Research Progress on the Photocatalytic Degradation Performance of Antibiotics by Bismuth-based Photocatalysts

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Abstract. The massive production and extensive use of antibiotics globally have led to a large amount of antibiotic residues entering the environment, threatening both the ecosystem and human health. Bismuth-based photocatalysts have gained significant attention and become a research hotspot in antibiotic degradation due to their strong visible-light absorption, low cost, etc. This study comprehensively summarizes their performance, degradation pathways, and mechanisms in degrading typical antibiotics, comparatively evaluates the band gaps and redox abilities of bismuth-based catalysts and their modified materials (via morphology/structure regulation, heterostructure construction, element doping, etc.), finding that these modifications can enhance catalytic performance effectively. It analyzes the performance and potential mechanisms of bismuth oxides, sulfides, oxyhalides, and bismuth-based metal oxides in antibiotic removal. Experiments show bismuth-based composites outperform single-component photocatalysts in antibiotic degradation, with H^+ playing a major role, and the crystal structure and morphology of bismuth-based catalysts significantly influencing degradation efficiency. Additionally, the study explores the impact of coexisting interfering substances in actual water matrices on photocatalytic ability and coupling processes to enhance degradation. In real wastewater treatment, coexisting substances compete with antibiotics for active sites on the photocatalyst surface, affecting degradation efficiency, while coupling photocatalysis with other technologies (such as ultrasound, electrochemistry) can improve the degradation rate and mineralization degree. Finally, the study summarizes current challenges (including improving catalyst stability, perfecting large-scale preparation technologies, and deepening understanding of degradation mechanisms in complex environments) and future prospects of bismuth-based catalysts for photocatalytic antibiotic degradation. Future research could focus on developing more efficient modification methods, optimizing the preparation process, and deeply investigating degradation mechanisms in complex systems to promote the practical application of bismuth-based photocatalysts in treating antibiotic pollution.

Keywords: Bismuth-based photocatalysts; Antibiotic degradation; Photocatalytic performance; Catalyst modification; Reactive oxygen species.

1. Introduction

With the extensive application of antibiotics in the fields of medicine, animal husbandry, and aquaculture, the problem of antibiotic residues in the environment has become increasingly serious, posing a potential threat to the ecosystem and human health. In the medical field, there is a lot of pollution caused by antibiotics. For example, a large amount of antibiotics are used during the treatment process in hospitals. Some antibiotics that are not absorbed by the human body are excreted through urine and feces and enter the urban sewage pipeline. If the sewage treatment is improper, antibiotics will remain in the environment. At the same time, some medical waste also contains antibiotics, and if the treatment is not standardized, it will also cause pollution.

In addition, the pollution of antibiotics also has a great impact on agricultural farming. In livestock, poultry, and aquaculture, antibiotics are widely used to prevent and treat diseases and promote growth. The discharge of aquaculture wastewater and the improper disposal of livestock and poultry manure have led to a large amount of antibiotics entering the environment.

When using the biological method to degrade antibiotics, the growth and metabolism of microorganisms are easily disturbed by environmental factors such as temperature and pH value. The degradation efficiency is unstable, and there is selectivity for specific antibiotics. The compatibility

of strains in the complex microbial system is poor. The adsorption method has problems such as limited adsorption capacity, selective adsorption, desorption and secondary pollution, and high cost. Although there are solutions such as developing new adsorbents and optimizing the microbial culture conditions, there are still limitations such as high cost and unstable effects, which are difficult to completely overcome.

The adsorption capacity is limited. The adsorption capacity of different adsorbents for specific antibiotics is likely to reach saturation. For example, activated carbon for tetracycline antibiotics. It has the characteristic of selective adsorption. Most adsorbents have obvious adsorption preferences for antibiotics with specific structures. For example, chitosan has a better adsorption effect on positively charged antibiotics. There are problems of desorption and secondary pollution. The adsorbed antibiotics are likely to desorb and return to the environment when the environmental conditions change. For example, the antibiotics adsorbed by montmorillonite will desorb under the influence of pH value. The cost of some highly effective adsorbents is relatively high. For example, metal-organic framework materials (MOFs), and the synthesis cost restricts their large-scale application.

However, there are corresponding solutions to these problems. New composite adsorbents such as the composite of carbon nanotubes and activated carbon can be developed to improve the adsorption capacity. The adsorption selectivity can be enhanced by chemical modification, such as glutaraldehyde cross-linking of chitosan. The desorption conditions can be optimized to avoid secondary pollution. Adsorbents can be prepared from waste biomass and the synthesis process can be optimized to reduce the cost.

