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MINI REVIEW

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Bio-photocatalysts: harnessing microbial and plant-based systems for sustainable water purification

Sasmita Das

Department of Chemistry, Utkal University, Odisha, India

ABSTRACT

Water pollution remains a pressing global challenge, necessitating the development of efficient, sustainable purification technologies. Bio-photocatalysis has emerged as a promising solution by integrating biological entities, such as microorganisms and plant-based materials, with photocatalytic processes to degrade pollutants. This mini-review explores the fundamental principles of bio-photocatalysis, with a focus on microbial and plant-based systems in sustainable water treatment. Microbial bio-photocatalysts, including bacteria, algae, and fungi, enhance pollutant degradation through enzymatic activity and biofilm formation, while plant-based systems contribute bioactive compounds that facilitate photocatalysis. The review delves into the mechanisms of microbial- and plant-mediated photocatalysis, their synergistic interactions, and applications in industrial and environmental water purification. Recent advancements demonstrate the effectiveness of these hybrid systems in addressing contaminants such as pesticides, heavy metals, and pharmaceuticals. This review highlights the potential of bio-photocatalytic technologies for large-scale implementation, positioning them as viable alternatives to conventional chemical treatments. The integration of biological and photocatalytic processes presents a sustainable opportunity for environmental remediation, warranting further exploration and optimization.

KEYWORDS

Environmental pollutants; Urbanization; Industrial development; Water purification; Plant extracts; Titanium dioxide

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Introduction

Water pollution, driven by industrialization, agriculture, and urbanization, has become a critical global concern. Traditional water purification methods, while effective, often rely on chemical treatments that can introduce secondary pollutants and increase operational costs. This necessitates innovative, eco-friendly solutions. Bio-photocatalysis, which merges biological systems with photocatalytic processes, offers a sustainable alternative. By leveraging natural biological mechanisms, bio-photocatalysts enhance photocatalytic efficiency, presenting a promising approach for large-scale water purification. This review examines the significance of bio-photocatalysis, differentiating microbial and plant-based systems, and discusses their potential for sustainable environmental remediation.

Background

Photocatalysis utilizes light-activated catalysts to accelerate chemical reactions, commonly employed to degrade organic pollutants. Traditional photocatalysts like titanium dioxide (TiO_2) have been widely studied due to their high stability and non-toxicity [1]. However, challenges such as low solar utilization efficiency and potential environmental risks limit their large-scale application.

Bio-photocatalysts address these challenges by introducing biological elements—microbial enzymes, biofilms, and plant extracts—that enhance catalytic performance and sustainability. Hybrid systems combining inorganic photocatalysts with living organisms or bio-derived compounds have shown improved efficiency and reduced toxicity. Recent research focuses on optimizing these hybrid systems to achieve higher degradation rates and broader contaminant removal, positioning bio-photocatalysis as a viable alternative for sustainable water purification.

Microbial Systems in Bio-Photocatalysis

Microorganisms such as bacteria, algae, and fungi play crucial roles in bio-photocatalysis by enhancing pollutant degradation through metabolic activities. Bacterial species like Pseudomonas putida and Bacillus subtilis support photocatalytic reactions by producing reactive oxygen species (ROS) and forming biofilms that facilitate electron transfer [2]. Photosynthetic bacteria, such as *Rhodobacter sphaeroides*, contribute by absorbing light and facilitating pollutant degradation. Algae, particularly microalgae, generate oxygen through photosynthesis, enhancing ROS production that accelerates pollutant breakdown. Fungi like *Aspergillus niger* produce extracellular enzymes, such as peroxidases and laccases, which effectively degrade organic pollutants.

Mechanistic insights

Microbial biofilms interact with semiconductor materials, enhancing charge separation and electron transport. This interaction reduces electron-hole recombination, improving photocatalytic efficiency. Studies have reported successful degradation of pharmaceuticals, dyes, and heavy metals in

*Correspondence: Ms Sasmita Das, Department of Chemistry, Utkal University, Odisha, India. e-mail: sasmitadas542@gmail.com

wastewater using microbial-assisted photocatalysis, demonstrating potential for industrial applications.

