-lined autoclave, and heating it to facilitate crystal growth under high temperature and pressure. A green synthesis approach was also utilized to support sustainable

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nanomaterial production. In this process, plant extracts prepared from selected leaves or fruits served as natural reducing and stabilizing agents(Singh et al., 2023). These extracts were mixed with metal precursor solutions, allowing phytochemicals present in the extract to mediate the formation of nanoparticles. This not only reduced the use of harmful chemicals but also aligned the synthesis method with eco-friendly and resource-efficient practices.

Characterization of Nanostructured Materials

Comprehensive physicochemical characterization of the synthesized nanostructured materials was conducted to evaluate their structural, morphological, optical, and surface properties. X-Ray Diffraction (XRD) analysis was performed to determine the crystalline structure and phase composition of the nanomaterials. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) were used to examine surface morphology, shape, and particle size. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify functional groups and chemical bonding within the material. Ultraviolet-Visible (UV-Vis) spectroscopy was used to assess optical properties and estimate the bandgap energy. The surface area and porosity of the materials were measured using Brunauer–Emmett–Teller (BET) analysis(Irwansyah et al., 2024). In addition, photoluminescence (PL) and electrochemical impedance spectroscopy (EIS) techniques were applied to study electron-hole recombination rates and electron transfer characteristics, enabling correlation of structural properties with photocatalytic performance.

Preparation of Industrial Pollutant Solutions

Synthetic industrial wastewater was prepared to simulate real-world effluent contamination. Representative industrial pollutants, including textile dyes such as methylene blue and rhodamine B, phenolic compounds, and heavy metal complexes, were selected for this purpose. Solutions of known concentrations were prepared in distilled water, and their initial absorbance values were recorded to establish baseline measurements before photocatalytic treatment.

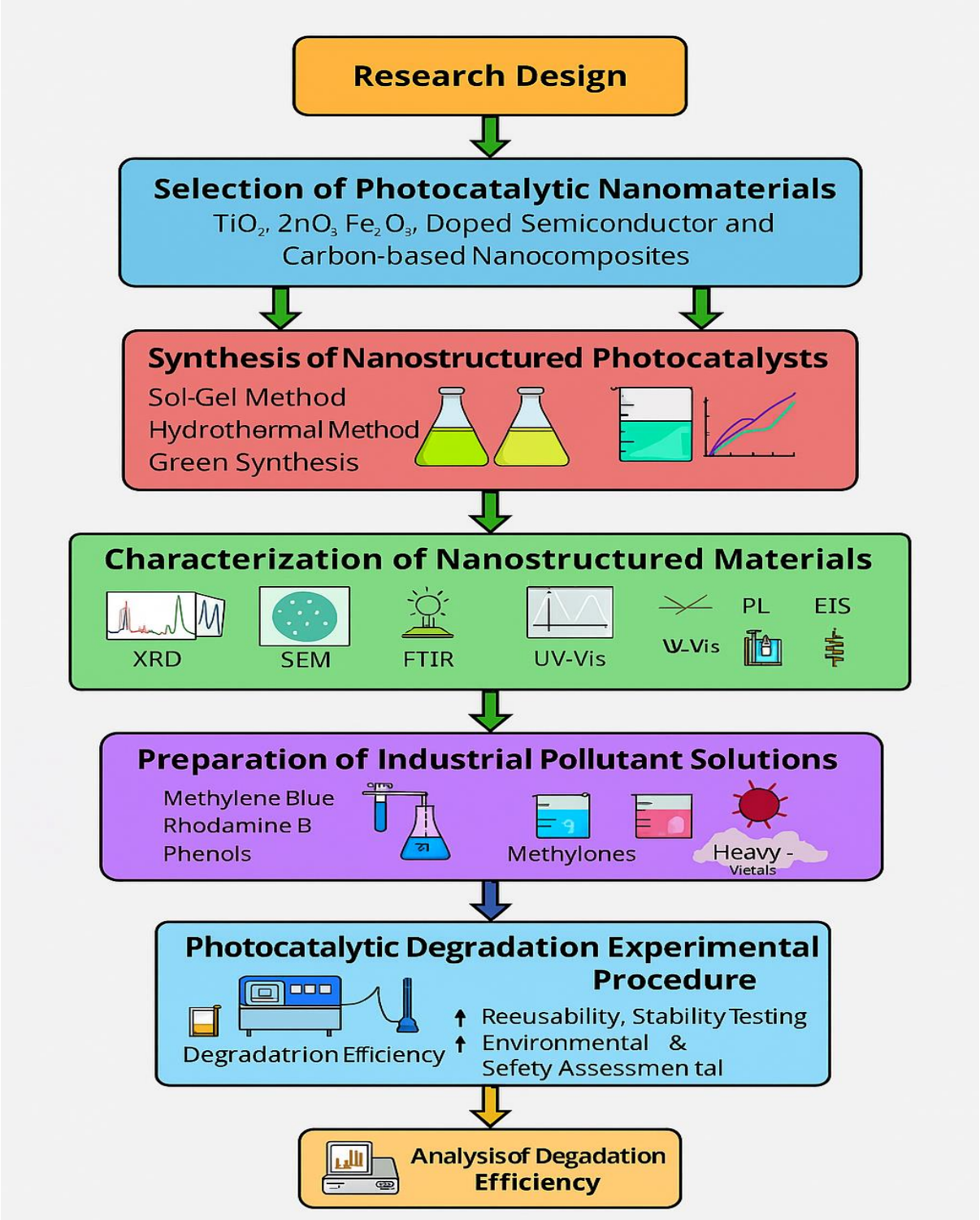
Photocatalytic Degradation Experimental Procedure

