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Engineering Application of New Environmental Treatment Materials in Water Pollution Control

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Abstract. With the increasingly serious problem of water pollution, the application of new environmental governance materials in water pollution control has become a research hotspot. This paper systematically discusses the engineering applications of a variety of novel environmental governance materials in water pollution control, including nanomaterials, biomaterials and composites, and analyzes in detail the mechanisms of physical adsorption, chemical degradation, biodegradation and photocatalysis of these materials in practical applications. In addition, the practical effects of novel materials in water pollution control are demonstrated through cases of river training, industrial wastewater treatment and drinking water purification. Although these materials show remarkable pollutant removal ability, they still face challenges in practical applications such as material stability, economic cost and environmental safety. The paper concludes with an outlook on the future development direction of new environmental control materials and the need for further research, with a view to providing more effective solutions for water pollution control.

Keywords: New environmental control materials, water pollution control, engineering applications, pollutant removal, environmental protection.

1. Iroduction

With the acceleration of industrialization and the expansion of urbanization, the problem of global water pollution has become increasingly serious and has become one of the major environmental problems threatening ecosystems and human health[1]. Traditional methods of controlling water pollution, such as physical, chemical and biological treatment technologies, have alleviated the pollution to a certain extent, but there are still problems such as low treatment efficiency, high cost and secondary pollution[2]. To address these challenges, researchers are gradually turning their attention to new environmental treatment materials, hoping to provide more efficient and sustainable solutions through the unique properties of these materials.

With excellent adsorption capacity, strong degradation performance and good environmental compatibility, new environmental control materials show great potential for application in water pollution control[3]. These materials can not only effectively remove harmful substances in water, such as heavy metals, pesticides, industrial organics, etc., but also actively degrade the pollutants through their own chemical or biological activity to purify the water body[4]. Research and promotion of the application of these new materials can not only improve the efficiency of water pollution control, but also reduce the secondary pollution brought about by traditional control methods, which has important social and environmental significance[5].

In recent years, with the development of materials science and nanotechnology, the types and performance of new environmental control materials have been continuously improved[6]. These materials include nanomaterials, biomaterials, composites, etc., which show excellent performance in water pollution treatment. For example, nanomaterials are capable of adsorbing and degrading pollutants in water in a very short time due to their huge specific surface area and unique surface chemistry, while biomaterials play an important role in pollutant adsorption and biodegradation through their biocompatibility and renewability. However, despite the excellent performance of these materials in laboratory studies, there are still many challenges in practical engineering applications, such as the stability of the materials, economy and environmental protection, which need to be solved.

In this paper, we will systematically discuss the engineering applications of new environmental governance materials in water pollution control. First, the types of new environmental control materials and their characteristics are introduced. Next, the application mechanism of these materials in water pollution control is analyzed, and their effects in river training, industrial wastewater treatment and drinking water purification are demonstrated through actual engineering cases. Finally, the challenges faced in the application of new environmental control materials are discussed, and their future development direction is envisioned, with a view to providing new ideas and references for water pollution control.

2. Types and Characteristics of New Environmental Control Materials

Nanomaterials are one of the important materials in water pollution control due to their huge specific surface area, excellent surface chemical activity and unique physicochemical properties[7]. Common nanomaterials include nano iron, nano titanium dioxide, nano silver and so on. These materials exhibit strong adsorption capacity and catalytic activity in water bodies and can effectively remove heavy metals, pesticides and organic pollutants[8]. For example, nano iron can convert heavy metals into insoluble and non-toxic compounds through reduction reaction, while nano titanium dioxide can catalyze the decomposition of organic pollutants in water under ultraviolet light irradiation. These materials exhibit high efficiency and rapidity in pollutant removal, and thus are widely used in experimental and preliminary engineering applications for water pollution control. Langmuir Adsorption Isotherm Equation:

$$q_e = \frac{q_m K_L C_e}{1+K_L C_e} \tag{1}$$

First-Order Kinetic Model (often used for chemical degradation mechanisms):