Types of Microbial Bio-Photocatalysts

Microbial bio-photocatalysts can be classified based on their functions, mechanisms, and interaction with photocatalytic materials

1. **Direct Catalysts:** Microorganisms that produce photocatalytically active compounds, such as pigments and enzymes, that directly participate in the degradation of pollutants. For example, Rhodobacter sphaeroides absorbs light and generates metabolites that facilitate pollutant breakdown [3].
2. **Indirect Catalysts:** Microorganisms that enhance photocatalysis by promoting electron transfer, reducing electron-hole recombination, and stabilizing semiconductor materials. Bacteria like Pseudomonas putida form biofilms that create a conducive environment for electron mobility, thus boosting photocatalytic reactions [4].
3. **Photosynthetic Microorganisms:** These microorganisms, including cyanobacteria and green microalgae, utilize photosynthesis to generate oxygen and other reactive species that assist in pollutant degradation. Cyanobacteria, for example, have been shown to improve the photocatalytic breakdown of organic dyes in wastewater.
4. **Enzyme-Producing Fungi:** Fungi such as *Aspergillus niger* and *Phanerochaete chrysosporium* secrete extracellular enzymes (laccases, peroxidases) that degrade complex organic pollutants. These enzymes can also mediate electron transfer, thus enhancing photocatalytic performance.
5. **Symbiotic Consortia:** Some microbial systems function more effectively in consortia, where multiple species interact synergistically. For example, bacteria-algae consortia combine photosynthetic oxygen generation with enzymatic degradation, leading to higher pollutant removal rates compared to individual species.
6. **Metal-Reducing Bacteria:** Certain bacteria, like *Shewanella oneidensis*, can reduce metal ions, facilitating the deposition of metal nanoparticles on photocatalysts. This process enhances light absorption and photocatalytic efficiency, especially in the degradation of heavy metals [5].
7. **Genetically Engineered Microorganisms:** Recent advances involve genetically modified microorganisms engineered to overproduce specific enzymes or metabolic products that improve photocatalytic degradation rates. Such engineered strains show promise in targeting persistent pollutants.

Mechanisms and Applications

Each type of microbial bio-photocatalyst operates through specific mechanisms, including:

- **Electron Shuttling:** Certain microbes secrete redox-active metabolites that shuttle electrons between the photocatalyst and pollutants.
- **Photoreduction of Pollutants:** Microbes assist in the reduction of metal ions and the breakdown of complex organic molecules.
- **Biofilm-Mediated Electron Transfer:** Dense microbial biofilms facilitate continuous electron flow, reducing recombination losses [6].
- Applications span across
- **Industrial Wastewater Treatment:** Microbial systems degrade dyes, pharmaceuticals, and toxic compounds.
- **Agricultural Runoff Purification:** Bacteria-algae consortia efficiently remove pesticides and fertilizers.
- **Heavy Metal Remediation:** Metal-reducing bacteria enhance photocatalytic degradation of metal-contaminated water.

Plant-Based Systems in Bio-Photocatalysis

Plants and their derivatives add another dimension to bio-photocatalysis by contributing bioactive compounds that improve catalytic performance. Plant extracts containing polyphenols, flavonoids, and antioxidants act as natural reducing agents, enhancing the degradation of pollutants.

Notable Examples:

- *Eichhornia crassipes* (water hyacinth) and *Lemna minor* (duckweed) absorb heavy metals and organic pollutants, creating favorable rhizosphere conditions for microbial communities [7].

Mechanisms of plant-based photocatalysis

1. Phytoremediation: Direct uptake of pollutants by plant roots.
2. Enzyme-Mediated Degradation: Oxidases and peroxidases excreted by plants break down contaminants.
3. Interaction with Nanomaterials: Plant-derived photosensitive compounds enhance photocatalytic reactions when integrated with semiconductor materials.

Recent studies highlight the synergy between plant-based and microbial systems, where plant roots provide substrates and support microbial growth, leading to enhanced pollutant degradation rates.

Applications of bio-photocatalysts in water purification

Bio-photocatalysts have shown promise in treating industrial wastewater, agricultural runoff, and drinking water. They effectively degrade pesticides, pharmaceuticals, and heavy metals, offering cost-effective and environmentally friendly alternatives to chemical treatments [8].

Pilot-Scale Applications

Several pilot-scale studies have demonstrated the feasibility of bio-photocatalytic reactors in real-world settings, highlighting their potential for large-scale implementation. For example, integrated microbial-plant bio-photocatalytic systems have achieved up to 90% degradation of complex organic pollutants in textile industry effluents.

Conclusion

Bio-photocatalysts offer a sustainable and innovative approach to water purification by combining natural biological

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mechanisms with photocatalytic processes. Microbial systems provide enzymatic degradation and electron transfer, while plant-based systems contribute bioactive compounds that enhance photocatalysis. Hybrid microbial-plant systems demonstrate synergistic effects, improving degradation efficiency and broadening application potential. Ongoing research continues to refine these systems, addressing challenges related to scalability and operational costs. As water pollution remains a significant global issue, bio-photocatalysis presents a promising solution for sustainable and effective water purification. Future efforts should prioritize optimizing hybrid systems, developing cost-effective reactor designs, and integrating these technologies into existing water treatment frameworks, aligning with global sustainability goals.

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