The Research Progress on Photocatalytic Materials for Pollutant Degradation: A Review

Gang Meng[1,#], Jiacheng Cui[1,#], Zongliang Zuo[1,2,*], Kaiqian Zhang[1], Yifan Wang[3], and Siyi Luo[1]

[1]*School of Environmental and Municipal Engineering, Qingdao University of Technology, No. 777, Jialingjiang East Rd., Qingdao, 266520, P.R. China*

[2]*Key Lab of Industrial Fluid Energy Conservation and Pollution Control (Ministry of Education), Qingdao University of Technology*

[3]*Jimo Branch of Qingdao Ecological Environment Bureau, No. 146-1 Zhenhua Street, Jimo District, Qingdao City, Shandong Province*

Abstract: Photocatalytic technology, as a clean, green, and sustainable method for pollutant degradation, has significant scientific research value and practical application significance in the field of water pollution control. Currently, the focus of photocatalysis research is on developing efficient, stable, and low-cost photocatalysts. Researchers are enhancing the light absorption capacity, electron-hole separation efficiency, and degradation rate of photocatalysts by designing novel photocatalysts, such as S-type heterojunctions, Z-scheme structures, precious metal doping, and non-metal regulation. The mechanistic study of the photocatalytic process, especially the separation, migration, and transfer mechanisms of photogenerated carriers, provides theoretical support for the optimization design of photocatalysts. At present, there are various types of catalysts for photocatalytic degradation of pollutants, including metal oxide catalysts (*e.g.*, TiO_2, ZnO), precious metal catalysts (*e.g.*, platinum, gold, silver), carbon-based catalysts (*e.g.*, graphene, carbon nanotubes), and composite catalysts (*e.g.*, metal oxide-carbon-based composite catalysts).Each type of catalyst has shown performance in improving photocatalytic efficiency and expanding the light absorption range, but also faces challenges such as limited light absorption range, poor catalyst stability, and high cost. Composite catalysts significantly improve photocatalytic efficiency through synergistic effects, especially excelling in the degradation of high-concentration pollutants. Future research will focus on further optimizing the performance of catalysts, particularly expanding the light absorption range, improving electron-hole separation efficiency, and enhancing catalyst stability. The design of composite catalysts remains the focus of research, especially the exploration of synergistic effects between different materials. At the same time, issues such as the long-term stability, recyclability, and selectivity of catalysts need to be addressed to support their large-scale application.

Keywords: Light absorption, Photocatalysts, electron-hole separation, Pollutant degradation, Catalytic efficiency, Environmental pollution control.

INTRODUCTION

With the rapid development of industrialization and urbanization, water pollution issues have become increasingly severe worldwide, particularly with the large quantities of persistent organic pollutants (such as dyes, antibiotics, phenolic compounds, etc.) and heavy metal ions found in industrial wastewater and domestic sewage. These pollutants not only harm the ecological balance but also pose a serious threat to human health. Traditional wastewater treatment technologies, such as adsorption, chemical precipitation, membrane separation, and biological treatment, although addressing pollution issues to some extent, still face limitations such as high treatment costs, harsh operating conditions, high energy consumption, low treatment efficiency, and secondary pollution, making them insufficient to meet the growing complexity of pollution control demands. Therefore, it is crucial to develop novel, efficient, and environmentally friendly wastewater treatment technologies.

Photocatalytic technology, as an emerging advanced oxidation process (AOP), uses semiconductor materials at its core. Advanced Oxidation Processes (AOP) are technologies that use strong oxidants to generate reactive oxygen species (such as hydroxyl radicals) to degrade pollutants in water. AOP originated in the 1970s when scientists discovered that oxidants like ozone and hydrogen peroxide could generate powerful oxidizing free radicals, effectively removing organic pollutants. As technology advanced, methods like photocatalysis became widely used, particularly in water treatment and environmental remediation [1]. Today, AOP is an important technology for treating wastewater, sewage,

*Address correspondence to this author at the School of Environmental and Municipal Engineering, Qingdao University of Technology, NO 777, Jialingjiang East Road, Qingdao, Shandong, P.R. China;
E-mail: zuozongliangneu@163.com

# These authors contributed equally to this work

and purifying air. By utilizing light energy to excite photogenerated electron-hole pairs on the surface of semiconductor materials, it generates highly reactive species, such as hydroxyl radicals (·OH) and superoxide radicals (O_2-·), which have strong oxidizing abilities. These species break down complex organic pollutants into non-toxic or low-toxicity small molecules (such as CO_2 and H_2O), achieving complete mineralization of pollutants. This process does not require additional chemical reagents, operates under mild conditions, and is green and pollution-free, making it a highly promising sustainable pollutant treatment technology. Photocatalytic degradation of pollutants originated in the 1970s when scientists discovered that light could excite catalysts (such as titanium dioxide, TiO_2) to generate reactive oxygen species (like hydroxyl radicals, ·OH), which have strong oxidizing power and can degrade organic pollutants in water. Initially, photocatalysis was mainly applied in water treatment, particularly in degrading refractory organic compounds and wastewater.In the 1980s, with advancements in titanium dioxide and other catalytic materials, photocatalysis gained broader attention. By the 1990s, new photocatalysts and more efficient reaction conditions were developed, leading to the expanded use of photocatalysis in air purification, wastewater treatment, and other areas.Since the 21st century, photocatalytic degradation technology has continuously improved, making significant progress in environmental protection and energy utilization. Today, photocatalysis is not only used for water and air purification but also in fields like antibacterial applications and exhaust treatment, achieving important results.

