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Research Progress of Intelligent Light-Responsive Graphene Materials in Industrial Wastewater Treatment

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Abstract. With the rapid advancement of industrialization, the refractory organic pollutants and heavy metal ions contained in industrial wastewater have become a core problem in water environment governance. Both conventional adsorption and conventional semiconductor photocatalytic technologies have obvious limitations in terms of efficiency and sustainability. In recent years, graphene materials have been widely used to construct highly efficient photocatalytic systems due to their excellent electrical and structural properties, and have shown unique advantages in industrial wastewater treatment. This paper systematically reviews the major progress of intelligent photoresponsive graphene materials in recent research, with a focus on their role in S-type heterostructure construction, interfacial electron transport regulation, and the synergistic mechanism of adsorption and photocatalysis coupling. At the same time, the article summarizes typical application scenarios such as smart photoresponsive membrane technology, AI-assisted material screening, and heavy metal reduction-fixation. Based on existing research, this paper further assesses the potential ecological risks of graphene materials and explores the main challenges they face in large-scale preparation and real water treatment. Comprehensive analysis suggests that intelligent design and macroscopic device-ization will be important directions for the future engineering of graphene photocatalytic materials. This review aims to provide references for the research and development of related materials and their environmental applications.

Keywords: Graphene; Industrial wastewater; Photocatalysis; S-type heterojunction; Machine learning

1. Introduction

Water security is always an important foundation for social development and ecological conservation. With the accelerated advancement of industrialization, the wastewater discharged from industries such as chemical engineering, pharmaceuticals and dyeing has become increasingly complex in composition, often containing refractory organic pollutants and heavy metal ions in various valence states. This kind of wastewater is not only highly toxic and colored, but also very poor in biodegradability; If discharged into water bodies without treatment, it will directly damage aquatic ecosystems and pose long-term risks to human health. Therefore, finding treatment technologies that are efficient, environmentally friendly and economical has become one of the core tasks in the field of current environmental science.

Although traditional water treatment technologies have been widely applied, each of them has insurmountable limitations. For example, adsorption is easy to operate but limited by adsorption capacity and the energy consumption of the adsorbent regeneration process; While semiconductor photocatalysis relies on light energy to degrade pollutants, due to the severe recombination of photogenerated carriers, its actual utilization efficiency is often not ideal. In this context, graphene and its derivatives are considered strong candidates for improving photocatalytic systems due to their high electrical conductivity, tunable surface structure and large specific surface area. Research suggests that the introduction of graphene can facilitate interfacial electron transport, and by constructing S-scheme heterojunctions, it helps to improve the separation efficiency of photogenerated carriers, thereby balancing high REDOX potential with stable reactivity [1,2]. In addition, specific functional groups on graphene can enhance the adsorption of contaminants, allowing them to accumulate on the surface and then achieve efficient mineralization under light exposure, thus forming a synergistic mechanism of adsorption and photocatalysis coupling [3].

Although graphene-based photoresponsive materials have shown excellent performance in the laboratory, there are still several key issues to be addressed, including the way the materials are structurally optimized, their suitability in complex real water bodies, and the stability challenges that may be faced when they are engineered to scale up. In line with these research trends, artificial intelligence-assisted material screening and intelligent light-responsive membrane technologies have gained attention in recent years, providing new ideasfor material design and application exploration [4,5]. In this context, this paper systematically reviews the enhancement mechanism, typical application scenarios and environmental risk assessment of graphene photoresponsive systems based on the latest research results from 2022 to 2025, and explores their future development directions, with the aim of providing a reference basis for subsequent material optimization and engineering applications [6].

2. Enhancement mechanisms and interface control strategies

2.1. Deep Analysis of the Electron Transport Mechanism: Experimental Verification of S-type heterojunctions

The core of the photocatalytic system lies in whether photogenerated electrons and holes can be effectively separated and participate in the reaction in a short time. For a long time, type II and type Z heterojunction models have been used to explain the synergistic effects of composites, but they are still limited when dealing with systems that require both strong REDOX capacity and high separation efficiency. The S-scheme heterojunction model proposed in recent years is theoretically more capable of explaining the high activity of some graphene composites, and experimental work has gradually provided strong support for this model.