2. Types and Structures of Bismuth-based Photocatalysts

2.1. Introduction to Different Types of Bismuth-based Photocatalysts

Among the common bismuth-based photocatalysts, bismuth oxide (Bi_2O_3) has various crystal forms, such as α, β, γ types, etc. The lattice parameters and energy band structures of different crystal forms are different, which affect its photocatalytic performance. For example, [1] Bi_2MoO_6, as the simplest Aurivillius structure compound, is composed of alternating stacking of $(Bi_2O_2)^{2+}$ layers and $(MoO_4)^{2-}$layers. The bandgap of Bi_2MoO_6 is approximately 2.5-2.8 eV, which can respond to visible light and has excellent photocatalytic activity, low cost, non-toxicity, and stable performance. However, Bi_2MoO_6-based catalytic materials have key problems that restrict their industrial applications, such as a high recombination rate of photogenerated [2] . As shown in Fig.1, the preparation of a material and its photocatalytic principle. First, Bi_2O_3 is transformed by calcination at 250°C for 2 hours, and then it reacts with Na_2CO_3 at 60°C for 12 hours to obtain Bi_2MoO_6 and other products. During the photocatalytic process, under the action of an electric field, different materials generate electron-hole pairs, achieving the degradation of phenol and other substances, and generating H_2O and CO_2.

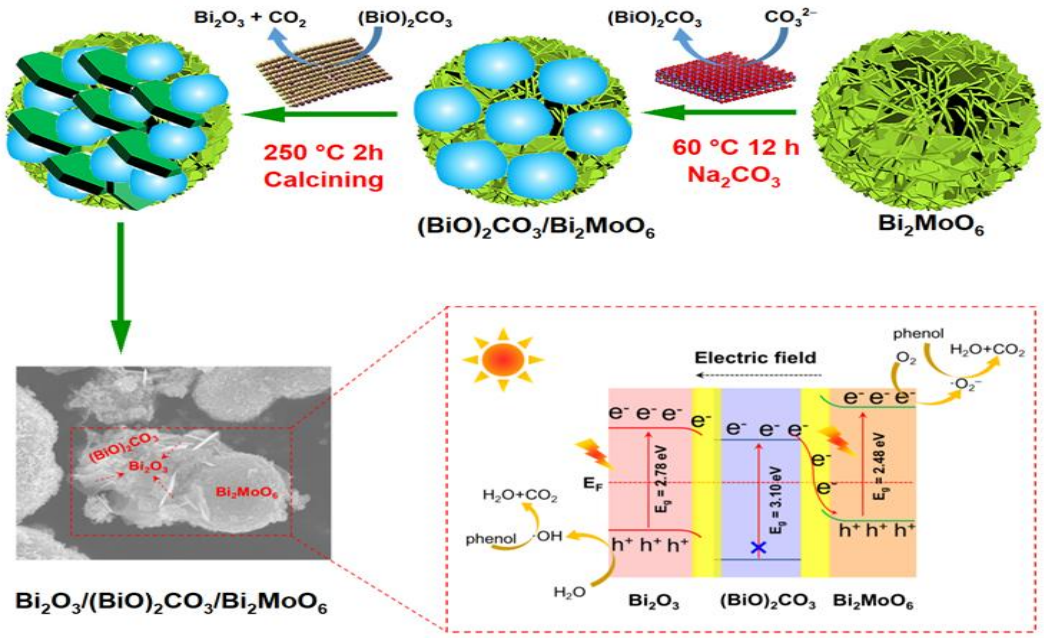

Fig 1. The preparation of a material and its photocatalytic principle.

2.2. Development of New Bismuth-based Photocatalysts

In recent years, bismuth-based composite photocatalysts and bismuth-based photocatalysts with special structures have become research hotspots, significantly promoting the development of the photocatalysis field.

Bismuth-based heterojunction photocatalysts effectively promote the separation of photogenerated carriers by constructing the heterojunction interface of different semiconductor materials. In a heterojunction, there are differences in the energy band structures of different semiconductors, forming a built-in electric field [3]. When illuminated by light, photogenerated electrons and holes migrate to different semiconductors respectively under the action of the built-in electric field, reducing the recombination probability. For example, in the heterojunction constructed by Bi_2WO_6 and TiO_2, the conduction band position of Bi_2WO_6 is higher than that of TiO_2. The photogenerated electrons transfer from the conduction band of Bi_2WO_6 to the conduction band of TiO_2, and the holes migrate in the opposite direction, thus improving the photocatalytic efficiency.

Bismuth-based nanocomposites utilize the unique advantages of the nanostructure to enhance their performance. The nanostructure has a high specific surface area, which can provide more active sites and increase the contact area between the catalyst and the reactants [2]. At the same time, the nanoscale size effect shortens the diffusion distance of photogenerated carriers and accelerates their migration rate [4]. For example, when carbon nanotubes are composited with bismuth-based materials, the good electrical conductivity of carbon nanotubes promotes the transmission of photogenerated carriers and enhances the photocatalytic activity.