However, single semiconductor materials still face issues during photocatalysis, such as narrow light absorption range, high recombination rate of photogenerated electron-hole pairs, and poor catalytic stability, which severely limits the practical application of photocatalysts. Therefore, in recent years, researchers have employed various strategies, such as constructing heterojunction photocatalysts, introducing doped elements, preparing nanostructured materials, and developing synergistic composite catalysts, to significantly improve the light absorption ability, carrier separation efficiency, and photocatalytic activity of photocatalysts. These new photocatalysts not only demonstrate excellent degradation performance in laboratory settings but also provide both theoretical and practical foundations for real-world environmental pollution control.

SIGNIFICANCE OF THE RESEARCH

Photocatalytic technology, as a clean, green, and sustainable pollutant degradation technology, has significant scientific research value and practical application significance in the field of water pollution control. With population growth and increased industrial production, large amounts of toxic and harmful pollutants are discharged into water bodies. These pollutants include dye wastewater, nitrogen-containing organic substances, antibiotics, heavy metal ions, etc. They are characterized by high toxicity, poor degradability, and strong persistence, posing a serious threat to water resource security and the sustainable development of the ecological environment. Photocatalytic technology can effectively degrade a variety of complex pollutants and transform them into harmless small molecules, providing new technological means and theoretical support for addressing the current global water pollution issue.

Photocatalytic reactions rely on sunlight or artificial visible light sources. As an inexhaustible and renewable energy source, the utilization of light energy gives photocatalytic processes the advantages of low energy consumption and no secondary pollution. In addition, photocatalytic technology can be performed under ambient temperature and pressure conditions, with simple operation, making it suitable for large-scale industrial applications and in line with the concept of green and sustainable development.

The core of current photocatalytic research is the development of efficient, stable, and cost-effective photocatalysts. Researchers have improved the light absorption capacity, electron-hole separation efficiency, and photocatalytic degradation rate of photocatalysts by constructing various new types of photocatalysts, including S-type heterojunctions, Z-type structures, porous nanomaterials, noble metal doping, and non-metal regulation. S-type heterojunctions, Z-scheme structures, porous nanomaterials, noble metal doping, and non-metallic modification are common strategies to enhance photocatalytic performance. S-type heterojunctions separate electrons and holes through n-type and p-type semiconductors, improving catalytic efficiency; Z-scheme structures promote the separation of electrons and holes through an external circuit, optimizing redox reactions. Porous nanomaterials provide a larger surface area, facilitating adsorption and the migration of photo-generated charge carriers, further enhancing catalytic efficiency. Noble metal doping (*e.g.*, platinum, gold) improves light

absorption and charge carrier separation, reducing recombination and boosting photocatalytic activity; non-metallic modification, through the incorporation of elements such as nitrogen or sulfur, optimizes the electronic structure and enhances responsiveness to visible light. These methods work together to advance photocatalytic technology. For example, new materials such as Ag/MoO_4 composite catalysts and Bi_2MoO_6/UiO-66 heterostructures exhibit remarkable degradation performance, providing important scientific evidence and practical foundation for the treatment of complex water pollutants [2].

The study of the mechanisms of the photocatalytic process is of great significance for improving the performance of photocatalysts. Using advanced characterization techniques (such as in situ XPS, EPR, UV-Vis spectroscopy, and density functional theory), the separation, migration, and transfer pathways of photo-generated charge carriers in photocatalytic reactions can be explored in depth, revealing the generation and action mechanisms of active species (·OH, O_2^{-}·). This not only provides theoretical guidance for the optimization design of photocatalysts but also helps promote the practical application of photocatalytic technology.

CURRENT RESEARCH STATUS

In recent years, significant progress has been made in the research of photocatalytic degradation of pollutants. The focus of the research has been on the design and synthesis of novel photocatalytic materials to improve photocatalytic efficiency and expand the light absorption range. Researchers have synthesized various nano-composite photocatalysts, including TiO_2 [3], $BiPO_4$, CdSe, g-C_3N_4, and their composites, using various preparation methods (such as hydrothermal and solvothermal methods). By controlling the materials' band gap structures, surface charge transfer, and carrier separation efficiency, they have achieved performance optimization.

METAL OXIDE CATALYSTS

The application of metal oxide catalysts in photocatalytic degradation of pollutants primarily relies on the electron-hole pairs generated in metal oxides (such as titanium dioxide TiO_2, zinc oxide ZnO, iron oxide Fe_2O_3, etc.) under ultraviolet light, which promote redox reactions and thereby degrade pollutants in the environment. The basic principle is that when metal oxide materials are irradiated with ultraviolet light, electrons in the valence band are excited to the conduction band, forming electron-hole pairs (e^-/h^+). These electrons and holes can participate in reactions on the catalyst surface, generating superoxide radicals (O_2·-) and hydroxyl radicals (·OH), which have strong oxidative properties and can decompose pollutants, especially organic pollutants, ultimately converting them into harmless substances.

The advantages of metal oxide catalysts are primarily reflected in their efficient photocatalytic performance, good stability, low cost, and environmental friendliness. Metal oxides, especially titanium dioxide (TiO_2) [26], exhibit strong catalytic activity under ultraviolet light and are capable of degrading pollutants at room temperature. Moreover, metal oxide catalysts generally possess high chemical stability, are less prone to degradation, and can be used for extended periods without losing efficiency. Additionally, their raw materials are abundant, and their cost is low, making them suitable for large-scale applications. They do not generate secondary pollution during use, which makes them environmentally friendly.