The B-rGO/$ZnFe_2O_4$ composites constructed by Das et al. are typical cases [1]. By in-situ XPS and Mot-Schottky analysis, they confirmed the presence of a distinct built-in electric field at the interface, which was directional precisely enough to drive the recombination of low-level carriers while retaining electrons and holes with high REDOX potential. Notably, the rate constant of the material in Cr(VI) reduction experiments was more than four times higher than that of the single $ZnFe_2O_4$ material, fully demonstrating the superiority of the S-type mechanism in maintaining reactivity.

Similarly, Sanei et al. obtained composites with coral-like structures by loading α-Fe_2O_3/ZnO on biomaterials derived from rGO. rGO not only improved light absorption in this system [2], but also acted as an electron migration path to effectively delay electron-hole recombination. In the experiment, the catalyst's degradation efficiency for tetracycline (OTC) was close to complete within 90 minutes, and it remained stable even after repeated use. These results once again demonstrate the irreplaceable role of graphene in the construction of highly efficient S-shaped heterojunctions.

2.2. "Adsorption-photocatalysis" synergistic mechanism

In industrial wastewater treatment, pollutant concentrations are typically low, and the efficiency of heterogeneous photocatalytic processes largely depends on the enrichment of pollutants on the catalyst surface. Therefore, a single photocatalytic mechanism often fails to meet the demand for efficient treatment. The "adsorption-photocatalysis" synergistic effect thus becomes an important means of enhancement, in which graphene materials play a key role.

Chen et al. 's research presents a typical system. The three-dimensional graphene /TiO_2 aerogel they prepared has a highly porous structure that enables contaminants to rapidly accumulate on the material surface during the dark reaction phase [3]. Experimental data show that the material can remove a considerable proportion of rhodamine B (RhB) molecules when not exposed to light, and when light is turned on, these adsorbed pollutants are rapidly oxidized and mineralized, achieving high removal rates in a short time. The follow-up work by Zhang et al. further emphasizes that as the pollutants decompose [7], the previously occupied adsorption sites are restored, thus enabling the adsorbent to complete the "in-situ regeneration" driven by light. This feature effectively overcomes the drawback of traditional adsorbents that rely on additional regeneration steps, significantly enhancing the durability of the system.

3. Specific application scenarios and technological breakthroughs

3.1. AI-assisted directed screening of materials

In the face of the complex composition and interwoven reaction pathways in industrial wastewater, the traditional experience-dependent approach to material development is often inefficient. In recent years, artificial intelligence methods such as machine learning have shown significant potential in the screening of photocatalytic materials, providing new ideas for optimizing parameters and shortening the experimental cycle.

Hasanmashaei and Khatamian's research is representative of this direction. Based on the construction of magnetic graphene-based photocatalysts, they developed predictive models for tetracycline degradation using adaptive neural fuzzy reasoning systems (ANFIS) [7]. The model input included key parameters such as catalyst dosage, solution pH and light exposure time, while the output was the degradation rate measured experimentally. Validation results showed that the predicted values of the model were highly consistent with the real experimental data ($R^2 > 0.99$), and the optimal operating conditions could be quickly determined on a limited experimental basis, resulting in a final removal efficiency of 94%. This case shows that through a data-driven approach, experimental design is no longer entirely dependent on trial and error, and researchers are able to lock in efficient material combinations in a shorter time.

Similar predictive work is also seen in Sui et al [8]. They built a database containing a variety of physicochemical parameters, such as specific surface area, band gap, etc., and used the random forest algorithm to identify the key factors influencing the activity of graphene nanocomposites. The optimal doping ratio screened out by the model was then verified experimentally, and the photocurrent response was significantly improved (by about 2.5 times) compared to the control sample. These results further demonstrate that the use of artificial intelligence technology can not only precisely analyze the structure-activity relationship of materials from multi-dimensional physicochemical parameters, thereby avoiding the resource consumption caused by relying on empirical trial and error in traditional experiments, but also provide a new data-driven paradigm for achieving efficient and rational structural design of graphene-based photocatalysts.