As shown in Fig 2, this set of pictures shows a series of experimental results regarding the degradation of antibiotics: Fig (a) and (b) present the change in the concentration of antibiotics over time and the degradation rate constants of different materials under illuminated and dark conditions; Fig(c) - (g) demonstrate the effects of factors such as the types of anions, the concentration of humic acid, the type of water body, the number of cycles, and free radical scavengers on the degradation efficiency of antibiotics; Fig (h) and (i) detect the signal intensities of superoxide radicals and hydroxyl radicals generated by different materials through electron paramagnetic resonance technology. From multiple aspects including the degradation process, influencing factors, and radical generation, the degradation situation of antibiotics and the related mechanisms are comprehensively explored. The BBN-2 sample has the optimal photocatalytic activity for degrading TC. The reaction rate constant (k) value is 0.0139 min^{-1}, which is 0.6 times higher than that of pure BiOBr (0.0085

min^{-1}) and 2.8 times higher than that of C_3N_5 (0.0037 min^{-1}). Meanwhile, it has a strong adaptability to the complex environment in actual water bodies (such as anions like NO_3^-, Cl^-, HCO_3^-, SO_4^{2-}, and organic acids, etc.). After the catalyst is recycled 5 times, it can still maintain good performance, demonstrating excellent stability and reusability. Photoelectrochemical analysis shows that the formation of the BBN heterojunction increases the current density, reduces the impedance, and effectively inhibits the recombination of electron-hole pairs [5].

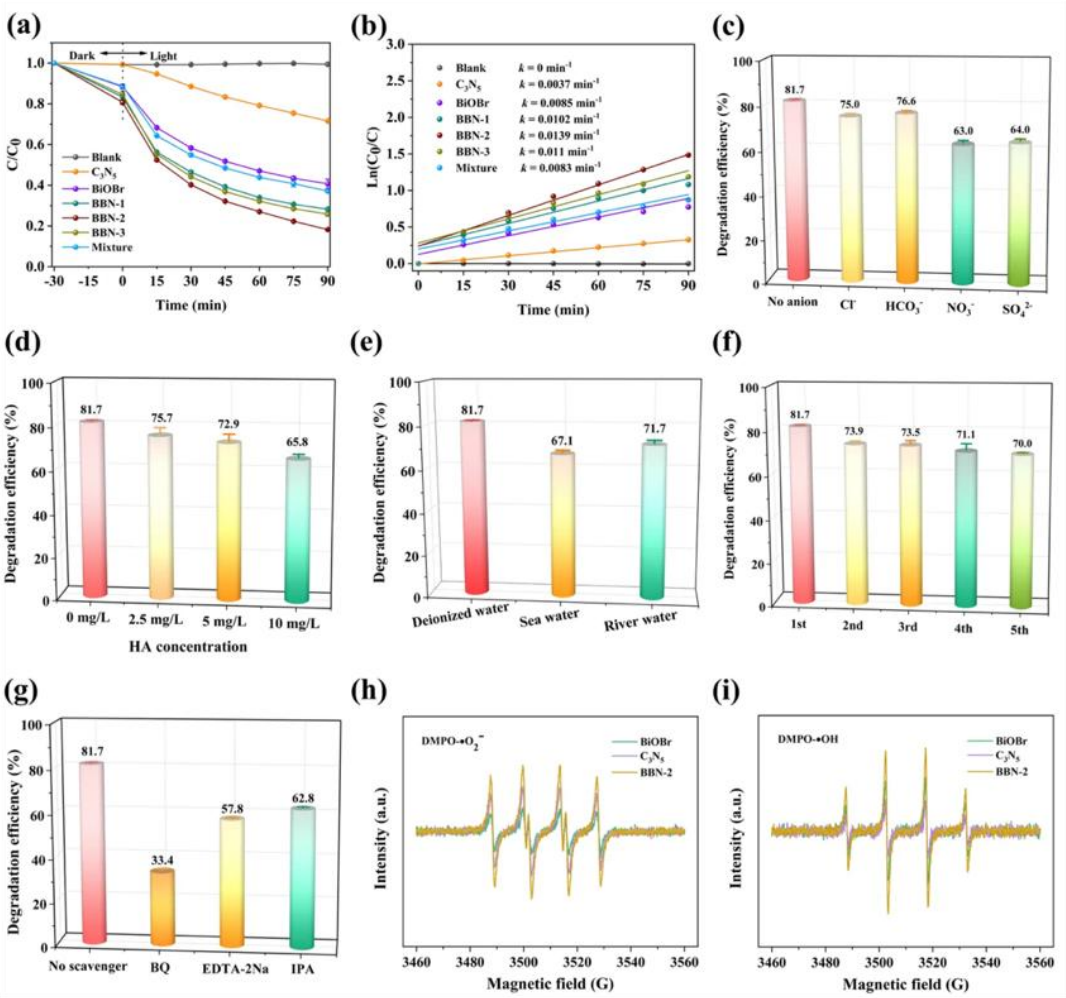

Fig 2. A series of experimental results regarding the degradation of antibiotics.

3. Mechanism of Photocatalytic Degradation of Antibiotics

3.1. Generation and Migration of Photogenerated Carriers

The photocatalytic reaction of bismuth-based photocatalysts starts with the generation of photogenerated carriers. When the energy of the illuminating photons is greater than the energy band gap of the photocatalyst, electrons in the valence band are excited and jump to the conduction band, forming electron-hole pairs. The separation and transfer efficiency of these pairs is the rate-determining step of the catalytic reaction [6]. Photogenerated carriers migrate within the catalyst through channels such as lattice vibrations and defects [7]. However, during the migration process, carriers are prone to recombination, which reduces the photocatalytic efficiency. Therefore, how to promote the migration of carriers and inhibit recombination has become a key issue.