However, metal oxide catalysts also have some drawbacks. First, the light absorption of most metal oxide catalysts is mainly concentrated in the ultraviolet region, lacking the ability to absorb visible light, which limits their catalytic efficiency under natural light. Secondly, the electron-hole pairs in metal oxides are prone to recombination, which reduces the catalytic efficiency. To overcome these issues, researchers typically improve the performance of metal oxide catalysts through doping or surface modification techniques. Additionally, metal oxide catalysts often lack selectivity towards pollutants, which may result in the simultaneous degradation of other substances in water, including beneficial ones. Finally, although metal oxide catalysts perform excellently in pollutant degradation, during long-term use, the catalyst surface may become covered with pollutants or poisoned, leading to a decrease in catalytic activity. Therefore, periodic cleaning or regeneration is required.

In summary, metal oxide catalysts have strong degradation capabilities in photocatalytic pollutant degradation and offer advantages such as high efficiency, stability, low cost, and environmental friendliness, despite challenges such as limited light absorption range, electron recombination, and poor selectivity. Through further modification and optimization, metal oxide catalysts are expected to play a greater role in environmental remediation.

TITANIUM OXIDE-BASED CATALYSTS

Zehbah A. Al-Ahmed [4] successfully prepared polyaniline-titanium dioxide quantum dots (PA-TQD) composites via an in-situ polymerization method. Using methyl orange as a model pollutant, the photocatalytic activity was measured under xenon lamp irradiation, with the PA-TQD degradation rate reaching 60.1%, which is higher than that of polyaniline (35%), with a rate constant of 0.032 min^{-1}.Zhikun Lu [5] used the traditional sol-gel method to prepare TiO_2 thin film photocatalysts, with phenol solution as the target pollutant. The study demonstrated a synergistic degradation effect of TiO_2 photocatalysis on phenol in a pulsed discharge system, which increased the concentration of active substances in the system. Dong Xu [6] prepared TiO_2 as a catalyst and used rhodamine B as a model organic pollutant. The study explored the cavitation bubbles under ultrasonic action, which undergo nucleation, growth, and collapse, generating high temperatures and "sonoluminescence," thus exciting nanoparticles to produce electron-hole pairs and triggering a series of strong oxidants for the degradation process. Luis A. González-Burciaga [7]used methylene blue (MB) as the target pollutant. The combination of UV/TiO_2/H_2O_2 and MF degradation of MB followed pseudo-first-order kinetics, with high ka and low EE/O. The degradation resulted in small molecules and inorganic substances, with H_2O_2 enhancing the degradation and catalyst dispersion, reducing membrane fouling, and increasing permeate flux. Focusing on TiO_2 heterogeneous photocatalytic degradation of cell growth-inhibiting pollutants. Cell growth-inhibiting drugs, which are emerging contaminants, exist in water bodies and are difficult to remove by traditional water treatment methods. Advanced oxidation processes have become a research hotspot, with photocatalysis receiving particular attention. In photocatalysis, although homogeneous photocatalysis is effective, the separation and recovery of catalysts is challenging. Heterogeneous photocatalysis, with TiO_2 as a key catalyst, involves degradation mechanisms related to electron-hole pairs and the generation of reactive species. This process is influenced by factors such as pH and temperature. In CSD degradation applications, different carriers and doping methods exhibit varying effects, while various immobilization techniques are continually being developed to address the problem of catalyst suspension. Overall, TiO_2 heterogeneous photocatalytic degradation of CSD has potential, but further in-depth research and improvements are needed [27]. Xiaoning Wang [8] focused on tetracycline, using TiO_2 (P25) as a catalyst. The study showed that the combination of photocatalysis and hydraulic cavitation exhibited a significant synergistic effect in the degradation of tetracycline, with a high removal rate. UV/Vis and SEM results indicated that the combination disrupted the structure, prevented aggregation, and enhanced the light efficiency. The synergistic coefficient increased with concentration, with higher concentrations showing a more pronounced advantage. Zoltán Z [9] used Degussa P25 as the catalyst. The rate of HBS degradation was related to the change in TOC, with characteristic changes in the intermediates during the combined method. The mineralization rate of DHBS was higher than that of HBS, and the synergistic effect was not significant in the combined method. LAS and LES showed improved mineralization efficiency in the combined method and were reusable.

MOLYBDENUM OXIDE-BASED CATALYSTS

Qingqing Wang [10] cleverly prepared Bi_2MoO_6/NH_2-UiO-66(Zr) (BMNU-x) composites using a two-step hydrothermal method. Tetracycline (TC) was used as the target pollutant, and the photocatalytic degradation performance of BMNU-x composites under visible light was comprehensively studied. BMNU-100 exhibited the highest degradation efficiency, with a degradation rate of 81.72% for TC within 90 minutes. Its kinetic rate constant was enhanced by 3.78 times compared to pure Bi_2MoO_6 and by 41.13 times compared to NH_2-UiO-66(Zr).

IRON OXIDE-BASED CATALYSTS

Wu C. [11] compared the degradation effects of ultrasound, photocatalysis, and ultrasound-assisted photocatalysis on phenol, and then investigated the effects of factors such as pH, saturated gases, salts, metal oxides, and Fe^{3+} ions on the ultrasound-assisted photocatalytic degradation process. It was confirmed that ultrasound-assisted photocatalysis achieved the highest degradation rate of 51.48% within 60 minutes, compared to 27.1% for ultrasound and 32.71% for photocatalysis.

