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GREEN SYNTHESIS OF PLANT-DERIVED METAL OXIDE NANOCOMPOSITES FOR ENHANCED VISIBLE-LIGHT PHOTOCATALYTIC REMOVAL OF HAZARDOUS ORGANIC CONTAMINANTS FROM WASTEWATER

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ABSTRACT

The increasing contamination of water resources by hazardous organic pollutants poses a serious threat to environmental sustainability and public health. Conventional wastewater treatment methods often fail to completely remove persistent organic contaminants, leading to the exploration of advanced remediation technologies. Among these, photocatalysis using metal oxide nanocomposites has emerged as an effective and environmentally friendly approach. Recently, green synthesis methods employing plant extracts have gained considerable attention due to their sustainability, low cost, and reduced environmental impact. Plant-derived phytochemicals act as reducing, stabilizing, and capping agents during nanoparticle formation, eliminating the need for hazardous chemicals. This study examines the development of plant-mediated metal oxide nanocomposites and their application in visible-light photocatalytic degradation of toxic organic pollutants in wastewater. The paper discusses synthesis mechanisms, structural characteristics, photocatalytic performance, and environmental significance. Furthermore, the role of nanocomposite engineering in enhancing charge separation, light absorption, and degradation efficiency is analyzed. The findings indicate that green-synthesized metal oxide nanocomposites offer a promising

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solution for sustainable wastewater treatment and environmental protection.

Keywords: Green Synthesis, Metal Oxide Nanocomposites, Plant Extracts, Photocatalysis, Visible Light, Wastewater Treatment, Organic Pollutants, Environmental Remediation.

I. INTRODUCTION

Water pollution has become one of the most significant environmental challenges of the twenty-first century. Rapid industrialization, urbanization, agricultural activities, and population growth have led to the release of large quantities of toxic organic pollutants into aquatic ecosystems. Industrial dyes, pesticides, pharmaceuticals, phenolic compounds, and endocrine-disrupting chemicals are among the most common contaminants found in wastewater. These pollutants exhibit high toxicity, persistence, and bioaccumulation potential, posing serious risks to human health and ecological balance.

Traditional wastewater treatment technologies such as adsorption, coagulation, filtration, and biological degradation have demonstrated varying degrees of effectiveness. However, many toxic organic compounds are resistant to conventional treatment processes, necessitating the development of advanced remediation techniques. Photocatalysis has emerged as a highly promising approach due to its ability to mineralize organic pollutants into harmless products such as carbon dioxide and water using light energy.

Metal oxide nanomaterials including titanium dioxide (TiO_2), zinc oxide (ZnO), iron oxide (Fe_2O_3), and copper oxide (CuO) have attracted considerable attention as photocatalysts. Their high surface area, tunable electronic properties, and chemical stability make them suitable for environmental applications. Nevertheless, conventional synthesis methods often involve hazardous chemicals, high energy consumption, and environmentally unfriendly procedures.

Green synthesis has emerged as a sustainable alternative for nanoparticle production. Plant extracts contain diverse bioactive compounds such as flavonoids, alkaloids, terpenoids, polyphenols, and proteins that facilitate nanoparticle synthesis through natural reduction and stabilization mechanisms. This approach minimizes environmental impact while offering enhanced biocompatibility and cost-effectiveness.

Plant-derived metal oxide nanocomposites exhibit unique physicochemical properties that

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improve photocatalytic efficiency under visible-light irradiation. The incorporation of multiple metal oxides into nanocomposite structures enhances charge carrier separation, suppresses electron-hole recombination, and broadens light absorption capabilities. These improvements contribute to higher degradation rates of toxic organic pollutants.

Visible-light photocatalysis is particularly important because visible light constitutes a major portion of solar radiation. The development of photocatalysts capable of utilizing visible light enhances energy efficiency and supports sustainable environmental remediation. Plant-mediated nanocomposites represent a promising pathway toward achieving this objective.

This paper explores the green synthesis of plant-derived metal oxide nanocomposites and their application in visible-light photocatalytic degradation of hazardous organic contaminants. It examines synthesis strategies, characterization techniques, photocatalytic mechanisms, and environmental benefits while highlighting future research opportunities in sustainable wastewater treatment.

II. GREEN SYNTHESIS AND CHARACTERIZATION OF PLANT-DERIVED METAL OXIDE NANOCOMPOSITES

Green synthesis of metal oxide nanocomposites utilizes plant extracts as natural reducing and stabilizing agents. Plant materials including leaves, roots, fruits, flowers, and bark contain phytochemicals capable of reducing metal ions into nanoscale particles. These bioactive compounds facilitate controlled nanoparticle growth and prevent aggregation, resulting in stable nanostructures with desirable properties.

