

Advances in Photocatalytic Degradation

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The rapid growth of industrialization and urban expansion has intensified environmental challenges associated with the continuous release of hazardous pollutants into natural water and air systems [1,2]. These contaminants, which include persistent organic pollutants, toxic metal ions, pharmaceuticals, pesticides, and other emerging compounds, represent a significant risk to ecosystems and human health due to their persistence, bioaccumulation potential, and resistance to conventional treatment technologies [3]. In recent years, this challenge has intensified as water treatment systems must remove substances specifically engineered to present high stability and prolonged functionality during their intended use. While these characteristics enhance product performance, they also increase environmental persistence and recalcitrance after release, as exemplified by per- and polyfluoroalkyl substances (PFAS), highlighting the urgent need for innovative, efficient, and sustainable remediation strategies capable of addressing both traditional and emerging pollutants [4].

In this context, heterogeneous photocatalysis has emerged as a versatile and promising approach for environmental remediation, clean energy production, and sustainable chemical processes [5,6]. This technology relies on the activation of semiconductor materials by light irradiation, leading to the generation of electron–hole pairs that drive redox reactions under relatively mild conditions [7]. The use of light as the primary energy source, particularly solar energy, positions photocatalysis as a key technology in the transition toward greener and more sustainable processes [8], while also opening opportunities for the implementation of advanced oxidation processes in regions of the Global South, where high solar irradiance can facilitate the development of cost-effective and sustainable treatment solutions. Moreover, its potential to simultaneously degrade pollutants and produce valuable energy carriers, such as hydrogen, makes it especially attractive within the framework of circular economy and sustainable development [9].

Photocatalysis is inherently interdisciplinary, integrating advances in materials science, surface chemistry, nanotechnology, environmental engineering, and theoretical modeling. Continuous progress in these areas has significantly enhanced the efficiency and applicability of photocatalytic systems [10]. In particular, the design and synthesis of novel photocatalytic materials have played a central role in improving light absorption, charge carrier separation, and surface reactivity. While early efforts focused on the development of



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new photocatalytic materials, current research increasingly emphasizes the rational design of photocatalysts based on a deeper understanding of the physicochemical properties driving light harvesting, charge transfer, and surface reaction pathways. This shift has enabled the targeted modification of materials to overcome specific performance limitations and improve photocatalytic efficiency. Among these materials, TiO₂-based systems remain one of the most widely studied due to their chemical stability, low cost, and strong oxidative power [11]. However, their limited absorption in the visible region has driven intense research toward the development of modified semiconductors, including doped materials, heterojunctions, mixed metal oxides, and noble metal-supported catalysts [12]. In addition, increasing attention has been given to the environmental implications of photocatalyst deployment, promoting the development of materials that are environmentally benign, readily recoverable and recyclable at the end of their operational life.

This Special Issue, entitled “Advances in Photocatalytic Degradation”, compiles two volumes that illustrate the broad evolution of photocatalysis from a pollutant-removal technology toward a multifunctional platform for environmental remediation, resource recovery, and sustainable energy production. Several contributions focus on the development of advanced photocatalytic materials for water treatment applications. Frías-Márquez et al. report the preparation of 1D TiO₂ nanostructures for pollutant removal in water, whereas Castro et al. address the more demanding challenge of degrading contaminants of emerging concern using quaternary mixed oxides derived from hydrotalcite precursors. Similarly, Nazir et al. describe the mechanochemical synthesis of polypyrrole/Ag-ZnO heterostructures for the degradation of methyl orange dye, while Ounis Dkhil et al. combine green synthesis approaches with mechanistic investigations of diclofenac and *p*-nitrophenol photodegradation using ZnO nanoparticles synthesized from chia seed extracts. The application-oriented nature of current photocatalysis research is further illustrated by Pérez et al., using TiO₂-CeO₂ thin films under natural sunlight for pesticide oxidation, and by Hernández Sierra et al., with their research on the influence of WO₃ loading and thermal treatment on the performance of TiO₂-ZrO₂-WO₃ as photocatalysts for sildenafil degradation. Complementing these studies, Ngwenya et al. review the occurrence, ecotoxicity, and photocatalytic removal of antiretroviral drugs. Also, Quintanilla-Villanueva et al. provide a comprehensive overview of visible-light-driven TiO₂-based systems for the degradation of Congo Red dye.