COMPOSITE METAL OXIDE CATALYSTS

Jin C [12] innovatively used ultrasound-assisted hydrothermal synthesis to successfully prepare a novel hollow amorphous N-doped TiO_2 (AH-NTO) photocatalyst. The performance of the AH-NTO photocatalyst was systematically studied for the

treatment of high-concentration Cr(VI)-containing wastewater. Under 120 minutes of visible light irradiation, it achieved complete removal of 0.15 g/L Cr(VI). For 0.274 g/L Cr(VI) wastewater, after five consecutive cycles of treatment, the removal efficiency decreased by only 0.18%, demonstrating its excellent cyclic stability and activity, using an ultrasound-assisted hydrothermal method for photocatalytic degradation of high-concentration Cr(VI). The synthesis was carried out using an Fe_3O_4 template method, where ultrasound helped ensure uniform shell thickness and promoted the formation of an amorphous phase. Various characterizations confirmed the N-doping and structural properties. Photocatalytic experiments demonstrated that AH-NTO exhibits high activity for Cr(VI) degradation, with AH_2-NTO effectively treating high-concentration wastewater and showing good cyclic stability. The photocatalytic mechanism involves a synergistic enhancement of light absorption and charge carrier separation due to the amorphous and hollow structure. The surface properties favor adsorption, and the main active species are electrons and $\cdot O_2^-$. AH-NTO showed great potential in treating high-concentration pollutants. Yinghui Q [13] synthesized Fe-MOF catalysts using solvothermal and calcination methods, and then prepared a series of Fe-MOF/BiOBr composites using the solvothermal method. Using RhB as the target pollutant, the photocatalytic and activation performance of the samples was studied through RhB degradation under visible light. The results showed that the best degradation conditions were achieved under 50 W light irradiation. Li Y [14] synthesized $BiPO_4$/$CdPSe_3$ (BPO/CPS) heterojunction photocatalysts with different molar ratios using hydrothermal methods, liquid-phase exfoliation, and mechanical mixing. Using RhB as the target pollutant, the B2C ($BiPO_4$/$CdPSe_3$ = 2:1) composite showed the best performance, achieving a RhB removal rate of 97.5% after 30 minutes of dark reaction and 60 minutes of light irradiation. Feng Haidong [15] prepared Fe/Ni@TiO_2 and Cu/Ni@TiO_2 catalysts and magnetic composite catalysts using a hydrothermal method. Methyl orange and tetracycline hydrochloride were used as target pollutants to systematically explore the catalyst performance. The bimetallic-doped catalysts exhibited superior degradation performance, with Cu/Ni@TiO_2-3 achieving a methyl orange degradation rate of up to 95.95% under specific conditions. This was better than Fe/Ni doping, and the degradation performance was optimal under acidic conditions, low pollutant concentrations, and moderate catalyst dosages.

NOBLE METAL CATALYSTS

Noble metal catalysts in photocatalytic degradation of pollutants can significantly enhance the efficiency of photocatalytic reactions by loading noble metals (such as platinum, gold, silver, etc.) onto the surface of semiconductor materials. The principle of their operation mainly relies on the excellent catalytic properties of noble metals. During the excitation of electron-hole pairs (e^-/h^+) under light irradiation, the noble metals can effectively capture and stabilize these excited electrons, reducing the recombination of electron-hole pairs, thereby improving the rate of photocatalytic reactions. In addition, noble metals can promote the redox reactions of pollutants, accelerating the degradation of organic pollutants (such as dyes and pesticides) and heavy metal ions [25]. The advantages of noble metal catalysts in photocatalytic degradation are mainly reflected in several aspects: First, they can significantly improve photocatalytic efficiency, especially maintaining high catalytic activity even under low light intensity or low temperature conditions; second, noble metals effectively suppress electron recombination, enhancing the stability of catalytic reactions; meanwhile, their strong selectivity allows the catalysts to selectively degrade specific pollutants, avoiding impacts on other substances. However, noble metal catalysts also have some notable drawbacks, mainly including high cost, which limits their economic feasibility in large-scale applications; short catalyst lifespan, as noble metals may be lost or become inactive during the catalytic process, requiring frequent replacements; moreover, the scarcity of noble metals is one of the factors restricting their widespread use, as long-term use may lead to resource shortages. Finally, the risk of secondary pollution caused by the catalyst's detachment or degradation should not be ignored, as it may cause additional environmental pollution. In conclusion, noble metal catalysts play an important role in photocatalytic degradation of pollutants. Despite challenges such as cost and resource constraints, their excellent catalytic performance still makes them widely applicable in the field of pollution control.

Yang Juan [26] focused on the synthesis of iron-based catalysts and the control of key properties such as size, morphology, crystal phase, and chemical valence. The catalysts are categorized into several types: Fe^{2+}/Fe^{3+}, zero-valent iron, iron oxides, pyrite, Fe-MOFs, and Fe-bimetallic catalysts. This paper summarizes the research progress on their application in the degradation of refractory organic pollutants through processes such as Fenton/Fenton-like

oxidation, ozonation, wet air oxidation, PMS/PS activation, and photocatalytic oxidation.Gao W W [16] synthesized Ag/$ZnFe_2O_4$ (Ag/ZFO) photocatalysts with different Ag contents through a one-step solvothermal method and studied their synergistic degradation performance of phenol with persulfate (PS) under visible light. The 10% Ag/ZFO photocatalyst achieved a phenol degradation rate of 94.3%, and its excellent performance was attributed to the surface plasmon resonance (SPR) effect of Ag, improved separation efficiency of photogenerated charge carriers, and the synergistic effect with $ZnFe_2O_4$.