$$\ln\left(\frac{C_0}{C_t}\right) = k_1 t \tag{2}$$

Biomaterials, such as biochar, chitosan and algal materials, have gained widespread attention in water pollution treatment due to their renewability, environmental friendliness and low cost[9]. Biochar is prepared by high-temperature cracking of biomass materials and has a rich pore structure and strong adsorption capacity, which is suitable for removing heavy metal ions and organic pollutants from water bodies. Chitosan, on the other hand, is a natural polymer material with good biocompatibility and adsorption capacity, and is commonly used to remove metal ions and dyes and other pollutants from water[10]. In addition, algal materials show great potential in removing nutrients and organic pollutants from water by virtue of their biosorption capacity and photosynthesis. The application of these biomaterials can not only effectively control water pollution, but also reduce the secondary pollution of the environment.

Composite materials are formed by combining the advantages of multiple materials to form a treatment material with multifunctional characteristics, usually including composite membranes, composite adsorbents and composite catalysts. In water pollution control, composite materials can simultaneously play the role of physical adsorption, chemical degradation and biodegradation. For example, polymer-based composite membranes are not only capable of removing suspended particles through physical sieving, but also reacting with pollutants through chemical functional groups, thus improving the removal efficiency of pollutants. In addition, composite catalysts are able to achieve efficient photocatalytic degradation while adsorbing pollutants by combining photocatalytic materials with adsorbents. The multifunctionality of such materials gives them a wide range of applications in water pollution control,showed in Figure 1:

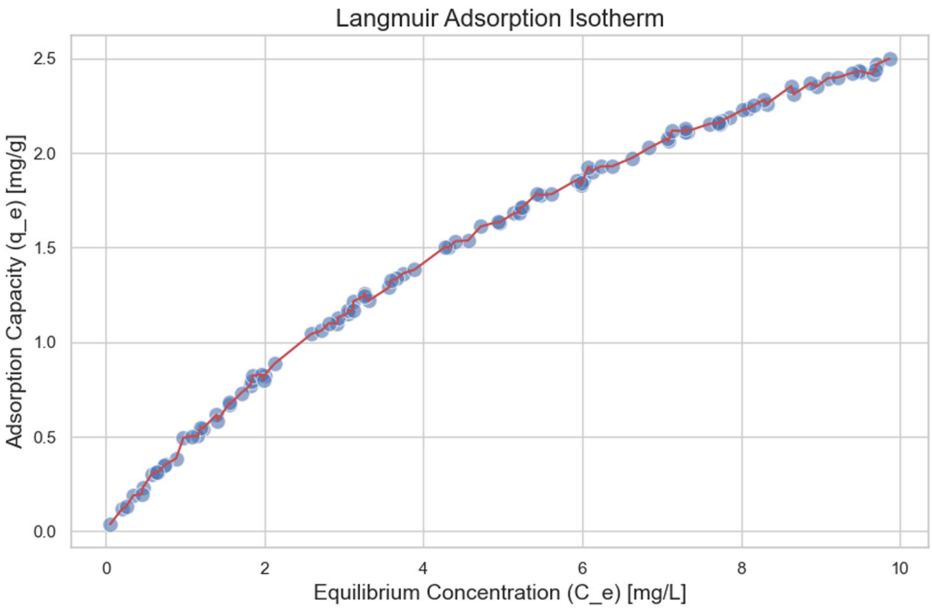

Figure 1. Langmuir Adsorption Isotherm

Functionalized materials are materials that are modified or modified by physical or chemical means to give them specific functions. Such materials have demonstrated excellent selectivity and high efficiency in water pollution control. For example, functionalized magnetic nanomaterials can be rapidly recycled through the action of a magnetic field while maintaining an efficient adsorption capacity for pollutants. Another class of functionalized materials are surface-modified materials, which can significantly improve their selective adsorption capacity for certain types of pollutants by introducing specific functional groups on the surface of the materials. In addition, light-responsive materials are able to stimulate the generation of free radicals under light conditions, thereby degrading organic pollutants. The development and application of these functionalized materials provide more options and possibilities for water pollution control.