Fig. 3 presents the mechanism of electron-hole pairs in the photocatalytic process of Bi_3O_4Cl and C-doped Bi_3O_4Cl. Firstly, under photoexcitation, due to the weak internal electric field of Bi_3O_4Cl, the separation of electron-hole pairs is limited; while C-doped Bi_3O_4Cl can achieve more effective separation relying on a strong internal electric field. Subsequently, when transferring along the [Bi_3O_4]

or [C_xCl_{1-x}] lamellar layers, the electron-hole pairs in Bi_3O_4Cl are prone to recombination, whereas the recombination probability of C-doped Bi_3O_4Cl is very low. Finally, C-doped Bi_3O_4Cl enables more electrons and holes to reach the surface, greatly improving the efficiency of the photocatalytic reaction. Doping is an important means to regulate the behavior of photogenerated carriers. By doping with metal elements, the electronic structure of bismuth-based photocatalysts can be changed, and impurity energy levels can be introduced. The impurity energy levels can capture photogenerated carriers, prolong their lifetimes, promote the migration of carriers, and improve the photocatalytic efficiency [8]. For example, Liu's research found that for bismuth-based photocatalysts doped with transition metal ions, the separation and migration efficiency of their photogenerated carriers is significantly improved.

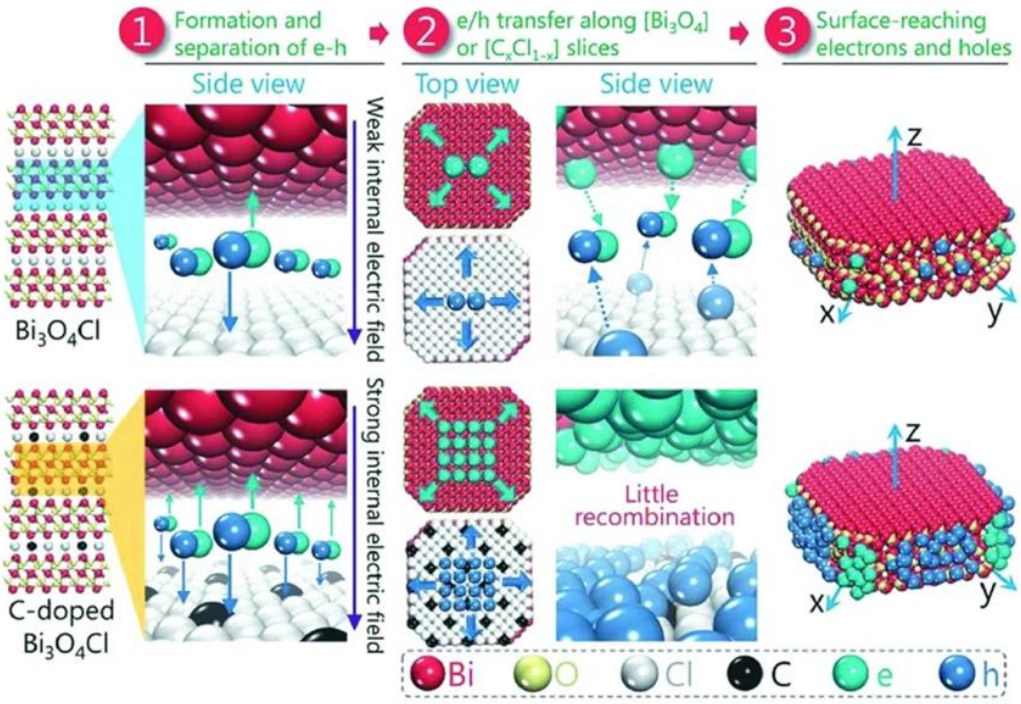

Fig 3. The mechanism of electron-hole pairs in the photocatalytic process of Bi_3O_4Cl and C-doped Bi_3O_4Cl.

Constructing heterojunctions is also an effective strategy to enhance the separation efficiency of photogenerated carriers. When a bismuth-based photocatalyst constructs a heterojunction with other semiconductors, the presence of the built-in electric field guides the directional movement of carriers, reducing the recombination probability [9]. For example, $BiVO_4$ serves as a cocatalyst to construct a $BiVO_4$/CdS Z-scheme heterojunction, which effectively improves the separation efficiency of photogenerated carriers and enhances the photocatalytic activity [10].

3.2. Generation and Function of Active Species

During the photocatalytic degradation of antibiotics, various important active species are generated, mainly including hydroxyl radicals (·OH), superoxide anion radicals ($\cdot O_2^-$), holes (h^+), etc. [11]. Experimental methods such as electron spin resonance technology and theoretical calculations have revealed the generation mechanisms of these active species: photogenerated electrons react with oxygen adsorbed on the catalyst surface to form ·OOH [12].

Different active species have selectivity for the oxidative degradation of different types of antibiotic molecules. Hydroxyl radicals (·OH) have strong oxidizing properties and can oxidize most antibiotic molecules almost non-selectively, being one of the main active species for the photocatalytic degradation of antibiotics [13]. While $\cdot O_2^-$ has a good degradation effect on some antibiotics containing specific functional groups. For example, for antibiotics containing unsaturated bonds or electron-rich groups, $\cdot O_2^-$ can specifically react with them to achieve effective degradation.

