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EXTENDED ABSTRACT BOOK

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Zinc Oxide-Based Photocatalysts for Wastewater Remediation: Recent Advances and Perspectives

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ABSTRACT

Zinc oxide (ZnO) is a cost-effective, non-toxic semiconductor with strong potential for photocatalytic degradation of persistent pollutants in wastewater. However, its wide bandgap (~3.37 eV) and rapid electron–hole recombination limit efficiency under solar light. This mini review summarizes the fundamentals of ZnO photocatalysis, identifies intrinsic limitations, and discusses recent advances in doping, heterojunction engineering, and green synthesis. Modified ZnO systems now demonstrate enhanced visible-light absorption, improved charge separation, and recyclability, with applications in dye, pharmaceutical, and heavy metal removal. Future work should address scalability, real wastewater testing, and sustainability assessment to bridge laboratory success with practical deployment.

Keywords: ZnO photocatalysis, wastewater treatment, doping, heterojunction, green synthesis

1. INTRODUCTION

Global water contamination from dyes, pharmaceuticals, and heavy metals is a growing environmental concern. Many of these pollutants are chemically stable, toxic, and resistant to conventional treatments (Mousa et al., 2024). Semiconductor photocatalysis, an advanced oxidation process (AOP), degrades organic contaminants into CO_2 and H_2O using light-activated reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide anions (O_2^{-}•) (Ramírez et al., 2021). ZnO has emerged as a promising photocatalyst due to its direct bandgap (~3.37 eV), high exciton binding energy, non-toxicity, and low cost (Zhu & Wang, 2025). It can degrade dyes like methylene blue and rhodamine B, pharmaceuticals such as tetracycline, and toxic metals like Cr(VI) through photoreduction. However, its activation is limited to the UV region (~5% of the solar spectrum), coupled with rapid electron–hole recombination and vulnerability to photocorrosion, which collectively restrict its potential for large-scale applications (Ghamarpoor et al., 2024).

2. FUNDAMENTALS OF ZnO PHOTOCATALYSIS

Upon UV illumination, ZnO generates electron–hole pairs: electrons in the conduction band (CB) reduce oxygen to O_2^{-}•, and holes in the valence band (VB) oxidize water to •OH. These ROS mineralize pollutants into harmless products. Nanostructured ZnO such as nanorods, nanosheets, flowers enhance performance by increasing active surface area and tuning defect states for better carrier lifetimes (Güell et al., 2023). Characterization techniques such as UV–Vis diffuse reflectance spectroscopy (DRS) and photoluminescence (PL) reveal bandgap shifts and recombination dynamics. Lower PL intensity in modified ZnO typically indicates suppressed recombination and improved photocatalytic potential (Aftab et al., 2022).

3. LIMITATION OF PURE ZnO

Pure ZnO suffers from several intrinsic drawbacks that limit its large-scale photocatalytic applicability. Its wide bandgap (~3.37 eV) confines photoactivation to the ultraviolet region, which accounts for only about 5% of the solar spectrum, thereby restricting solar energy utilization. Moreover, photogenerated electrons and holes in ZnO tend to recombine rapidly, resulting in short carrier lifetimes and reduced yields of reactive oxygen species (ROS). Prolonged operation under irradiation can also induce photocorrosion, in which surface Zn^{2+} ions are leached into solution, degrading the catalyst's structural integrity and potentially introducing secondary contamination (Ramírez et al., 2021). In addition, ZnO's performance in real wastewater systems is often markedly lower than in laboratory dye tests due to the presence of natural organic matter, ionic strength variations, and pH-dependent surface charge effects that compete for ROS and inhibit target pollutant degradation (Nazim et al., 2023).

4. RECENT ADVANCES

Recent developments have focused on overcoming ZnO's intrinsic limitations through doping, heterojunction construction, and green synthesis approaches. Doping with transition metals such as Ag, Ni, Fe, and Ru, as well as non-metals including N, C, and S, has proven effective in narrowing ZnO's bandgap, thereby extending light absorption into the visible range and suppressing electron–hole recombination. For example, AgCl/ZnO/g-C_3N_4 composites demonstrated over 90% tetracycline degradation under visible light, highlighting the synergistic role of plasmonic silver species and g-C_3N_4 in enhancing charge transfer (Ding et al., 2023). Heterojunctions between ZnO and semiconductors such as g-C_3N_4, CuO, or TiO_2 create built-in electric fields at the interface, which promote efficient spatial separation of photoexcited carriers. A Ru–ZnO@g-C_3N_4 composite achieved rapid methylene blue degradation due to the Z-scheme charge transfer pathway, which preserved strong redox ability while minimizing recombination (Albadri et al., 2023). Green synthesis routes using plant-based precursors, such as lychee peel extract or marine algae (Padina pavonica), have gained attention for producing ZnO nanoparticles with high crystallinity, small particle sizes, and abundant surface functional groups. These bio-inspired nanoparticles have achieved dye removal efficiencies exceeding 98%, offering an eco-friendly alternative to conventional chemical synthesis while reducing production costs and environmental footprint (Alprol et al., 2024; Mousa et al., 2024).

5. CONCLUSION

Recent advances in doping, heterojunction engineering, and green synthesis have upgraded ZnO from a UV-only photocatalyst to a visible-light-active material with better charge separation, stability, and reusability. These strategies address its narrow light absorption, rapid recombination, and photocorrosion while promoting eco-friendly production. However, large-scale application remains limited, as most studies use model pollutants under controlled conditions. Future work should prioritize pilot-scale tests in real wastewater, long-term stability, scalable green synthesis, and integration with solar-driven systems. Meeting these challenges could enable ZnO-based photocatalysts to transition from laboratory research to practical, sustainable wastewater treatment solutions.

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