Beyond pollutant degradation, several contributions point out the growing role of photocatalysis in sustainable energy production and resource valorization. Suárez-Quezada et al. and Herrera-Ramos et al. explore visible-light-driven hydrogen generation using mixed metal oxide and CdS/TiO₂ photocatalysts, respectively. On the other hand, Edirisooriya et al. demonstrate the production of hydrogen through the photoreforming of PET waste, and thus how photocatalytic processes can simultaneously address plastic waste accumulation and renewable fuel generation. This transition from pollutant removal to resource recovery represents one of the most significant emerging trends in the field.

The collection also presents efforts to move photocatalytic technologies closer to practical implementation. Gines et al. evaluate pyridine degradation in a fluidized-bed photocatalytic reactor using Pt-ZnO supported on Al₂O₃ as a photocatalyst, while Schweitzer et al. present an improved flow-through photodegradation device for the treatment of emerging contaminants. Additional applications include the solar photoreduction of CO₂ into methane and ethane using TiO₂-based nanomaterials, reported by Rangel-Vázquez et al., the photocatalytic inactivation of multidrug-resistant bacteria in greywater developed by Rincón-Barón et al., and the density functional theory study by Oprea et al., which provides molecular-level insights into the photocatalytic degradation of penicillin. These contribu-

tions demonstrate the remarkable diversity of contemporary photocatalysis research along with the common goals centered on sustainability, efficiency, and real-world applicability.

Despite the remarkable progress achieved in recent years, several challenges must still be addressed to fully realize the potential of photocatalytic technologies. These include improving the long-term stability of photocatalysts, enhancing their performance under natural sunlight, and developing cost-effective synthesis methods suitable for large-scale production. Furthermore, the complexity of real environmental matrices requires the investigation of photocatalytic processes under realistic conditions, including the presence of competing species and variable operating parameters. Particular attention should be given to regions of the Global South, where abundant solar irradiation coincides with increasing pressures on water resources and the growing use of reclaimed wastewater for agricultural and productive activities. In these settings, photocatalytic technologies could provide an attractive platform for simultaneously addressing contaminant removal and renewable energy generation.

Future advances will likely rely on the integration of high-throughput experimentation, computational modeling, and data-driven approaches. The combination of DFT, automated material synthesis, and rapid screening platforms offers new opportunities to accelerate the discovery of photocatalysts with tailored optical and electronic properties. At the same time, artificial intelligence and machine learning can be powerful tools for predicting photocatalytic performance, optimizing operational conditions, identifying promising catalyst compositions, and reducing the need for extensive experimental screening. The integration of mechanistic models with machine learning algorithms may further improve predictive capabilities under realistic environmental conditions, while AI-assisted reactor control, digital twins, and autonomous optimization strategies could facilitate the development of smart, scalable, and energy-efficient photocatalytic systems. Addressing these challenges will require continued collaboration across disciplines and the integration of fundamental research with applied engineering.

This Special Issue presents the dynamic and multidisciplinary nature of photocatalysis while illustrating the ongoing transition of the field from pollutant degradation toward integrated solutions for environmental remediation, resource recovery, and sustainable energy production. The contributions presented herein highlight advances in photocatalyst design, mechanistic understanding, reactor development, and real-world applications, while also revealing emerging opportunities associated with solar-driven processes, circular economy strategies, and data-assisted materials discovery. As environmental challenges continue to evolve, photocatalysis is expected to play an increasingly important role in the development of sustainable technologies capable of simultaneously addressing water quality, resource scarcity, and energy demands. We hope that this collection will stimulate new collaborations and inspire future research aimed at translating photocatalytic innovations into practical solutions with tangible environmental and societal benefits.

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List of Contributions

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