CARBON-BASED CATALYSTS

The application of carbon-based catalysts in photocatalytic degradation of pollutants mainly relies on carbon materials (such as graphene, activated carbon, carbon nanotubes, carbon quantum dots, etc.) as catalysts or supports, combined with photocatalytic reactions to degrade organic pollutants. Carbon-based materials possess good electrical conductivity and large specific surface area, which can promote efficient electron transfer and enhance the degradation reaction of pollutants. The working principle is that when the carbon-based catalyst is illuminated, it generates electron-hole pairs, which migrate effectively through the conductivity of the carbon material and react with water molecules or oxygen to generate reactive oxygen species (such as OH, $O2^{\cdot -}$). These free radicals have strong oxidation properties and can attack and decompose organic pollutants. In addition, some carbon-based catalysts, such as graphene and carbon quantum dots, can absorb visible light, broadening the spectral response range of photocatalytic reactions, allowing them to maintain high catalytic efficiency even under visible light. The advantages of carbon-based catalysts mainly include good electrical conductivity, which improves electron migration efficiency and reduces electron-hole recombination; tunable structure and properties, allowing the catalyst to be adjusted according to the degradation needs of different pollutants; high specific surface area, providing more reaction sites; and broad light absorption range, enabling catalytic action under visible light. In addition, carbon-based catalysts are low-cost, widely available, and environmentally friendly, causing no secondary pollution during use. Carbon-based catalysts exhibit good catalytic activity, low cost, and environmental friendliness in photocatalytic degradation of pollutants, but they also face challenges such as low catalytic activity, poor stability, and poor selectivity. Through doping, surface modification, or compounding with other catalysts, the performance of carbon-based catalysts is expected to be further enhanced, providing more efficient and sustainable solutions for pollutant remediation.

Yao Wang [17] successfully prepared Bi_3NbO_7 loaded onto porous carbon (BNO/PC) composite photocatalyst using an in situ sol-gel method and conducted a detailed study on the degradation performance of BNO/PC composite photocatalyst with tetracycline (TC) as the target pollutant under visible light and hydrogen peroxide (H_2O_2) synergistic conditions. The "cata+H_2O_2+vis" system exhibited excellent photocatalytic activity, achieving a TC degradation rate of 86.9% after 60 minutes of visible light irradiation, which was 6.6 times and 6.0 times higher than the "H_2O_2+vis" and "cata+H_2O_2" systems, respectively.

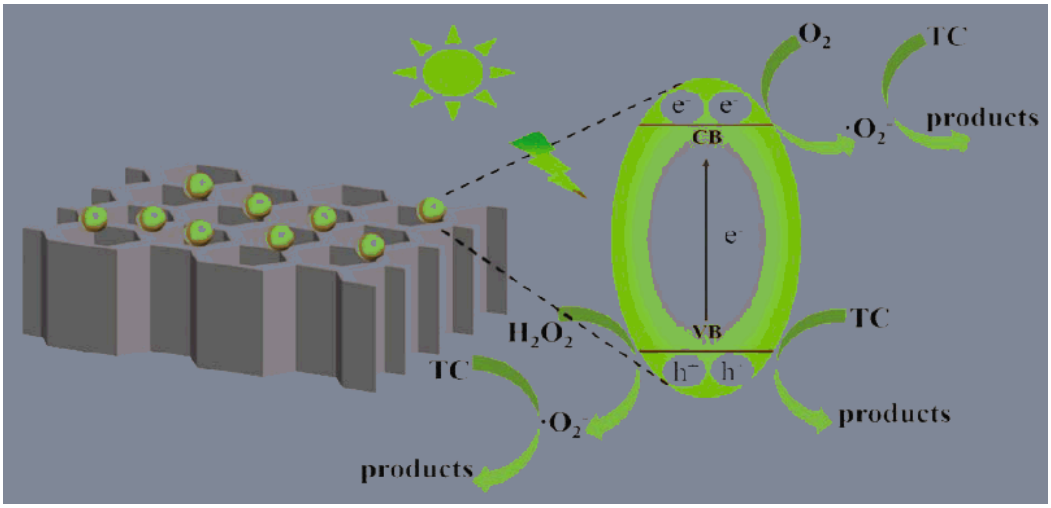

Figure1: 35%BNO/PC photocatalytic mechanism in TC degradation process [17].

Yijun Wang [18] used a mechanochemical method to prepare graphdiyne (GDY) and successfully synthesized GDY/$Ag_2Mo_2O_7$ (G/AMO) composite material by in situ loading onto $Ag_2Mo_2O_7$ via a hydrothermal method. With 2,4-dichlorophenol (2,4-DCP) as the target pollutant, the G/AMO composite catalyst activated persulfate (PDS) to degrade 2,4-DCP under simulated visible light, achieving 99% degradation of 2,4-DCP within 60 minutes, with a degradation rate constant of 0.0514 min^{-1}. Zhiyuan Wang [19] synthesized a porous heterojunction g-C_3N_4/TiO_2 photocatalyst using a biomimetic template method and studied its performance in the degradation of methyl orange (MO). Experimental results showed that the degradation rate of this catalyst within 60 minutes was significantly higher than that of TiO_2 and g-C_3N_4 single catalysts, demonstrating a synergistic enhancement effect.