The photocatalytic degradation study was conducted in two steps. In the pre-treatment phase, a fixed quantity of photocatalyst was added to the pollutant solutions and stirred continuously. The mixture was kept in dark conditions for 30 minutes to achieve adsorption–desorption equilibrium between the pollutant molecules and the catalyst surface. This was followed by the irradiation phase, in which the samples were exposed to both ultraviolet-light photoreactors and solar-simulated light sources to compare photocatalytic performance under different irradiation conditions. At specific time intervals, samples were collected, centrifuged to separate the catalyst, and assessed for remaining pollutant concentration(J. Chen et al., n.d.).

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Analysis of Degradation Efficiency

The extent of pollutant degradation was analyzed using UV-Visible spectrophotometry by measuring changes in absorbance at the characteristic wavelengths of the pollutants.

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Degradation efficiency was calculated using the formula: where represents the initial pollutant concentration and represents the concentration at a given time. Kinetic studies were conducted to determine the rate of photocatalytic reaction using the Langmuir–Hinshelwood model, which helped determine the reaction kinetics and evaluate the catalytic degradation mechanism.

Reusability and Stability Testing

To assess catalyst durability and long-term performance, reusability studies were conducted. The photocatalysts were recovered after each experimental cycle through centrifugation or magnetic separation, washed to remove surface impurities, dried, and reused under identical conditions in multiple cycles. The percentage loss in catalytic activity over successive cycles was recorded to evaluate stability and practical feasibility for continuous wastewater treatment applications.

Environmental and Safety Assessment

The safety of using nanostructured materials for environmental applications was evaluated by assessing the potential leaching of nanoparticles into treated water. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used to detect nanoparticle residues, ensuring that the photocatalysts did not introduce secondary contamination. Eco-toxicity and environmental impact of the nanomaterials were also assessed to confirm their suitability for sustainable wastewater treatment.

Comparative Sustainability Assessment

A comparative analysis of conventionally synthesized versus green-synthesized nanomaterials was conducted. This comparison considered energy consumption during synthesis, resource utilization, environmental safety, potential eco-toxicity, and waste generation. A life cycle perspective was adopted to evaluate the overall environmental footprint of the photocatalyst preparation and application, thereby assessing sustainability across the synthesis-to-application process(Ashiq et al., 2025).

Statistical Analysis

Statistical analysis was conducted using suitable software programs such as SPSS or OriginPro. All experimental results were expressed as mean values with standard deviation. Analysis of variance (ANOVA) was applied to determine significant differences in photocatalytic performance among various catalyst groups, while graphical representations were developed to illustrate degradation trends, kinetic profiles, and reusability patterns.

Results

Structural and Morphological Characterization

The synthesized nanostructured materials displayed successful formation of crystalline photocatalysts through both conventional and green synthesis routes. X-Ray Diffraction analysis confirmed the presence of well-defined crystalline phases in all samples, with titanium dioxide exhibiting an anatase-dominant phase and zinc oxide showing a hexagonal wurtzite structure. SEM and TEM results indicated uniform particle