3.2. Intelligent photoresponsive membrane technology

Membrane separation technology is widely used in wastewater treatment due to its high selectivity and ease of operation, but membrane fouling remains the main obstacle to its long-term stable operation. In recent years, combining photocatalytic function with membrane materials to use light for self-cleaning has become an effective strategy to solve this problem.

The g-C_3N_4/rGO/PVDF hybrid matrix membrane (MMM) developed by Zhang et al [5]. demonstrates the advantages of this concept. When dealing with water samples containing protein contaminants, the membrane flux decreased significantly after severe contamination, but under visible light irradiation, the active free radicals generated by the catalyst were able to gradually oxidize the organic contaminant layer attached to the membrane surface. In just 30 minutes, the membrane flux almost fully recovered, with a recovery rate of 96.5%. This result indicates that the light-driven self-cleaning strategy can effectively extend the service life of the membrane system.

In addition, in terms of oily wastewater, the graphene-based composite membrane designed by Liu et al. also performed exceptionally well [9]. The membrane exhibits superhydrophilic/underwater superoleophobic properties, making it difficult for oil droplets to adhere to the membrane surface. Meanwhile, the photocatalytic function can further break down dissolved organic pollutants. The dual function of the material not only enhances the separation efficiency but also significantly alleviates the clogging problem of traditional membranes in the treatment of oily wastewater.

3.3. Reduction and fixation of heavy metals

The treatment of heavy metals in industrial wastewater has always been a complex issue because their persistence and toxicity in the environment are often much higher than those of general organic pollutants. The application of graphene photocatalytic systems in heavy metal treatment demonstrates a "reduction-fixation" dual mechanism, making it one of the promising solutions.

For example, Yang et al. used sulfur-doped graphene (S-rGO) as the base material [10], taking advantage of the strong adsorption property of sulfur sites for Hg^{2+}, combined with photogenerated electrons to reduce it, and the products included Hg^0 or HgS. In the experiment, the total removal rate of the system was as high as 99.8%, and the treated water quality met the discharge standards. The results suggest a high synergy between the surface chemistry of the material and the photocatalytic reaction.

In terms of Cr(VI) treatment, the rGO/Bi_2S_3 composite catalyst constructed by Wang et al. was able to reduce the more toxic Cr(VI) to Cr(III) under light exposure [11], which was then captured and precipitated by oxygen-containing functional groups on the graphene surface. This process effectively avoids the risk of re-release of heavy metals, demonstrating the multiple advantages of graphene materials in dealing with highly toxic inorganic pollutants.

4. Environmental safety and feasibility assessment

Although many graphene-based light-responsive materials have performed well in laboratory evaluations in recent years, their potential ecological risks cannot be ignored. Due to the small size and large specific surface area of graphene and its derivatives, their interactions with aquatic organisms after entering the water environment may bring about a series of unexpected effects. Therefore, a comprehensive environmental safety assessment is essential before advancing the engineering application.

Fekete-Kertesz et al. conducted a more systematic study on the chronic toxicity of graphene oxide (GO) in aquatic ecosystems. They selected ecorepresentative species at multiple trophic levels [6], including plankton and benthic organisms, and analyzed the effects of different concentrations of GO exposure. The results showed that when the GO concentration exceeded 1mg/L, the reproductive capacity of large fleas decreased significantly, and the level of oxidative stress in their bodies increased significantly. These findings suggest that if the release of the material cannot be avoided in practical applications, it may cause long-term stress on the ecosystem.

To reduce the risk of material leakage, researchers have begun to explore strategies for immobilizing graphene catalysts on macroscopic carriers. Yuan et al. used a melamine sponge as the support to assemble the graphene photocatalyst into its porous structure [12]. The results showed that the macroscopic assembly maintained more than 90% activity over ten consecutive cycles, and no significant nanomaterial shedding was detected under vigorous stirring conditions. This immobilization strategy not only enhances the material's recovery efficiency but also provides an important safety guarantee for its engineering application.

