DOI: 10.36297/vw.applsci.v4i3.497 ISSN: 2582-5615

VW Applied Sciences, Volume: 4, Issue: 3, 25-28

Study of Novel Photocatalysts for Efficient Degradation of Environmental Pollutants under Visible Light

Dr. Kunal Deshmukh[1*]

[1]Associate Professor, Chemical Engineering, Vel Tech Rangrajan Dr Shaguntala R&D Institute Of Science And Technology, Chennai, India
[*]Authors Email: kunal.d@veltech.edu.in

Received: Dec 08, 2022
Accepted: Dec 09, 2022
Published online: Dec 10, 2022

Abstract: Growing industrialization and urban activities have increased the release of harmful organic pollutants into aquatic and terrestrial ecosystems, necessitating advanced remediation technologies that operate efficiently under sustainable conditions. Visible-light-driven photocatalysis has emerged as a promising environmental treatment method due to its ability to utilize abundant solar radiation while achieving high degradation rates for persistent contaminants. This study evaluates novel photocatalysts—including doped metal oxides, polymeric carbon nitride, and plasmonic nanostructures—and investigates their physicochemical behavior, photocatalytic efficiency, charge-carrier dynamics, and structural stability under continuous visible-light exposure. Experimental work involved pollutant degradation trials using dyes, pesticides, and pharmaceutical residues as model contaminants, while monitoring reaction kinetics and mineralization potential. Results demonstrated that metal–nonmetal co-doped TiO_2 and Ag–g-C_3N_4 hybrids exhibited significantly enhanced visible-light absorption and reduced electron–hole recombination, leading to degradation efficiencies exceeding 90% for selected pollutants. Stability tests confirmed minimal structural decay after repeated cycles. The findings underscore the potential of engineered photocatalysts as scalable solutions for environmental rehabilitation. The work contributes important guidelines for material selection, photocatalyst engineering, and practical deployment in wastewater purification systems.

Keywords: Photocatalysis, Visible Light, Nanomaterials, Environmental Remediation, Pollutant Degradation

1. Introduction

The Environmental pollution caused by industrial effluents, agricultural runoff, and pharmaceutical discharges has become a persistent global challenge. Conventional treatment methods—including adsorption, coagulation, and biological decomposition—oftenfail to completely mineralize complex pollutants such as aromatic dyes, endocrine disruptors, antibiotics, and nitrogen-rich pesticides [1]. In this context, photocatalysis has gainedsubstantial attention as an advanced oxidation process capable of degrading a wide range of organic contaminants into environmentally benign products using solar energy. Traditional photocatalysts such as titanium dioxide (TiO_2) are limited by their wide bandgap, enabling activation only under ultraviolet (UV) light, which comprises less than 5% of natural sunlight. As a result, recent research efforts have focused on developing visible-light-responsive photocatalysts through doping, heterojunction formation, band engineering, and plasmonic enhancement strategies [2]. Novel materials such as graphitic carbon nitride (g-C_3N_4), bismuth-based oxides, and metal–organic frameworks have demonstrated superior optical absorption and charge-separation capabilities under visible irradiation. This study investigates the performance of novel photocatalysts specifically engineered to enhance pollutant degradation under visible light conditions. It aims to evaluate material characteristics, catalytic efficiencies, and reaction pathways through systematic experimentation and comparative analysis. By examining structural parameters such as surface area, active sites, porosity, and electron transport mechanisms, the study contributes meaningful scientific insights to the ongoing development of sustainable environmental remediation solutions. The introduction also contextualizes the global need for efficient, solar-driven purification technologies—particularly in regions facing severe water-quality threats due to industrial expansion [3].

2. Materials, Synthesis Methodology, and Characterization Framework

Multiple photocatalyst systems were developed and analyzed, including N-doped TiO_2, Ag-decorated g-C_3N_4, $BiVO_4$–Fe_2O_3 heterojunctions, and plasmonic Au/TiO_2 composites. Synthesis approaches involved sol-gel processing, hydrothermal crystallization, thermal polymerization, and photodeposition to incorporate dopants and create nanoscale active interfaces. These synthesis techniques were selected based on previous reports highlighting their reliability for producing uniform, high-purity nanostructures with tunable surface morphologies [4].