4. Research Achievements on the Degradation Performance of Antibiotics by Bismuth-based Photocatalysts

4.1. Degradation Effects on Different Antibiotics

Bismuth-based photocatalysts exhibit good degradation ability towards tetracycline antibiotics [14]. In numerous studies, tetracycline, oxytetracycline, etc. are common research objects. Different bismuth-based photocatalysts have different degradation efficiencies for tetracycline. For example, the degradation efficiency of BiOBr/BCN for tetracycline under visible light is higher than that of Bi_2O_3. This may be attributed to the unique crystal structure and energy band structure of BiOBr, which enables it to more effectively absorb visible light and generate photogenerated carriers, thereby promoting the degradation of tetracycline [15]. Research shows that under certain illumination time and catalyst dosage conditions, BiOBr can degrade tetracycline to a lower concentration within several hours.

For quinolone antibiotics, $BiVO_4$ can effectively degrade norfloxacin and others under specific conditions. $BiVO_4$ has a suitable energy band structure and can absorb light of specific wavelengths, exciting the generation of photogenerated carriers to participate in the degradation reaction of norfloxacin. Experimental parameters have a significant impact on its degradation effect. When the light intensity increases, the photocatalytic reaction rate accelerates because more photons are absorbed and more photogenerated carriers are generated. However, too high a light intensity may lead to the inactivation of active sites on the catalyst surface, inhibiting the degradation reaction [16]. When the catalyst dosage increases within a certain range, the degradation efficiency increases because more active sites participate in the reaction. But excessive use will cause an increase in light scattering, reducing the light utilization efficiency, which is instead unfavorable for degradation [17].

4.2. Factors Affecting Degradation Performance

The crystal structure, for example, plays a crucial role in the transmission path of photogenerated carriers [18]. Different crystal structures will lead to different migration modes and speeds of photogenerated carriers within the catalyst. For example, bismuth-based photocatalysts with a specific crystal plane orientation can enable photogenerated carriers to be more efficiently transported to the catalyst surface to participate in the reaction, thus improving the photocatalytic performance [6]. At the same time, the larger the specific surface area, the more active sites there are. A large specific surface area provides more sites for the adsorption of antibiotic molecules and the photocatalytic reaction, which is conducive to improving the photocatalytic performance. By preparing bismuth-based photocatalysts with nanostructures or porous structures, their specific surface area can be increased, thereby enhancing the degradation ability of antibiotics [19].

The energy band structure determines the absorption range and ability of the photocatalyst to light. Composite photocatalysts have a unique energy band structure that enables bismuth-based photocatalysts to more effectively absorb visible light and broaden the light response range, thus achieving excellent photocatalytic performance [20]. Surface defects can capture photogenerated carriers and inhibit their recombination [21]. Appropriate surface defects can prolong the lifetime of photogenerated carriers, giving them more opportunities to participate in photocatalytic reactions, thereby improving the degradation effect of antibiotics.

Different types of light sources provide different photon energies and intensities, which directly affect the photocatalytic reaction. For example, the photocatalytic activities of bismuth-based photocatalysts under ultraviolet light sources and visible light sources are different. Selecting an appropriate light source type can give full play to the performance of bismuth-based photocatalysts and improve the degradation efficiency of antibiotics. Generally speaking, as the reaction temperature increases, the reaction rate will accelerate because an increase in temperature can increase the activity of molecules and the reaction rate constant. But too high a temperature may lead to changes in the catalyst structure and even inactivation, reducing its service life [22]. Coexisting ions such as Cl^-, NO_3^- may compete with antibiotic molecules for active sites, affecting the degradation effect. The

adsorption of these ions on the catalyst surface will occupy some active sites, reducing the contact opportunities between antibiotic molecules and active sites, thus reducing the degradation efficiency.

The humidity of the external environment will affect the adsorption and reaction processes on the catalyst surface. Appropriate humidity can promote the adsorption of water on the catalyst surface, providing the necessary reactants (such as generating hydroxyl radicals) for the photocatalytic reaction. But too high a humidity may affect the propagation of light and the absorption of light by the catalyst. At the same time, the longer the illumination time, the higher the degradation degree generally is. As the illumination time is extended, more photogenerated carriers are generated and have more opportunities to participate in the degradation reaction of antibiotics. However, too long an illumination time may cause the inactivation of the catalyst. For example, the active species on the catalyst surface are excessively consumed or the catalyst structure changes.

5. Strategies for Improving the Performance of Bismuth-based Photocatalysts

5.1. Material Modification Methods

Material modification is one of the core strategies to enhance the performance of bismuth-based photocatalysts. Doping is a commonly used and effective modification method. On the one hand, the doping of metal elements has a significant effect. For example, the introduction of metal elements such as Fe and Cu can form impurity energy levels in the energy band structure of bismuth-based photocatalysts. These impurity energy levels are like bridges, promoting the generation and migration processes of photogenerated carriers, enabling photogenerated electron-hole pairs to participate in photocatalytic reactions more efficiently. The bismuth-based photocatalyst doped with an appropriate amount of Fe shows a significant improvement in photocatalytic activity compared with the undoped sample when degrading organic pollutants [23]. On the other hand, the doping of non-metal elements also has a unique role. The doping of non-metal elements such as N and S can expand the light response range of the photocatalyst, extending it from the ultraviolet light region to the visible light region. This means that the photocatalyst can make more full use of the visible light part in sunlight, greatly improving the photocatalytic performance [24].