As can be seen from the above, environmental safety research is gradually moving from single toxicity assessment to risk analysis throughout the entire life cycle of materials, and has become an important prerequisite for promoting the practical application of graphene photocatalysts.

5. Challenges and Developments

Although some progress has been made in the construction of S-shaped heterostructures and in AI-assisted design in recent years, there are still some challenges to achieving large-scale industrial applications. One of the main challenges at present is the complexity of actual water bodies. Many existing studies are based on simulated wastewater, but Zhang et al [7]. Wang et al. Point out that actual wastewater often contains higher concentrations of inorganic salts (such as Cl^- and SO_4^{2-}) and a variety of competing ions [11], which have a significant quenching effect on active radicals in photocatalytic reactions. This leads to a reduction in photocatalytic efficiency in complex water bodies compared to pure water systems. Therefore, how to develop catalysts with stronger anti-interference capabilities has become an important direction of current technological development.

Another urgent problem to be solved is the large-scale preparation of catalysts. Although high-quality heterojunction catalysts have shown excellent performance in the laboratory, their complex preparation process and high cost undoubtedly increase the difficulty of moving the technology from the laboratory to industrial application. Therefore, how to reduce the cost of catalyst preparation and simplify the process remains the key to promoting the industrial application of this technology.

Looking ahead, in order to accelerate the engineering process of the technology, this study suggests focusing on the following aspects: First, there is a need to strengthen the testing of the real environment, especially conducting pilot-scale studies for industrial wastewater with complex matrices to evaluate the long-term stability and performance of the material in practical applications; Secondly, the development of macroscopic devices will be an effective way to address the risk of leakage of nanomaterials. As Yuan et al. have shown [12], developing large-sized composites that are easy to recycle and have high mechanical strength will effectively reduce the potential safety hazards that nanomaterials may bring in practical applications. Finally, it is particularly important to establish a complete lifecycle management system. This involves not only the preparation and use of materials, but also the recycling process after disposal. By assessing the environmental impact of the entire process, ensure that the technology achieves efficient decontamination without imposing an excessive burden on the ecological environment, and ensure the sustainability of the technology application.

6. Conclusion

This article systematically reviews the latest research progress and application potential of intelligent light-responsive graphene materials in the field of industrial wastewater treatment. First, the article delves into the reinforcement mechanism of the material, pointing out that by constructing S-shaped heterojunctions and optimizing interfacial electron transport, the separation efficiency of photogenerated carriers can be significantly improved; At the same time, by taking advantage of the structural properties of graphene to achieve "adsorption-photocatalysis" synergy, the problem of enrichment and mineralization of low-concentration pollutants was effectively solved. Secondly, this paper summarizes the breakthrough applications of this type of material in cutting-edge scenarios such as intelligent photoresponsive membrane self-cleaning, heavy metal "reduction-fixation", and artificial intelligence (AI) -assisted material screening, presenting a complete technical path from microscopic mechanism design to macroscopic performance prediction.

The significance of this review lies not only in clarifying the structure-activity relationship of graphene-based materials in complex wastewater treatment, but also in providing a theoretical basis for breaking through the limitations of traditional water treatment technologies in terms of efficiency and energy consumption. Looking ahead, in order to move the technology from the laboratory to engineering applications, subsequent research should focus on the following directions: First, strengthen the full-process pilot studies in real complex water bodies (containing multiple interfering ions and organic matrices) to verify the anti-interference ability and long-term stability of the materials; Second, efforts should be made to solve the recycling problem of nanomaterials by developing macroscopic device assembly technologies based on porous matrices such as sponges and aerogels to prevent secondary pollution; Third, establish a complete life-cycle environmental risk assessment system to ensure the ecological safety of materials during production, use and disposal while pursuing efficient decontamination.

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