3. Mechanisms for the Application of New Environmental Control Materials in Water Pollution Control

The application mechanisms of new environmental control materials in water pollution control mainly include physical adsorption, chemical degradation and photocatalysis and other modes of action. These materials can effectively remove various pollutants from water bodies through their unique physical and chemical properties. The physical adsorption mechanism utilizes the surface area and pore structure of the materials to adsorb pollutants, while the chemical degradation mechanism converts pollutants into harmless substances through the chemical activity of the materials. The photocatalytic mechanism relies on the photocatalytic reaction generated by the material under light to realize the degradation of organic pollutants. The synergistic effect of these three mechanisms makes the new environmental control materials show remarkable effects in water pollution control.

3.1. Physical adsorption mechanism

The physical adsorption mechanism refers to the process by which pollutants are adsorbed by the surface or pores of new environmental treatment materials through physical forces such as intermolecular van der Waals forces, electrostatic attraction or hydrogen bonding. This mechanism does not involve the formation or breaking of chemical bonds, so the adsorption process is usually reversible. When adsorbing pollutants, the new materials rely mainly on their large specific surface area, abundant pore structure and surface active sites, which significantly increase the adsorption capacity of pollutants. Physical adsorption is usually applied to remove pollutants such as organic matter, heavy metal ions and suspended particles from water,showed in Figure 2:

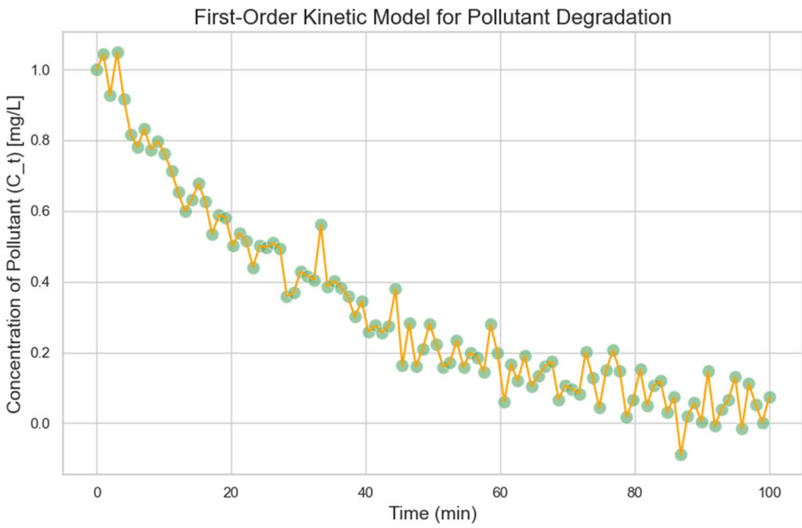

Figure 2. First-Order Kinetic Model for Pollutant Degradation

Nanomaterials exhibit excellent performance in physical adsorption processes due to their large specific surface area and nanoscale pore size. For example, titanium dioxide and iron nanoparticles can not only adsorb pollutants in large quantities through their surface and pore structures, but also enhance the selective adsorption of pollutants through electrostatic attraction or surface-active sites. The size effect of nanomaterials enables them to effectively capture and hold tiny pollution particles in water bodies, significantly improving the efficiency of water purification. In addition, the high surface energy of nanomaterials also contributes to the aggregation of pollutants during the adsorption process, thus accelerating the adsorption process.

Biomaterials, such as biochar and chitosan, exhibit significant advantages in physical adsorption due to their unique pore structure and biocompatibility. Biochar has a high specific surface area and microporous structure, enabling it to effectively adsorb organic pollutants and heavy metal ions in water. Chitosan, as a natural polymer material, is rich in amino and hydroxyl groups on its surface, and these active groups can not only adsorb metal ions through electrostatic attraction, but also organic pollutants through hydrogen bonding. In addition, the renewability and environmental friendliness of biomaterials make them widely used in water pollution treatment.