Composite modification is also an important way to improve the performance of bismuth-based photocatalysts. [For the elaboration of the advantages of composite with different materials, more practical application cases can be supplemented. For example, in actual sewage treatment, compared with single photocatalysts, the actual improvement of the degradation effect of composite photocatalysts on antibiotics, as well as the problems and solutions that may be encountered in actual applications. It is better to introduce the synthesis process diagram in the literature.] In actual sewage treatment, composite photocatalysts can often significantly improve the degradation effect of antibiotics compared with single photocatalysts. This is because composite photocatalysts can integrate the advantages of multiple components, enhance light absorption, and promote charge separation and transfer, thereby improving the degradation efficiency. For example, some composite photocatalysts can expand the response range to visible light and enhance the photocatalytic activity. However, there are also many problems in actual applications. First, it is easily interfered by the complex components in sewage. For example, coexisting organic and inorganic substances will compete with antibiotics for photocatalytic active sites, reducing the degradation efficiency. Second, the recovery and reuse of the catalyst are difficult. The separation and recovery of suspended photocatalysts are costly and complex in operation. Third, the photocatalytic reaction rate is relatively slow, making it difficult to meet the rapid treatment requirements of large-scale sewage treatment.

In response to these problems, the following solutions can be adopted: remove some interfering substances in the sewage through pretreatment; develop composite photocatalysts with easy separation characteristics such as magnetism to facilitate recovery; optimize the photocatalytic reaction device, such as using high-efficiency light sources and reasonably designing the reactor structure to increase the reaction rate. For example, composite with other semiconductor materials can construct a heterojunction structure. Taking the composite of Bi_2WO_6 and ZnO as an example,

the two semiconductors have different energy band positions, forming a built-in electric field in the composite system. This built-in electric field can effectively promote the separation of photogenerated carriers and reduce the recombination probability of electron-hole pairs, thus significantly improving the photocatalytic activity. Composite with carbon materials also has significant advantages. Graphene has excellent electrical conductivity and a large specific surface area. When composited with BiOBr, graphene can not only quickly transfer photogenerated carriers but also enrich reactants through its strong adsorption performance, increasing the active sites of the photocatalytic reaction, and thus greatly improving the photocatalytic activity. In addition, preparing nanostructures through morphology control, such as peeling bulk g-C_3N_4 into g-C_3N_4 nanosheets, can greatly increase the specific surface area of the material, shorten the diffusion distance of photogenerated carriers, and effectively improve the photocatalytic performance [25].

5.2. Optimization of Reaction Conditions

In addition to material modification, the optimization of reaction conditions also plays an indispensable role in improving the performance of bismuth-based photocatalysts. The pH value of the solution is one of the key factors affecting the photocatalytic reaction. Different pH values will change the existing forms of antibiotic molecules and the charge properties of the catalyst surface, thus affecting the adsorption and reaction processes between the two [26]. Research has found that under specific pH value conditions, the adsorption amount of bismuth-based photocatalysts for antibiotics increases significantly, thereby improving the photocatalytic degradation efficiency.

The selection of the light source and light intensity is also crucial. Selecting a matching light source according to the light response range of the photocatalyst can ensure that the photocatalyst fully absorbs photon energy and excites photogenerated carriers. At the same time, optimizing the light intensity can avoid the problem of low photocatalytic efficiency caused by too strong or too weak light, thereby improving the photocatalytic efficiency.

In addition, adding cocatalysts (such as noble metals Pt, Au, etc.) and sacrificial agents (such as methanol, ethanol, etc.) is also an effective method to improve the performance of bismuth-based photocatalysts. Cocatalysts can promote the separation of photogenerated carriers [27], while sacrificial agents can consume photogenerated holes and inhibit the recombination of electron-hole pairs, thus improving the degradation efficiency of bismuth-based photocatalysts for antibiotics [28].

6. Challenges and Prospects in Practical Applications

6.1. Problems in Practical Applications

Stability is a major problem faced by bismuth-based photocatalysts in practical applications. Under illumination conditions, photocorrosion is a common problem in the photocatalytic process. Its principle is that the photocatalyst is photoexcited to generate electron-hole pairs. After some of them migrate to the surface, if there are elements with variable valence states in the catalyst itself, they may be oxidized or reduced by the photogenerated carriers, resulting in the destruction of the structure. There are many factors affecting photocorrosion. From the perspective of the catalyst itself, the crystal structure, energy band structure, and surface state are crucial. Catalysts with more crystal defects or a narrow band gap are more prone to photocorrosion. In terms of illumination conditions, high-intensity illumination and light of specific wavelengths will increase the probability of photocorrosion. In the reaction system, oxidants, reductants, and pH values will also have an impact.