COMPOSITE CATALYSTS

The application of composite catalysts in photocatalytic degradation of pollutants involves combining different types of catalytic materials (such as metal oxides, carbon-based materials, precious metals, etc.) to leverage the synergistic effects between materials, significantly enhancing photocatalytic degradation efficiency. The working principle of composite catalysts relies on the synergistic effect between different catalysts, which is mainly reflected in the following aspects: First, composite catalysts can enhance the separation of electron-hole pairs and reduce recombination, thereby improving the efficiency of photocatalytic reactions. Second, composite catalysts expand the light absorption range, especially by combining visible-light catalysts with ultraviolet-light catalysts, allowing the catalyst to also function under visible light. Additionally, composite catalysts can increase the generation of reactive oxygen species (such as OH, $O_2^{\cdot -}$) and improve the degradation rate of pollutants. Finally, composite catalysts can enhance the stability of the catalyst, prolonging its service life and preventing catalyst deactivation due to environmental factors. The advantages of composite catalysts include improving photocatalytic efficiency, expanding the light absorption range, enhancing catalyst stability, and increasing the generation of selective and active species. Composite catalysts can also reduce production costs, especially by combining inexpensive materials (such as carbon-based materials) with precious metal catalysts to lower the overall cost of the catalyst. However, composite catalysts also have some drawbacks, such as a complex preparation process, the stability of the catalyst potentially being affected by contamination or deactivation, and the interfacial interactions between different materials in the catalyst, which may reduce catalytic performance. In summary, composite catalysts significantly enhance the performance of photocatalytic degradation of pollutants through synergistic effects, offering high catalytic efficiency, a broad light absorption range, and low production costs. However, they also face challenges such as complex preparation, poor stability, and difficulties in recovery. With further research, optimizing the design and preparation processes of composite catalysts will be key to improving their application effectiveness in the future.

METAL OXIDE-CARBON-BASED COMPOSITE CATALYSTS

Metal oxide-carbon-based composite catalysts have significant advantages in photocatalytic degradation of pollutants. Carbon-based materials such as graphene can effectively promote the separation of photogenerated electron-hole pairs, enhance photocatalytic activity, and expand the visible light absorption range. Metal oxides provide good light absorption and electron transport properties, while carbon-based materials improve the catalyst's stability, corrosion resistance, and electron migration ability, extending the catalyst's lifespan. Zheng Jiahong [20] used a hydrothermal method to prepare Fe_3O_4/CoS/g-C_3N_4 composite catalysts and investigated their degradation efficiency for rhodamine B (RhB) in the PMS/visible light system, comparing different catalysts and conditions. The catalyst exhibited excellent degradation performance, with a degradation rate of 97.5% for a 10 mg/L RhB solution within 5 minutes, and demonstrated a wide pH adaptability (3-11). The optimal PMS and catalyst dosage were determined, with the degradation rate decreasing as RhB concentration increased. Rui Wang [21] successfully prepared WO_3/g-C_3N_4 composite samples using the hydrothermal method. In the photocatalytic degradation experiment of methylene blue (MB), the WO_3/g-CN composite sample achieved a higher MB degradation rate within 50 minutes compared to the single components, with WCN-2 reaching up to 95%. Huijuan Wang [22] used the precipitation method to synthesize nitrogen-doped zinc oxide, palladium-doped zinc oxide, and graphene oxide-containing composite photocatalysts. The study revealed the promoting effect of increased ultrasound power on the degradation of imidacloprid and the synergistic effect of ultrasound pre-treatment. It demonstrated the remarkable

performance of ultrasonic photocatalysis in shortening reaction time and improving degradation efficiency. Xuyang Zheng [3] successfully synthesized graphitized mesoporous carbon (GMC)-TiO_2 nanocomposites using the extended resorcinol-formaldehyde (R-F) method. From an organic chemistry perspective, they established the CIP degradation pathway and proposed new intermediate structures, which contribute to a deeper understanding of the CIP degradation mechanism. Mark Croxall [23] used P25 TiO_2 and g-C_3N_4 as photocatalysts to study the degradation of a mixture of methyl orange (MO) and methylene blue (MB). For the photocatalytic degradation of the mixture, homogeneous photocatalysis may occur due to the specific chemical properties of the added molecules, and its rate may be comparable to traditional heterogeneous photocatalysis.

OTHER CATALYSTS

In addition to the aforementioned catalysts, many innovative catalysts have multiple advantages: First, their high degradation efficiency enables them to effectively treat high concentrations of pollutants. Second, their good cyclic stability ensures that the catalysts can be reused multiple times while maintaining high efficiency. Meanwhile, synergistic effects, such as the combination of ultrasonic assistance and photocatalysis, significantly accelerate the reaction process and increase the degradation rate. Furthermore, some catalysts use inexpensive and renewable materials (such as seashells), demonstrating environmental friendliness and cost-effectiveness, with good economic and sustainability prospects. Maham [24] used waste lemon peel extract (LPE) as a green stabilizer and successfully synthesized novel Gd-doped CaO nanoparticles (Gd-doped CaO NPs) via the hydrothermal method. Nnabuk Okon Eddy [25] used seashells as raw materials and synthesized CaO nanoparticles through multi-step reactions. O_2 oxidation predominantly drives TCN degradation. Adsorption site studies revealed that carbonyl oxygen is the key site for TCN adsorption on CaO-NPs. After adsorption, degradation is achieved through free radical oxidation. Significant progress has been made in photocatalytic degradation technology for pollutants. Metal oxides, precious metals, carbon-based catalysts, and their composite materials have shown excellent performance in improving catalytic efficiency and expanding the light absorption range. Metal oxide catalysts, such as TiO_2, have good stability and low cost, but their light absorption is mainly concentrated in the ultraviolet range, and the issue of electron recombination limits their catalytic efficiency. Precious metal catalysts enhance photocatalytic efficiency, but their high cost and scarcity are major challenges. Carbon-based catalysts improve catalytic activity through excellent conductivity and large specific surface area, but there is still a need to enhance their stability and catalytic efficiency. Precious metal catalysts enhance photocatalytic efficiency, but their high cost and scarcity are major challenges. Carbon-based catalysts improve catalytic activity through excellent conductivity and large specific surface area, but there is still a need to enhance their stability and catalytic efficiency. Composite catalysts improve photocatalytic degradation efficiency through synergistic effects, especially excelling in the degradation of high-concentration pollutants. Future research will focus on optimizing the performance of catalysts, particularly in expanding light absorption range, improving electron-hole separation efficiency, and enhancing catalyst stability. The design of composite catalysts remains an important direction, especially exploring the synergistic effects between different materials. The long-term stability and recyclability of catalysts need to be addressed to support their large-scale application. In addition, the selectivity of catalysts and on-site application validation will also be important topics for future research. With technological advancements, photocatalytic degradation of pollutants will play a greater role in environmental management, especially when combined with other technologies, such as ultrasound and peroxides, to improve treatment efficiency and reduce costs [28].