Composites significantly enhance the effectiveness of physical adsorption by combining the advantages of multiple adsorbent materials. For example, carbon-based composites, by combining activated carbon with metal oxides or polymers, not only provide a large number of adsorption sites, but also enhance selective adsorption of specific pollutants. In addition, magnetic composites are able to achieve rapid material recovery through an applied magnetic field after physical adsorption of pollutants, reducing the risk of secondary contamination. The multifunctionality of the composites allows them to exhibit excellent adsorption performance in complex water pollution treatment, while being both efficient and maneuverable.

3.2. Chemical degradation mechanisms

Chemical degradation mechanism refers to the process of converting pollutants in water bodies into harmless or low-toxicity substances through chemical reactions. New environmental control materials play the role of catalyst or reactant in chemical degradation, effectively decomposing organic pollutants and inorganic pollutants through redox reaction, photocatalytic reaction or electrochemical reaction. Unlike physical adsorption, chemical degradation can completely destroy the chemical structure of pollutants to avoid secondary pollution. This mechanism is widely used to remove organic compounds, heavy metal ions, and persistent pollutants in water that are difficult to degrade.

Nanomaterials show unique advantages in chemical degradation, especially nanometal and metal oxide materials. Nano zero-valent iron (nZVI), a nanomaterial commonly used in water pollution control, has a strong reducing ability and is capable of degrading toxic organic chlorides and reducing heavy metal ions through redox reactions. Titanium dioxide (TiO2) nanomaterials are another important photocatalytic material, which can generate strong oxidizing radicals under ultraviolet light irradiation to rapidly decompose organic pollutants in water. These nanomaterials not only remove pollutants efficiently through chemical degradation mechanisms, but also have the advantages of continuity and stability.

Biomaterials also play an important role in chemical degradation through their unique biochemical properties. For example, chitosan and biochar are not only able to remove pollutants through physical adsorption, but also participate in chemical degradation reactions through their surface functional groups. The amino groups of chitosan can form coordination bonds with heavy metal ions, thus precipitating or converting them into harmless compounds. The surface of the carbon base formed during high-temperature cracking of biochar contains a large number of reactive groups, which can catalyze oxidation reactions and decompose organic pollutants. In addition, certain algal materials are also able to facilitate the biodegradation process of organic pollutants by secreting enzymes such as oxidase.

Composites significantly enhance the efficiency of chemical degradation by integrating the functions of multiple materials. For example, iron-carbon composites combine the reducing power of iron with the adsorption properties of carbon materials to provide excellent results in the removal of organic pollutants and heavy metals from water. These materials are able to break down pollutants into harmless products through redox reactions, while reducing the generation of reaction by-products. Another common class of composites are photocatalytic composites, which are able to enhance the separation efficiency of photogenerated electrons by combining a photocatalyst with a conductive material, thereby increasing the rate of degradation of organic pollutants. The synergistic effect of these composites allows them to exhibit excellent chemical degradation performance in the treatment of complex water pollution.

3.3. Mechanisms of biodegradation

Biodegradation mechanisms are processes that utilize microorganisms or biological enzymes to break down pollutants into simple, harmless substances. This mechanism plays an important role in water pollution treatment, especially in dealing with organic pollutants and persistent organic pollutants (POPs). By promoting or enhancing the activity of microorganisms, new environmental treatment materials provide favorable environmental conditions for biodegradation, thus improving the degradation efficiency of pollutants. The biodegradation mechanism is not only environmentally friendly, but also effective in achieving complete removal of pollutants and reducing the risk of secondary pollution.

Biomaterials have significant advantages in the biodegradation process, especially materials such as biochar and chitosan. Biochar not only serves as a growth substrate for microorganisms, but also adsorbs and concentrates pollutants, providing an efficient reaction platform for the microbial degradation process. Chitosan, through its good biocompatibility and high adsorption, can adsorb organic pollutants in water and work synergistically with microorganisms to accelerate the biodegradation of pollutants. In addition, certain algal materials are also capable of generating oxygen through photosynthesis, which promotes the biodegradation activities of aerobic microorganisms.