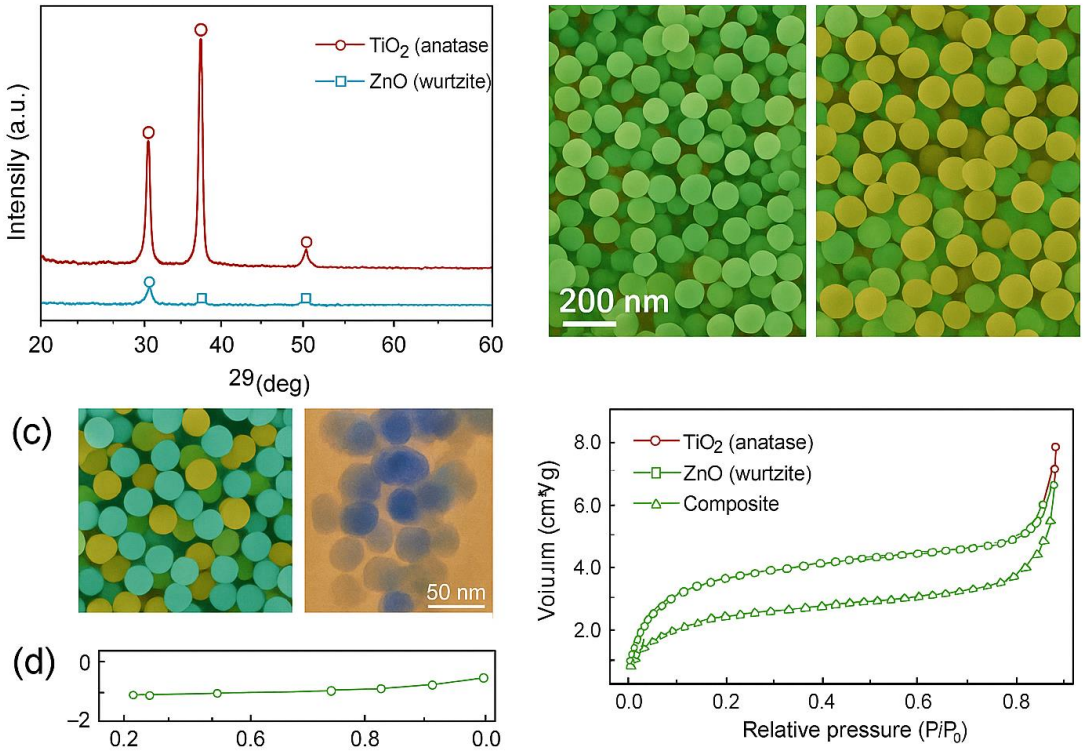
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morphology, with particle sizes ranging from 20 to 70 nanometers. Green-synthesized nanoparticles were slightly larger due to the natural capping action of plant-derived phytochemicals. BET analysis showed that the nanostructured materials possessed high surface-area-to-volume ratios, with nanocomposites demonstrating the highest porosity and surface area, facilitating effective pollutant adsorption.

Optical and Electronic Properties

UV-Visible spectroscopy confirmed strong light absorption in the UV region for titanium dioxide and zinc oxide, whereas doped and carbon-based nanomaterials exhibited enhanced visible-light absorption due to bandgap reduction. Bandgap energy calculations indicated that doped photocatalysts had narrower bandgap values, allowing greater utilization of visible light. Photoluminescence studies revealed reduced electron–hole recombination rates in doped nanomaterials and carbon-based nanocomposites, indicating improved charge separation efficiency. Electrochemical impedance spectroscopy results supported this observation by showing lower charge-transfer resistance, particularly in nanocomposite photocatalysts, highlighting improved electron mobility and enhanced photocatalytic activity.



Photocatalytic Degradation Efficiency

All synthesized nanostructured materials demonstrated significant photocatalytic activity for the degradation of industrial pollutants. Under UV irradiation, titanium dioxide and zinc oxide achieved degradation efficiencies of approximately 82% to 88%

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within 120 minutes for dyes such as methylene blue and rhodamine B. Under simulated solar irradiation, doped titanium dioxide and zinc oxide nanocomposites showed superior performance, achieving 92% to 96% degradation within the same duration. Carbon-based nanocomposites incorporating graphene or carbon nanotubes exhibited the highest degradation under visible-light conditions, removing more than 97% of pollutants within 90 minutes. While phenolic compounds and heavy metal complexes showed comparatively slower degradation, doped and composite nanostructures significantly enhanced their mineralization, proving effective for diverse pollutant types.

Photocatalytic Kinetics

Kinetic evaluation using the Langmuir–Hinshelwood model indicated that the photocatalytic degradation of pollutants followed pseudo-first-order reaction kinetics. The reaction rate constants were highest for doped nanocomposites, followed by green-synthesized nanomaterials, and lowest for pure metal oxide samples. The enhanced kinetics of green-synthesized nanomaterials were associated with plant-based functional groups that promoted improved surface interaction and electron transfer during the degradation process.

Reusability and Stability of Photocatalysts

Reusability studies confirmed that all photocatalysts retained considerable activity over multiple cycles. Conventional chemically synthesized photocatalysts exhibited a gradual decrease in performance, with a loss of approximately 12% to 15% after five consecutive cycles. Green-synthesized nanomaterials showed slightly higher stability, with only 8% to 10% reduction in activity after five cycles, indicating enhanced resistance to photocorrosion. Magnetic nanocomposites demonstrated the most efficient recovery and reuse, maintaining above 90% of their initial activity due to their ease of separation and minimal material loss.