Currently, there are various solutions to photocorrosion. Element doping can change the electronic structure of the catalyst and inhibit the recombination of carriers. For example, N-doped TiO_2 can improve the resistance to photocorrosion. Surface modification can prevent corrosive substances from contacting the catalyst surface by wrapping polymers and other methods. Constructing a composite heterojunction structure, such as the TiO_2-CdS heterojunction, can promote the separation of carriers and reduce photocorrosion. Through practical verification, these methods have effectively improved the stability and service life of photocatalysts to a certain extent, providing strong support for the

practical application of photocatalytic technology. At the same time, in the actual environment, there are many impurities, and the problem of poisoning cannot be ignored. These impurities are adsorbed on the surface of the catalyst, occupying key active sites, leading to the inactivation of the catalyst and seriously affecting its photocatalytic performance. It is also difficult to prepare bismuth-based photocatalysts on a large scale. The current preparation process is costly and complex, and it is difficult to meet the needs of large-scale industrial production. This limits the promotion of bismuth-based photocatalysts in practical applications and prevents them from fully playing their role in environmental governance. The complexity of the actual environment also hinders the application of bismuth-based photocatalysts. Multiple pollutants coexist in actual water bodies, and the water quality varies greatly. The interactions between different pollutants may change the reaction pathway, affect the performance of photocatalytic degradation of antibiotics, and increase the uncertainty and complexity of the photocatalytic reaction.

6.2. Future Research Directions and Prospects

Looking ahead, the research on bismuth-based photocatalysts has broad and promising directions. In the development of new bismuth-based photocatalysts, on the one hand, the doping modification with transition metal elements can be attempted. For example, doping the manganese (Mn) element with a special electronic structure into bismuth-based materials, using its multivalent state characteristics to adjust the energy band structure of bismuth-based photocatalysts, and enhancing the absorption and utilization efficiency of light. It is also possible to consider compositing bismuth-based materials with two-dimensional materials, such as graphene with a high specific surface area and excellent electron transport performance. By reasonably regulating the composite ratio and preparation process, a heterojunction structure is constructed to promote the separation and migration of photogenerated carriers, which is expected to greatly improve the photocatalytic activity. In-depth research on the mechanism of photocatalytic reactions, the application of new experimental technologies will be the key. For example, using advanced in-situ spectroscopy technologies, such as in-situ infrared spectroscopy and in-situ Raman spectroscopy, to monitor the intermediate products and chemical bond changes on the surface of the catalyst in real-time during the photocatalytic reaction process, so as to more accurately analyze the reaction pathway.

In terms of theoretical calculations, the application of density functional theory (DFT) calculations can be further expanded. By establishing an accurate atomic model, simulating the generation, migration, and recombination processes of photogenerated carriers, predicting the active sites and reaction kinetics of the catalyst, it provides theoretical guidance for experimental research and accelerates the design and development of new bismuth-based photocatalysts. In addition, at the practical application level, it is also crucial to study how to improve the stability and recyclability of bismuth-based photocatalysts. Surface modification or encapsulation technologies can be explored to enhance the resistance to photocorrosion and poisoning of the catalyst in complex reaction systems. At the same time, developing magnetic bismuth-based photocatalysts or designing structures that are convenient for separation and recovery, so that they can be more efficiently applied to environmental governance fields such as actual sewage treatment and air purification. Strengthening practical application research is also urgent. Designing new photocatalytic reactors to improve the light utilization efficiency and the contact efficiency between the catalyst and pollutants. Actively exploring the coupling of bismuth-based photocatalytic technology with other sewage treatment technologies, for example, combining it with biological treatment technology, giving full play to their respective advantages and making up for each other's deficiencies, promoting the industrial application of bismuth-based photocatalytic degradation of antibiotic technology, and contributing more to actual environmental governance.

7. Conclusion

Bismuth-based photocatalysts have achieved certain results in the field of photocatalytic degradation of antibiotics. Different types of bismuth-based photocatalysts have their own characteristics. The mechanism of photocatalytic degradation has been gradually clarified, the influencing factors of performance have been widely studied.

References

[1] Shen, H. et al. Construction of Ternary Bismuth-Based Heterojunction by Using $(BiO)_2CO_3$ as Electron Bridge for Highly Efficient Degradation of Phenol. Chemistry-A European Journal 29, e202300748 (2023).

[2] Qin, J., An, Y. & Zhang, Y. In Situ Assembled $ZnWO_4$/g-C_3N_4 S-Scheme Heterojunction with Nitrogen Defect for CO_2 Photoreduction. Acta Physico-Chimica Sinica 40, 2408002 (2024).

[3] Liu, Z.-L. et al. Constructing strong built-in electric field in lead-free halide-perovskite-based heterojunction to boost charge separation for efficient CO_2 photoreduction. Applied Catalysis B: Environment and Energy 366, 125012 (2025).

[4] Zhu, S.-C. & Xiao, F.-X. Transition Metal Chalcogenides Quantum Dots: Emerging Building Blocks toward Solar-to-Hydrogen Conversion. ACS Catal. 13, 7269–7309 (2023).