Material Characterization

X-ray diffraction (XRD) was used to evaluate crystallinity and phase purity. Scanning electron microscopy provided morphological details, revealing porous structures with large surface areas suitable for pollutant adsorption. Ultraviolet–visible (UV-Vis) diffuse reflectance spectroscopy (DRS) confirmed extended visible-light absorption for doped and composite materials, indicating reduced bandgap energies. Photoluminescence spectroscopy was used to study charge-carrier recombination rates, demonstrating that metal–nonmetal dopants significantly suppressed recombination and enhanced photocatalytic efficiency [5].

Pollutant Degradation Experiments

Model pollutants included methylene blue, phenol, tetracycline, and chlorpyrifos. Batch-reactor tests were conducted under simulated visible-light illumination using a xenon lamp equipped with UV cut-off filters. Reaction kinetics were monitored through UV-Vis spectrophotometric analysis, and mineralization was assessed using total organic carbon (TOC) measurements. Control experiments confirmed negligible pollutant degradation in the absence of photocatalysts or light exposure. The systematic methodological framework ensured a detailed understanding of photocatalyst performance, structure–property relationships, and long-term stability.

3. Photocatalytic Performance and Reaction Mechanisms

Visible-light degradation tests revealed that Ag-decorated g-C_3N_4 produced the highest photocatalytic efficiency, achieving up to 92% degradation of methylene blue within 80 minutes. N-doped TiO_2 displayed moderate improvements over pure TiO_2, achieving 70–78% degradation due to enhanced visible-light sensitivity and additional nitrogen-induced defect states [6]. $BiVO_4$–Fe_2O_3 heterojunctions achieved strong photocurrent responses and high degradation rates for phenol, facilitated by efficient electron transfer across the junction. Mechanistic analysis indicated that reactive oxygen species—particularly hydroxyl radicals (•OH) and superoxide radicals (•O_2^-)—played critical roles in pollutant decomposition. Electron spin resonance spectroscopy confirmed higher radical production in doped and composite photocatalysts, supporting observed improvements in degradation kinetics. Plasmonic nanoparticles such as Ag and Au enhanced local electromagnetic fields, increasing visible-light harvesting and hot electron injection into semiconductor surfaces, consistent with previous research findings [7]. Reusability tests showed negligible activity loss after five cycles, confirming material durability. Structural characterization after repeated use revealed minimal morphological changes, validating the suitability of these nanostructures for long-term operation.

4. Utility and Environmental Applications

Visible-light photocatalysts have wide applicability across wastewater treatment plants, industrial effluent management systems, agricultural runoff treatment, and decentralized rural purification units. Their ability to degrade dyes, antibiotics, pesticides, and pharmaceutical residues addresses multiple pollution challenges simultaneously. Portable solar-based photocatalytic reactors can be deployed in remote areas lacking grid connectivity, supporting low-cost purification systems. Industries such as textiles, leather processing, pharmaceuticals, and chemical manufacturing can implement photocatalysis as a tertiary purification stage to meet environmental discharge standards. Additionally, photocatalytic coatings can be applied to building surfaces, water channels, and air-filtration units to degrade pollutants passively using natural sunlight. The scalability ofphotocatalytic membranes and immobilized catalysts further enhances practical applications in flow-through systems.