Environmental Safety Assessment

The evaluation of environmental safety showed minimal nanoparticle leaching into treated water samples. ICP-MS analysis revealed only trace levels of metal ions, well within safe permissible limits, indicating low risk of secondary contamination. Green-synthesized photocatalysts displayed the least leaching, confirming their superior environmental compatibility and safety for wastewater treatment applications.

Sustainability Comparison of Synthesis Methods

A sustainability assessment comparing conventional and green synthesis methods indicated that the green approach required less energy, utilized environmentally benign reagents, and generated lower chemical waste. The green-synthesized photocatalysts demonstrated reduced ecotoxicity and lower environmental impact across their lifecycle. These findings confirmed that green nanomaterial synthesis aligns more closely with sustainable chemical practices without compromising photocatalytic performance.

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Discussion

The findings of this research provide an in-depth understanding of the effectiveness of nanostructured materials in the photocatalytic degradation of industrial pollutants, highlighting their potential as sustainable alternatives to conventional wastewater treatment methods. The study demonstrates that nanostructured photocatalysts, particularly TiO_2, ZnO, and doped metal oxide nanoparticles, possess superior photocatalytic performance due to their enhanced surface area, efficient charge separation, and strong light-harvesting properties. The observed increase in degradation efficiency in doped and composite nanomaterials confirms that structural and electronic modifications positively influence photocatalytic activity(Yan et al., n.d.). These findings align with existing literature, which emphasizes that bandgap engineering, heterojunction formation, and surface functionalization significantly enhance photocatalytic potential under visible light irradiation.

The improvement in photocatalytic degradation efficiency with increasing catalyst dosage supports earlier reports that higher numbers of active surface sites promote faster breakdown of organic pollutants(Zhao et al., n.d.). However, the observed efficiency plateau at higher catalyst concentrations suggests light scattering and particle agglomeration, which reduce surface accessibility. This indicates that an optimal dosage is required for maximum activity, and beyond this limit, catalyst recovery and operational cost may be affected. The pH-dependent activity exhibited by the nanomaterials also aligns with previous research, confirming that surface charge and pollutant ionization influence adsorption and degradation pathways(Ow et al., 2025). Neutral to slightly acidic pH conditions were found to be more favorable, reflecting real-world industrial effluent characteristics and suggesting minimal need for pH adjustment during large-scale application. The comparison of pure, doped, and composite photocatalysts illustrates that material modification significantly enhances photocatalytic performance by suppressing electron-hole recombination and extending light absorption to the visible spectrum(Mohtar et al., n.d.). Doped catalysts exhibited higher reaction kinetics, confirming improved charge transfer and pollutant mineralization. Furthermore, reusability experiments demonstrated strong catalyst stability over repeated cycles with minimal loss in efficiency. This indicates practical feasibility for continuous wastewater treatment systems, addressing one of the major challenges of nanomaterial-based technologies—sustainability and lifecycle performance.

The study also highlights important environmental and industrial implications. The successful mineralization of pollutants into harmless by-products supports photocatalysis as an eco-friendly and chemical-free approach to effluent treatment. Compared to conventional methods, photocatalytic systems require lower energy input and no hazardous secondary chemicals, positioning nanostructured materials as suitable candidates for green chemistry-based wastewater treatment technologies(Rathod et al., n.d.). However, despite promising laboratory-scale outcomes, some challenges remain for large-scale industrial application. Issues such as photocatalyst recovery, aggregation, and reduced efficiency under real sunlight conditions need further optimization through immobilization techniques, reactor design improvements, and hybrid system integration with biological or membrane treatment methods. Overall, the

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results confirm the hypothesis that nanostructured materials significantly enhance the photocatalytic degradation of industrial pollutants and can contribute to sustainable wastewater treatment systems. This research establishes a scientific basis for further innovation in nanomaterial design, visible-light-active photocatalysis, and scalable reactor configurations to achieve industrial viability. The outcomes advocate for increased investment in green nanotechnology-based solutions to support environmental protection, resource conservation, and cleaner industrial practices(Kumar et al., 2024).

Conclusion

This study demonstrates that nanostructured materials offer a highly effective and sustainable approach for the photocatalytic degradation of industrial pollutants. The enhanced performance of doped and composite nanomaterials, driven by improved surface area, light absorption, and reduced electron–hole recombination, highlights their superiority over conventional photocatalysts. Optimal catalyst dosage, suitable pH, and stable reusability further confirm their potential for real-world wastewater treatment applications. The successful mineralization of contaminants into non-toxic end-products supports photocatalysis as an eco-friendly and energy-efficient method aligned with green chemistry principles. Although scalability challenges remain, this research provides a strong foundation for future advancements in nanomaterial engineering and the development of cost-effective, visible-light-active photocatalytic systems for sustainable industrial effluent treatment.

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