Application and Prospect of Photocatalysis: A Review

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Abstract: This review summarizes the research on photocatalysis, including its basics, types, uses, and challenges. Photocatalysis, which utilizes solar energy for chemical reactions, is crucial for energy production, environmental cleanup, and synthesis. Despite low efficiency and high costs, strategies like improving catalysts and combining technologies are being explored. Future advancements in the integration of materials and technology could revolutionize photocatalysis, thereby helping to address global energy and environmental issues.

Keywords: Photocatalysis; Semiconductor; Composite photocatalyst; Application; Challenges and Countermeasures

1. Introduction

1.1 Background and Significance of Photocatalysis

In the context of the global energy crisis and environmental pollution issues becoming increasingly prominent, photocatalysis technology has emerged as a promising solution to these challenges. Photocatalysis, a method that employs light energy to facilitate chemical reactions with the assistance of a catalyst, is a multidisciplinary field that combines principles from photochemistry, catalysis science, semiconductor physics, materials science, and environmental science. This technology has the potential to address an extensive range of problems, including energy production, environmental remediation, and sustainable chemical synthesis, making it a crucial area of research in the pursuit of a more sustainable future.

Photocatalysis is notable for utilizing solar energy to drive chemical reactions, providing a sustainable and environmentally friendly approach to energy conversion and environmental purification [1]. In particular, photocatalytic processes have demonstrated considerable potential in environmental remediation by effectively degrading a broad spectrum of pollutants, including organic contaminants, heavy metals, and pathogenic microorganisms, with applications in industrial wastewater treatment, the removal of textile dyes, and indoor air purification for improved air quality.

2. Principle and Classification of Photocatalysis

2.1 Basic Principle of Photocatalysis

Photocatalysis refers to chemical reactions initiated by light energy in the presence of a catalyst. The basic principle of photocatalysis is based on the unique energy band structure of semiconductor materials. Semiconductors commonly have a filled valence band and an empty conduction band, separated by a band gap (Eg). When a photon with energy equal to or greater than the band gap energy ($h\nu \geq E_g$) irradiates the semiconductor photocatalyst, an electron in the valence band can be excited to the conduction band, leaving a positive hole in the valence band, thus generating electron-hole pairs ($e^- - h^+$) [2].

2.2 Classification of Photocatalysts

2.2.1 Semiconductor photocatalysts

TiO_2 is one of the most popular semiconductor photocatalysts, which exists in three primary crystal forms: anatase, rutile, and brookite. Among them, the anatase phase typically exhibits higher photocatalytic activity due to its suitable bandgap energy and crystal structure. For example, in the study of photocatalytic degradation of organic pollutants, anatase-phase TiO_2 nanoparticles can effectively decompose dyes such as methylene blue and rhodamine B under ultraviolet light irradiation [3].

ZnO is another common semiconductor photocatalyst. It can be used for the degradation of various organic pollutants and antibacterial applications. For example, in the research conducted by K. K. Supin and Vasundhara M., nanoparticles of ZnO created from extracts of

Neem and Eucalyptus leaves were utilized for the photocatalytic breakdown of methylene blue dye, highlighting the photocatalytic capabilities of ZnO.[4].

CdS is a semiconductor photocatalyst with a narrower band gap, which enables it to respond to visible light. This makes CdS attractive for applications where the utilization of visible light is crucial. For example, in the study by Ratnawati et al., CdS-modified TiO_2 (CdS-TiO_2) was prepared via a hydrothermal method for the degradation of visible-light-driven textile wastewater [5]. The incorporation of CdS broadened the light absorption spectrum of TiO_2 into the visible light range, thereby improving the photocatalytic efficacy for the degradation of textile wastewater when illuminated with visible light.

2.2.2 Composite photocatalysts

Composite photocatalysts are formed by combining two or more different materials to overcome the limitations of single-component photocatalysts and improve photocatalytic performance. They can be composed of different semiconductors or a combination of semiconductors and other materials such as metals, metal oxides, or carbon-based materials.

One common type of composite photocatalyst is the combination of different semiconductors to form a heterojunction. For example, in the study of Adil Raza et al., a ternary $Fe_3O_4/TiO_2/g/C_3N_4$ nanocomposite was prepared by a hydrothermal route[6]. The gradual enhancement in performance resulted from the stepwise combination of anatase TiO_2 and magnetic Fe_3O_4 on the g-C_3N_4 framework at a calcination temperature of 200 C.

Another type of composite photocatalyst is the combination of semiconductors with metal nanoparticles. Metal nanoparticles, like silver (Ag) and gold (Au), can be applied to the surfaces of semiconductors. When exposed to light, these nanoparticles exhibit surface plasmon resonance (SPR), which enhances light absorption and promotes the formation of electron-hole pairs. For example, in the work of Jaspal Singh et al., Ag-TiO_2 plasmonic nanocomposite thin films were synthesized by the atom beam co-sputtering technique [7].