Nanomaterials mainly play the role of enhancing microbial activity or providing a reaction interface in biodegradation mechanisms. Nanoparticles can promote the degradation of pollutants by providing a favorable environment for microorganisms to attach and grow through their high surface area and special surface properties. For example, nano-iron enhances microbial degradation of organic pollutants by releasing biodegradable iron ions. Nano titanium dioxide, on the other hand, can generate free radicals that are harmless to microorganisms under photocatalytic conditions, further enhancing the biodegradation efficiency of organic pollutants. These nanomaterials significantly enhance the effectiveness of water pollution treatment by synergizing with microorganisms.

Composite materials exhibit multifunctionality in biodegradation and are able to provide multiple roles such as adsorption, catalysis and biodegradation at the same time. For example, magnetic biochar composites not only have excellent adsorption properties, but are also capable of accelerating the biodegradation process of pollutants by promoting the growth and metabolism of microorganisms through active groups on their surfaces. Another common type of composites is enzyme immobilized materials, which can significantly improve the stability and reaction efficiency of enzymes by immobilizing them on the surface or in the pores of the materials, thus realizing the efficient degradation of organic pollutants. These composites not only have excellent degradation effect in biodegradation mechanism, but also can maintain their activity and function for a long time.

4. Challenges in the Application of New Environmental Control Materials

Novel environmental control materials have shown excellent results in water pollution control, but their high cost is still one of the main obstacles to their widespread application. Many efficient nanomaterials and composites are complicated to manufacture and expensive raw materials make large-scale application difficult. In addition, the sustainability of the production process of the materials and their disposal after disposal are also important factors to be considered. How to reduce the production cost and enhance the environmental friendliness of materials while maintaining their high efficiency is an important challenge in current research.

The stability and longevity of new environmental control materials is also a key issue. In practical application, these materials may be affected by the environment of the water body, such as pH value, temperature, pollutant concentration, etc., leading to a decrease in their performance or failure. Especially during long-term use, the materials may suffer from aging, structural changes, or adsorption saturation, thus reducing their treatment effect. How to improve the durability of the materials and ensure that they maintain their efficient pollutant removal ability in complex environments is an area that requires in-depth research.

New materials may pose a risk of secondary pollution during their application. For example, some nanomaterials may release particles or chemicals in water bodies that are harmful to the environment or living organisms, leading to new pollution problems. In addition, some materials may produce by-products during the degradation of pollutants, and the toxicity and ecological impacts of these by-products need to be carefully assessed. How to ensure that materials are effective in removing pollutants while avoiding the creation of new environmental problems is one of the challenges that must be faced in the application of materials.

While laboratory studies have demonstrated the excellent pollutant removal efficacy of novel environmental treatment materials, the application of these materials to large-scale water treatment still faces the challenge of technology translation. This involves not only material preparation and process optimization, but also how to effectively translate laboratory results into viable industrial solutions. In addition, in actual water treatment, different types of pollutants and complex environmental conditions put higher requirements on the materials, and how to realize the efficient application of the materials in actual projects and ensure their stable operation for a long period of time is an urgent problem to be solved.

5. Conclusion

New environmental treatment materials have demonstrated great potential and advantages in water pollution control. Through various mechanisms, such as physical adsorption, chemical degradation and biodegradation, these materials can efficiently remove various harmful pollutants and significantly improve water quality. However, in the process of application, these materials still face a series of challenges, such as cost, stability, secondary pollution, and technology conversion. Future research should focus on optimizing the performance of the materials, reducing production and application costs, and ensuring their safety and sustainability in the real environment. With the continuous progress of science and technology, new environmental control materials are expected to play a more important role in water pollution control, providing strong support for the realization of environmental protection and sustainable development goals.

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