The synthesis process generally begins with preparation of plant extracts through solvent extraction techniques. Metal precursor solutions are subsequently mixed with the extracts under controlled conditions. Reduction reactions lead to nanoparticle formation, while phytochemicals adsorb onto particle surfaces, providing stability and functionalization. Calcination and annealing treatments may be employed to improve crystallinity and photocatalytic activity.

Several plant species have been successfully utilized for nanocomposite synthesis. Extracts from Azadirachta indica, Moringa oleifera, Aloe vera, Camellia sinensis, and Ocimum sanctum have demonstrated effectiveness in producing metal oxide nanoparticles. The choice of plant source significantly influences particle morphology, size distribution, and

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photocatalytic performance.

Characterization techniques play a critical role in evaluating nanocomposite properties. X-ray diffraction analysis provides information regarding crystalline structure and phase composition. Scanning electron microscopy and transmission electron microscopy reveal particle morphology and size. Fourier-transform infrared spectroscopy identifies functional groups associated with phytochemical interactions. UV-visible spectroscopy and photoluminescence studies assess optical properties and charge transfer behavior.

Nanocomposite engineering further enhances material performance. Combining metal oxides such as TiO_2-ZnO, ZnO-CuO, and Fe_2O_3-TiO_2 creates heterojunction structures that facilitate efficient charge separation. The resulting materials exhibit improved light harvesting capabilities and enhanced photocatalytic activity under visible-light irradiation.

Green synthesis offers numerous advantages including reduced toxicity, lower production costs, environmental compatibility, and scalability. These benefits make plant-derived nanocomposites attractive candidates for sustainable environmental applications.

III. VISIBLE-LIGHT PHOTOCATALYTIC DEGRADATION OF ORGANIC POLLUTANTS AND ENVIRONMENTAL APPLICATIONS

Photocatalysis involves the generation of electron-hole pairs upon light absorption by semiconductor materials. These charge carriers participate in redox reactions that produce reactive oxygen species such as hydroxyl radicals and superoxide radicals. The generated species attack organic pollutants, leading to their degradation and eventual mineralization.

Visible-light-responsive nanocomposites are particularly valuable because they utilize a significant portion of the solar spectrum. Plant-mediated metal oxide nanocomposites exhibit enhanced visible-light absorption due to reduced band-gap energies and improved charge separation efficiency. These characteristics contribute to superior photocatalytic performance compared with conventional photocatalysts.

Numerous studies have demonstrated the effectiveness of green-synthesized nanocomposites in degrading industrial dyes such as methylene blue, rhodamine B, methyl orange, and congo red. These materials also show significant potential for removing pharmaceutical residues, pesticides, antibiotics, and phenolic compounds from wastewater.

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Photocatalytic degradation mechanisms involve adsorption of pollutant molecules onto catalyst surfaces followed by oxidation through reactive oxygen species. Nanocomposite heterojunctions facilitate rapid electron transfer and minimize recombination losses, thereby increasing degradation efficiency. Surface functionalization by plant-derived compounds further enhances adsorption capacity and catalytic activity.

Environmental applications extend beyond wastewater treatment. Plant-derived nanocomposites can be utilized for air purification, antimicrobial coatings, soil remediation, and environmental sensing. Their eco-friendly synthesis and renewable nature align with principles of green chemistry and sustainable development.

Challenges remain regarding catalyst recovery, long-term stability, and large-scale implementation. Future research should focus on optimizing synthesis protocols, improving catalyst durability, and developing integrated treatment systems suitable for industrial applications.

IV. CONCLUSION

Green synthesis of plant-derived metal oxide nanocomposites represents a sustainable and innovative approach to addressing environmental pollution challenges. By utilizing naturally occurring phytochemicals, researchers can produce high-performance photocatalytic materials without relying on hazardous chemicals or energy-intensive processes.

The unique structural and optical properties of these nanocomposites contribute to enhanced visible-light photocatalytic degradation of hazardous organic contaminants. Improved charge separation, increased surface area, and broadened light absorption capabilities enable efficient pollutant removal and support environmentally friendly wastewater treatment.

Applications in dye degradation, pharmaceutical removal, pesticide remediation, and broader environmental protection demonstrate the versatility and effectiveness of plant-mediated photocatalysts. Furthermore, their compatibility with solar energy utilization aligns with global efforts to promote renewable and sustainable technologies.

Despite significant advancements, challenges related to catalyst stability, scalability, and commercialization require further investigation. Continued interdisciplinary research involving materials science, nanotechnology, environmental engineering, and green

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chemistry will be essential for overcoming these limitations.

In conclusion, plant-derived metal oxide nanocomposites offer substantial potential for sustainable environmental remediation. Their development contributes to the advancement of green technologies and provides promising solutions for mitigating water pollution and protecting ecological health.

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