In photocatalytic materials research, it is essential to distinguish between heterojunctions and nanocomposites. A heterojunction refers to the interface formed between two semiconductors with different band structures, which facilitates charge separation and transfer through the built-in electric field at the junction. In contrast, a nanocomposite generally describes a hybrid material comprising nanoscale components of different compositions, structures, or phases, where the enhanced performance often arises from synergistic effects such as increased surface area or improved stability rather than solely from band alignment.

Composite photocatalysts can also be formed by combining semiconductors with carbon-based materials, such as graphene and carbon nanotubes. Carbon-based materials have excellent electrical conductivity and a large specific surface area. In a study by Seongpil An et al., graphene-decorated zinc oxide (G-ZnO) nanofibers were fabricated using the electrospinning technique [8]. The G-ZnO mats infused with 0.5 wt.% graphene exhibited remarkable photocatalytic performance, breaking down methylene blue when exposed to UV light.

3. Applications of Photocatalysis

3.1 Air Purification

3.1.1 Degradation of harmful gases

Photocatalysis technology offers an effective solution for degrading these harmful gases. It works by generating reactive species on the surface of a photocatalyst. These species, especially hydroxyl radicals, are powerful oxidants that can break down harmful gas molecules into harmless substances.

For formaldehyde, the degradation reaction can be expressed as follows:

$$HCHO+OH \rightarrow HCOO^{-}+H_2O \quad (1)$$

$$HCOO^{-}+OH^{-} \rightarrow CO_2+H_2O \quad (2)$$

Many research studies have shown that photocatalysis is effective in breaking down harmful gases. For instance, in work related to air purification using photocatalysis [9], it has been shown that TiO_2-based photocatalysts can effectively degrade formaldehyde and benzene under ultraviolet or visible light irradiation.

3.1.2 Removal of odors

Photocatalysis is capable of breaking down these substances by producing reactive species that oxidize and dismantle the odorous molecules into benign materials, such as carbon dioxide and water.

Photocatalysis eliminates bacteria through a combination of physical and chemical actions. Bacteria on the photocatalyst surface are affected by photo-generated holes and reactive oxygen species, which damage cell membranes and walls. These species also oxidize proteins and nucleic acids, disrupting bacterial functions and ultimately leading to cell death. Research indicates that TiO_2-based photocatalysts can inactivate common bacteria, such as Escherichia coli and Staphylococcus aureus, under light [10].

3.2 Water Treatment

3.2.1 Degradation of organic pollutants

Organic pollutants in water represent a critical environmental concern, and photocatalysis offers a practical and emerging solution for their degradation.

Pharmaceuticals in water are a growing concern. Many pharmaceuticals, such as antibiotics and anti-inflammatory drugs, are not entirely removed by traditional water treatment processes and can enter the water environment. John Akach et al. investigated the solar photocatalysis and adsorption of the antibiotic sulfamethoxazole (SMX) in wastewater[11]. A composite catalyst of activated carbon (AC), TiO_2, and silica xerogel was synthesized.

3.2.2 Removal of Heavy Metal Ions and Microorganisms

In addition to degrading organic pollutants, photocatalysis also exhibits excellent potential in removing heavy metal ions and microorganisms from water, which is of great significance for improving water quality and ensuring water safety.

$$Cr_2O_7^{2-}+14H^{+}+6e^{-}\rightarrow 2Cr^{3+}+7H_2O \quad (3)$$

In some studies, semiconductor photocatalysts like TiO_2 have been used to remove heavy metal ions from water. The photocatalyst first adsorbs the heavy metal ions on its surface. Then, under light irradiation, the photo-generated electrons reduce the heavy metal ions to a lower valence state or even to a metallic state, which can then be separated from the water by precipitation or other methods [12].

Microorganisms in water, including bacteria, viruses, and fungi, can cause waterborne diseases and pose a significant threat to human health. Photocatalysis can effectively inactivate these microorganisms. For instance, research conducted by Yingqing Guo and colleagues examined the integration of photocatalysis and biological contact oxidation for the pretreatment of micro-polluted raw water. The findings indicated that this integrated approach could successfully eliminate turbidity, chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), and total phosphorus (TP) from the water. For example, in the work of Yingqing Guo et al., the combined technology of photocatalysis and biological contact oxidation was studied for the pretreatment of micro-polluted raw water. The results showed that this combined technology could effectively remove turbidity, chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), and total phosphorus (TP) from the water [13].

4. Challenges and Solutions in Photocatalysis

4.1 Existing Challenges

4.1.1 Low photocatalytic efficiency

One of the most prominent challenges in photocatalysis is the low photocatalytic efficiency, which significantly limits its practical applications.