CONCLUSION AND OUTLOOK

Significant progress has been made in photocatalytic degradation technology for pollutants. Metal oxides, precious metals, carbon-based catalysts, and their composite materials have shown excellent performance in improving catalytic efficiency and expanding the light absorption range. Metal oxide catalysts, such as TiO_2, have good stability and low cost, but their light absorption is mainly concentrated in the ultraviolet range, and the issue of electron recombination limits their catalytic efficiency. Precious metal catalysts enhance photocatalytic efficiency, but their high cost and scarcity are major challenges. Carbon-based catalysts improve catalytic activity through excellent conductivity and large specific surface area, but there is still a need to enhance their stability and catalytic efficiency. Precious metal catalysts enhance photocatalytic efficiency, but their

high cost and scarcity are major challenges. Carbon-based catalysts improve catalytic activity through excellent conductivity and large specific surface area, but there is still a need to enhance their stability and catalytic efficiency. Composite catalysts improve photocatalytic degradation efficiency through synergistic effects, especially excelling in the degradation of high-concentration pollutants. Future research will focus on optimizing the performance of catalysts, particularly in expanding light absorption range, improving electron-hole separation efficiency, and enhancing catalyst stability. The design of composite catalysts remains an important direction, especially exploring the synergistic effects between different materials. The long-term stability and recyclability of catalysts need to be addressed to support their large-scale application. In addition, the selectivity of catalysts and on-site application validation will also be important topics for future research. With technological advancements, photocatalytic degradation of pollutants will play a greater role in environmental management, especially when combined with other technologies, such as ultrasound and peroxides, to improve treatment efficiency and reduce costs.

ACKNOWLEDGMENTS

The study was funded by the National Natural Science Foundation of China (NO.52104397), Open Project of Key Laboratory of Industrial Fluid Energy Conservation and Pollution Control, Ministry of Education (NO. CK-2024-0034) and Natural Science Foundation of Shandong Province of China (NO. ZR2023ME116).

CONFLICTS OF INTEREST

The author declared no conflicts of interest.

REFERENCES

[1] Hubbard R, Brown KP, Kropf A. Action of Light on Visual Pigments [J]. Nature, 1959, 183(4659): 442. https://doi.org/10.1038/183442a0

[2] Qi S, Jiang L, Bin W, *et al*. Direct Z-scheme Bi2MoO6/UiO-66-NH2 heterojunctions for enhanced photocatalytic degradation of ofloxacin and ciprofloxacin under visible light [J]. Applied Catalysis B: Environmental, 2022, 318 https://doi.org/10.1016/j.apcatb.2022.121820

[3] Zheng XY, *et al*. (2018). "Enhanced degradation of ciprofloxacin by graphitized mesoporous carbon (GMC)-TiO₂ nanocomposite: Strong synergy of adsorption-photocatalysis and antibiotics degradation mechanism." Journal of Colloid and Interface Science 527: 202-213. https://doi.org/10.1016/j.jcis.2018.05.054

[4] Ahmed AAZ, Alenazi AN, Almotairy RA, *et al*. Remarkable recycling processes of conjugated polymers with titanium dioxide quantum dots as photocatalysts for photodegradation of hazardous industrial wastewater [J]. Results in Engineering, 2024, 24103412-103412.

[5] Zhikun L, Yifeng X, Lai P, *et al*. A two-stage degradation coupling photocatalysis to microalgae enhances the mineralization of enrofloxacin [J]. Chemosphere, 2022, 293133523-133523.

[6] Dong X, Hailing M. Degradation of rhodamine B in water by ultrasound-assisted TiO2 photocatalysis [J]. Journal of Cleaner Production, 2021, 313 https://doi.org/10.1016/j.jclepro.2021.127758

[7] González-Burciaga LA, *et al*. (2022). "Challenges of TiO₂ heterogeneous photocatalysis on cytostatic compounds degradation: state of the art." Environmental Science and Pollution Research 29(28): 42251-42274. https://doi.org/10.1007/s11356-021-17241-8

[8] Wang X, Jia J, Wang Y. Combination of Photocatalysis with Hydrodynamic Cavitation for Degradation of Tetracycline [J]. Chemical Engineering Journal, 2017, 315274-282. https://doi.org/10.1016/j.cej.2017.01.011

[9] Zoltán Z, Orsolya F, Erzsébet S, *et al*. Degradation of industrial surfactants by photocatalysis combined with ozonation [J]. Environmental science and pollution research international, 2014, 21(19): 11126-34. https://doi.org/10.1007/s11356-014-2527-2