[5] You, C. et al. Improved Photo-Carrier Transfer by an Internal Electric Field in BiOBr/Nrich C_3N_5 3D/2D S-Scheme Heterojunction for Efficiently Photocatalytic Micropollutant Removal. Acta Physico-Chimica Sinica 40, 2407014 (2024).

[6] Yixue, X. et al. Enhanced Photogenerated Carrier Separation and Transport of Bismuth-Based Catalysts by Surface Interface Modulation. Advances in Chemistry 35, 509–518 (2023).

[7] Li, B., Liu, X., Zhu, H., Guan, H. & Guo, R. A Review on Bi_2WO_6-Based Materials for Photocatalytic CO_2 Reduction. Small 20, 2406074 (2024).

[8] Ding, H., Peng, B., Wang, Z. & Han, Q. Advances in Metal or Nonmetal Modification of Bismuth-Based Photocatalysts. Acta Physico-Chimica Sinica 40, 2305048 (2024).

[9] Tian, J. et al. Oxygen vacancy mediated bismuth-based photocatalysts. Advanced Powder Materials 3, 100201 (2024).

[10] Chen, WW., Huang, FF., Qu, QY. et al. Construction of $BiVO_4$/CdS Z-type heterojunction for sunlight-driven degradation of quinolone antibiotics. Rare Met. (2025).

[11] Wang, X. et al. $Cu_2(OH)_3NO_3$/γ-Al_2O_3 catalyzes Fenton-like oxidation for the advanced treatment of effluent organic matter (EfOM) in fermentation pharmaceutical wastewater: The synergy of $Cu_2(OH)_3NO_3$ and γ-Al_2O_3. Water Research 261, 122049 (2024).

[12] Sun, X. et al. Construction of visible-light-response photocatalysis-self-Fenton system for the efficient degradation of amoxicillin based on industrial waste red mud/CdS S-scheme heterojunction. Separation and Purification Technology 324, 124600 (2023).

[13] Zhang, W. et al. Bismuth-rich strategy intensifies the molecular oxygen activation and internal electrical field for the photocatalytic degradation of tetracycline hydrochloride. Chemical Engineering Journal 430, 132963 (2022).

[14] Ma, J. et al. Boosting charge transfer of BiOBr/AgBr S-scheme heterojunctions via interface Br atom co-sharing for enhanced visible-light photocatalytic activity. Green Energy & Environment (2024).

[15] Mohammadi, Z., Sharifnia, S. & Shavisi, Y. Photocatalytic degradation of aqueous ammonia by using TiO_2-ZnO/LECA hybrid photocatalyst. Materials Chemistry and Physics 184, 110–117 (2016).

[16] Bei, L.et al. B-g-C_3N_4/BiOBr Study on Photocatalytic Degradation of Tetracycline Hydrochloride by Composites. Study on Photocatalytic Degradation of Tetracycline Hydrochloride by Composites,2024,47(03):199-207.

[17] Liu, S. et al. Morphology-Controlled Long-Range Photogenerated Charge Carrier Transfer Pathway for Enhanced Photocatalytic Hydrogen Production. Nano Lett. 25, 4596-4604 (2025).

[18] Yuan, M. et al. Facile synthesis of a novel Zn2Ti3O8 aerogel with porous structure for high-efficient degradation of antibiotics under simulated sunlight. Ceramics International 49, 23264–23275 (2023).

[19] Qingfeng, A. et al. Progress in Preparation and Application of BiOBr-based Photocatalytic Materials for Wastewater Treatment. hydrometallurgy,2023,42(06):559-567.

[20] Deng, Y.-H. Identifying and Understanding the Positive Impact of Defects for Optoelectronic Devices. Advanced Sensor Research 3, 2300144 (2024).

[21] Wang, P., Shi, R., Zhao, J. & Zhang, T. Photodriven Methane Conversion on Transition Metal Oxide Catalyst: Recent Progress and Prospects. Advanced Science 11, 2305471 (2024).

[22] Liu, C. et al. Photo-Fenton degradation of tetracycline over Z-scheme Fe-g-C_3N_4/Bi_2WO_6 heterojunctions: Mechanism insight, degradation pathways and DFT calculation. Applied Catalysis B: Environmental 310, 121326 (2022).

[23] Yali, S., et al. Research progress of non-metallic element doped graphite phase carbon nitride photocatalytic materials. Chemical progress,2023,42(10):5299-5309.

[24] Li, J. et al. In situ growing Bi_2MoO_6 on g-C_3N_4 nanosheets with enhanced photocatalytic hydrogen evolution and disinfection of bacteria under visible light irradiation. Journal of Hazardous Materials 321, 183–192 (2017).

[25] Xiang, W., et al. Degradation of tetracycline by persulfate activated cobalt-iron spinel supported by MOFs. Chemical Industry and Engineering,2024,41(03):170-178.

[26] Feng, Y. et al. Noble-Metal-Free Cocatalysts Reinforcing Hole Consumption for Photocatalytic Hydrogen Evolution with Ultrahigh Apparent Quantum Efficiency. Advanced Materials 37, 2412965 (2025).

[27] Xi, N. et al. The critical role of coordination interaction between hole scavenger and $ZnIn_2S_4$ for photocatalytic hydrogen evolution. Nano Energy 136, 110750 (2025).