Most traditional photocatalysts, such as TiO_2 and ZnO, have a relatively large band gap, which restricts their light-absorption range mainly to the ultraviolet region. Ultraviolet light constitutes a minor fraction (approximately 5%) of the solar spectrum, resulting in minimal utilization of solar energy by these photocatalysts. For instance, TiO_2, which is extensively researched and applied, possesses a band gap of around 3.2 eV for its anatase phase, meaning it can only be activated by ultraviolet light with wavelengths shorter than 387 nm.

4.1.2 High preparation cost

The high preparation cost of photocatalytic materials is another significant challenge that restricts the large-scale application of photocatalysis. The preparation of high-performance photocatalysts often requires complex processes and expensive raw materials, which increases the overall cost.

The synthesis of some composite photocatalysts and modified photocatalysts may require the use of precious metals or rare-earth elements. For example, in the preparation of some photocatalysts with enhanced photocatalytic activity, noble metals such as Ag and Au are often deposited on the surface of semiconductors to utilize their surface plasmon resonance (SPR) effects [14].

4.2 Solutions and Strategies

4.2.1 Optimization of photocatalyst performance

The Institute of Macromolecular Chemistry engineered Ni, Co-codoped ZnO nanoparticles using the co-precipitation technique. The photocatalytic efficiency of the Ni, Co-codoped ZnO nanoparticles was evaluated through the degradation of Rhodamine B (RhB) dye when exposed to visible-light irradiation. The introduction of Ni and Co created additional energy levels within the band gap of ZnO, thereby enhancing the absorption of visible light and improving the separation of electron-hole pairs, which resulted in improved photocatalytic performance [15].

Another practical approach is the formation of composite photocatalysts. Hanxiang Chen et al. demonstrated this principle in their study on the Co_3O_4/Ag_3PO_4 heterojunction. As a standard photocatalytic material, Ag_3PO_4 typically struggles with the fast recombination of photo-generated electron-hole ($e-h^+$) pairs. However, by preparing a Co_3O_4/Ag_3PO_4 heterojunction through an in situ precipitation method, they were able to create a more efficient photocatalyst [16].

4.2.2 Cost-reduction measures

Reducing the preparation cost of photocatalytic materials is crucial for their large-scale application. One strategy is to improve the preparation process to make it more efficient and less resource-consuming. In the study conducted by Xiao-Na Wei and colleagues, a new and simple method was presented for creating tunable carbon-modified mesoporous TiO_2 photocatalysts. This method involves the in-situ carbonization of PAA-Ti/TiO_2 combined with a hydrothermal reaction process and subsequent calcination treatment.[17]. This method not only modified TiO_2 but also reduced the complexity and cost of the preparation process compared to some traditional methods.

Furthermore, utilizing waste materials as starting points for synthesizing photocatalysts presents a viable strategy for reducing costs. In research conducted by the Advanced Materials Group and others, waste iron oxide nanopowder containing 7.6 wt.% titanium dioxide (IOW-9 h) was created from industrial byproducts through a straightforward and economical planetary wet ball milling method. The production of IOW-9 h nanopowder occurred without the involvement of any chemical processes.[18]. This method not only reduced the cost of raw materials but also provided a solution for the disposal of industrial waste.

5. Future development trends of Photocatalysis

The development of new photocatalytic materials is a crucial aspect of the future of photocatalysis research. Scientists are constantly exploring materials with unique structures and properties to overcome the limitations of existing photocatalysts and achieve more efficient photocatalytic reactions.

Perovskite-based photocatalysts are a promising development due to their optical and electrical properties. These materials, with a general formula of ABO_3, have a narrow band gap and high charge-carrier mobility, which enhances the separation of electron-hole pairs. For instance, methylammonium lead iodide ($CH_3NH_3PbI_3$) has been investigated for water splitting and the degradation of organic pollutants. The crystal structure of perovskites enables the easy manipulation of their electronic properties, thereby optimizing bandgap energy, light absorption, and surface reactivity, which leads to improved photocatalytic performance [19].

Metal-organic frameworks (MOFs) are promising materials for photocatalysis due to their ordered porous structures, large surface areas, and tunable pore sizes. They can be tailored to improve pollutant adsorption and photocatalytic efficiency. Combining MOFs with semiconductors yields composites with enhanced light absorption and improved charge transfer. Challenges include low conductivity and instability under light, which researchers are addressing through doping and structural modifications [20].

6. Conclusion

Photocatalysis holds great promise in air and water treatment, energy production, and organic synthesis. Harnessing light energy and utilizing the unique properties of photocatalysts drives reactions such as pollutant degradation and the production of clean fuels, offering sustainable solutions to global energy and environmental challenges.

In summary, photocatalysis has significant potential. Continuous research and innovation will strengthen its role in addressing global issues, promoting sustainable development, and enhancing quality of life. Collaboration among the scientific community, industry, and policymakers is vital for realizing its full potential.

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