[10] Wang Q, Zhou W, Li C, *et al*. Construction of Bi2MoO6 sheets/NH2-UiO-66(Zr) hetero junction photocatalysts toward enhanced degradation of tetracycline under visible light [J]. Journal of Alloys and Compounds, 2025,1010177589-177589. https://doi.org/10.1016/j.jallcom.2024.177589

[11] Wu C, Zhang J, Wu Y, *et al*. Degradation of phenol in water by the combination of sonolysis and photocatalysis [J]. Desalination and Water Treatment, 2014, 52(10-12): 1911-1918. https://doi.org/10.1080/19443994.2013.795879

[12] Jin C, Wang C, Huang T, *et al*. Hollow amorphous N-doped TiO2 microspheres with uniform shell thickness and high carrier separation efficiency for photocatalytic of high-concentration Cr(VI) [J]. Optical Materials, 2025, 159116516-116516. https://doi.org/10.1016/j.optmat.2024.116516

[13] Yinghui Q, Zhenyu C, Yukuan D, *et al*. H2O2 assisted photocatalysis over Fe-MOF modified BiOBr for degradation of RhB[J].Journal of Chemical Technology & Biotechnology, 2022, 97(10): 2881-2888. https://doi.org/10.1002/jctb.7199

[14] Li Y, Song J, Yang J, *et al*. A novel S-scheme heterojunction based on BiPO4/CdPSe3 for effective photocatalytic degradation of organic pollutants [J]. Journal of Alloys and Compounds, 2025, 1010177491-177491. https://doi.org/10.1016/j.jallcom.2024.177491

[15] 冯海东. 廉价金属掺杂TiO2光催化剂制备与性能研究[D]. 沈阳大学,2024.DOI:10.27692/d.cnki.gsydx.2024.000001.

[16] Gao WW, He PZ, Wang HY, *et al*. Enhanced persulfate-assisted photocatalytic degradation of phenol by Ag/ZnFe2O4 composite[J].Journal of Alloys and Compounds, 2025, 1010177578-177578. https://doi.org/10.1016/j.jallcom.2024.177578

[17] Wang Y, Zhang P, Li F, *et al*. H2O2-assisted Bi3NbO7 loaded on porous carbon for enhancing the photocatalytic degradation of tetracycline[J].Solid State Sciences, 2024, 158107763-107763. https://doi.org/10.1016/j.solidstatesciences.2024.107763

[18] Wang Y, Li M, Ding M, *et al*. Construction of Ag2Mo2O7-loaded graphdiyne S-scheme hetero junction for

photocatalytically coupled peroxydisulfate -activated degradation of 2,4-dichlorophenol [J]. Chemical Engineering Journal, 2025, 503158196-158196. https://doi.org/10.1016/j.cej.2024.158196

[19] 王智远, 田伟光, 余伟, 等. 多孔异质结g-C3N4/TiO2光催化剂的制备及其光催化性能研究[J/OL].功能材料, 1-8[2024-12-22]. http: //kns.cnki. net/kcms/detail/ 50.1099 .th.20241204.1110.046.html.

[20] 郑佳红, 黄植. Fe3O4/CoS/g-C3N4催化剂的制备及降解罗丹明B [J]. 硅酸盐学报, 2024, 52(12): 3748-3760. https://doi:10.14062/j.issn.0454-5648.20240461

[21] Wang R, Fu X, Guo Y, *et al*. WO3/g-C3N4 synergistic photocatalysts for degradation and H2 production [J]. Ceramics International, 2024, 50(24PC): 55714- 55725. https://doi.org/10.1016/j.ceramint.2024.10.442

[22] Wang H, Chu J, Ou H, *et al*. Analysis of TiO2 photocatalysis in a pulsed discharge system for phenol degradation [J]. Journal of Electrostatics, 2009; 67(6): 886-889. https://doi.org/10.1016/j.elstat.2009.07.008

[23] Mark C, Reece L, Cynthia G. Heterogeneous vs homogenous photocatalysis: what dominates in the degradation of methyl orange and methylene blue mixtures? [J]. Photochemical & photobiological sciences: Official journal of the European Photochemistry Association and the European Society for Photobiology, 2023, 22(6): 1463-1474. https://doi.org/10.1007/s43630-023-00390-9

[24] Maham, Muneer I, Cheema NA, *et al*. Hydrothermal synthesis of Gd-doped CaO nanoparticles from lemon peel extract for efficient photocatalytic degradation of methylene blue under UV and sunlight [J].Ceramics International,2024, 50(24PB): 54064-54075. https://doi.org/10.1016/j.ceramint.2024.10.264

[25] Eddy ON, Oladede J, Eze SI, *et al*. Synthesis and characterization of CaO nanoparticles from periwinkle shells for the treatment of tetracycline-contaminated water by adsorption and photocatalyzed degradation [J]. Results in Engineering, 2024, 24103374-103374. https://doi.org/10.1016/j.rineng.2024.103374

[26] SMH, Giridhar M, CKP. Noble metal ionic catalysts [J]. Accounts of chemical research, 2009, 42(6): 704-12. https://doi.org/10.1021/ar800209s

[27] Dal Santo, V. and A. Naldoni (2018). "Titanium Dioxide Photocatalysis." Catalysts 8(12). https://doi.org/10.3390/catal8120591

[28] Yang R, Lingjun K, Yiwen Z, *et al*. Review on the synthesis and activity of iron-based catalyst in catalytic oxidation of refractory organic pollutants in wastewater [J]. Journal of Cleaner Production, 2021, 321 https://doi.org/10.1016/j.jclepro.2021.128924

Received on 25-11-2024 Accepted on 27-12-2024 Published on 30-12-2024

https://doi.org/10.31875/2410-2199.2024.11.10