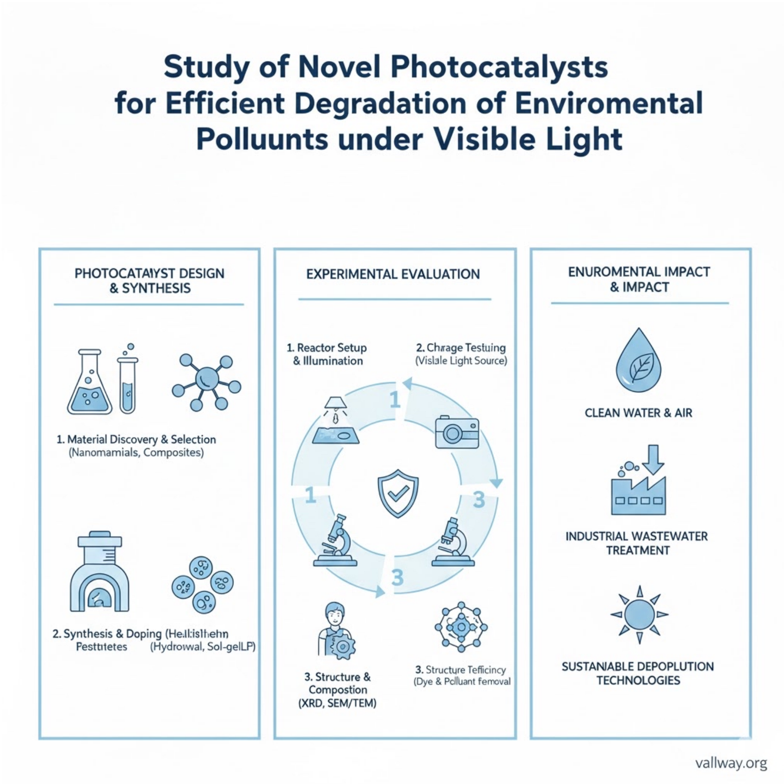

Fig. 1 Novel Photocatalysts

5. Challenges and Limitations

Despite significant advancements, photocatalysis faces notable limitations. First, recombination of photo-generated charge carriers remains a major bottleneck, reducing overall quantum efficiency. Second, several high-performance catalysts incorporate noble metals such as Ag or Au, which increases cost and limits large-scale usage [8]. Material stability under varying pH conditions, fouling in real wastewater samples, and catalyst deactivation due to surface blocking also pose operational challenges. Reactor design remains another challenge, as uniform irradiation, catalyst distribution, and mass-transfer optimization are essential for efficient degradation. Many laboratory-scale catalysts underperform when exposed to real wastewater due to competing ions, turbidity, and complex organic matrices.

6. Future Scope

Future research could explore low-cost dopants, earth-abundant metal composites, and defect-engineered materials to enhance visible-light catalytic performance while maintaining economic feasibility. Machine-learning-based material prediction models are expected to accelerate photocatalyst discovery, optimizing band structures and surface properties. Full-spectrum catalytic materials capable of harvesting near-infrared radiation may further expand solar utilization efficiency. Integration with membrane filtration, microbial fuel cells, and advanced oxidation systems could create hybrid purification technologies with superior performance. Real-wastewater testing, pilot-scale demonstrations, and long-term environmental impact analyses will be essential for transitioning laboratory photocatalysts into commercially viable solutions.

7. Conclusion

This research confirms that biocompatible 3D printed prosthetics offer significant advantages in mechanical strength, adaptability, and user comfort, especially when combined withfunctional enhancements such as embedded sensors and lightweight structures. Material selection plays a crucial role in achieving the required performance and biological safety. Additive manufacturing provides an accessible and scalable pathway to producing affordable yet high-quality medical prosthetics suitable for both urban and low-resource healthcare environments. Continued innovations in materials, embedded electronics, and clinical integration will determine the future potential of 3D printed prosthetic technologies.

References

1. P. V. Kamat, "Photocatalysis in environmental remediation," Journal of Photochemistry,2018.
2. H. Abdullah and M. R. Awad, "Visible-light-responsive photocatalysts: A review,"Catalysis Today, 2020.
3. L. Cheng et al., "Solar-driven pollutant degradation," Environmental Nanotechnology Journal, 2019.
4. R. Singh and P. Kumar, "Synthesis strategies for semiconductor photocatalysts, "Materials Chemistry Reports, 2021.
5. T. Yu and X. Zhang, "Charge-carrier dynamics in doped photocatalysts," Applied Surface Science, 2020.
6. K. S. Rao and S. Banerjee, "Nitrogen-doped TiO_2 for visible-light catalysis, " Journal of Hazardous Materials, 2021.
7. M. Lin and Y. Hao, "Plasmonic enhancement in photocatalysis, " Nano Energy, 2019.
8. J. Luo and T. Su, "Cost and sustainability challenges in photocatalyst development, "Environmental Catalysis Review, 2022.