Proceedings of ICEGEE 2026 Symposuim: AI-Based Medicine and Biological Data Analysis
DOI: 10.54254/2753-8818/2026.AU33356

Efficient Removal and Resource Utilization of Microplastics in Aquatic Environment by Biomass-derived Functional Carbon

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Abstract. This study focuses on the global environmental challenge of microplastic pollution in aquatic environments, using biomass-derived functionalized carbon as the core research material. It systematically explores the preparation and functionalization modification techniques, microplastic removal efficiency and mechanism, as well as the resource utilization pathways after adsorption. By analyzing the limitations of existing microplastics treatment technologies and exploring the material advantages of biomass functional carbon, people have identified key technical points for the preparation and modification of functional carbon. People have revealed the multi-mechanism synergistic effect of its adsorption of microplastics and explored resource utilization pathways such as soil improvement, catalyst carrier, and pyrolysis energy conversion after adsorption. Research has found that biomass-derived functional carbon exhibits significant advantages in the field of microplastics removal. However, it still faces challenges such as high costs for large-scale production, uncertain application effects in complex water bodies, and unclear environmental risks associated with resource utilization. This study provides novel materials and technical insights for the efficient and environmentally friendly management of microplastics pollution in aquatic environments. Further efforts are needed to advance material research and engineering applications, aiming to achieve technological industrialization.

Keywords: Microplastics, biochar, aquatic environment

1. Introduction

Microplastics, as a new type of persistent pollutant with a particle size less than 5mm, have become a prominent challenge in the global management of freshwater environments [1]. Their pollution is characterized by widespread distribution, high concentration, and difficulty in degradation.According to existing monitoring data, the concentration of microplastics in global freshwater bodies can reach up to 4.27 million particles per cubic meter [2], covering rivers, lakes, and remote protected areas, with a diffusion range far exceeding expectations.Compared to conventional pollutants, microplastics can bioaccumulate along the food chain, penetrate human physiological barriers to enter the bloodstream and brain tissue, and adsorb heavy metals and

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polycyclic aromatic hydrocarbons to form compound pollution [2,3], posing dual risks of ecological damage and health hazards. Therefore, it is of great practical necessity to conduct systematic research on the prevention and control of microplastics in freshwater environments.

Currently, the removal of microplastics in the water environment primarily relies on three major technical systems: physical, chemical, and biological [4,5]. While various technologies have achieved certain application effectiveness, they all exhibit significant shortcomings.Physical methods are convenient to operate, but membrane filtration is costly and flocculation and sedimentation tend to produce secondary sludge; chemical methods can degrade microplastics, but they are prone to generating toxic by-products, damaging aquatic ecosystems; biological methods are green and low-carbon, but they have low degradation efficiency, require long periods, and are greatly influenced by environmental factors.In general, the traditional technology is not satisfactory in the three main aspects of efficiency, economy and environmental protection, showing the defect of treating the symptoms rather than the root cause. There is an urgent need for new environmentally friendly alternative materials and technologies in this field.

Biomass derived functional carbon is prepared from agricultural and forestry wastes, which has developed porous structure, large specific surface area and rich active functional groups on the surface. It has excellent adsorption capacity for microplastics [3,6]. In addition, the raw materials are easy to obtain, the cost is low, and there is no secondary pollution. Therefore, it has become a new direction in the field of microplastic management [4,6]. This review focuses on the preparation, modification and application of this material, which not only fills the research gap in this field, improves the green management theory of micro plastics, but also provides a feasible technical reference for the prevention and control of actual water pollution, and promotes the collaborative implementation of biomass resource utilization and micro plastics management.

2. Research progress on the preparation and functional modification technology of biomass-derived functional carbon

2.1. Progress in the preparation process

At the current stage, the preparation process of biomass-derived functional carbon has achieved leapfrog optimization. The core breakthroughs are concentrated in three major dimensions: precise control of key preparation parameters, upgrading of raw material pretreatment technology, and development of new green preparation pathways. These advancements have comprehensively overcome the limitations of traditional preparation processes, such as low efficiency, uncontrollable performance, and high cost. On the one hand, scholars both domestically and internationally have systematically clarified the deep influence mechanisms of core parameters such as carbonization temperature, heating rate, holding time, and reaction atmosphere conditions on the development of pore structure, specific surface area size, and the types and contents of surface functional groups in functional carbons through multiple sets of orthogonal experiments and mechanism analysis [3,5]. They have thoroughly achieved the full-chain directional matching of "parameter regulation-structural design-performance optimization", enabling the targeted preparation of functional carbon materials with exclusive pore structures and suitable surface properties according to the removal needs of microplastics with different particle sizes and chemical properties in aqueous environments, thereby significantly enhancing the targeted adsorption capacity of the materials; On the other hand, by optimizing and upgrading the integrated pretreatment processes such as crushing, screening, acid washing for impurity removal, and pre-carbonization, inorganic ash, impurities, and volatile useless components in biomass raw materials are effectively removed. This not only

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significantly improves the efficiency of subsequent pyrolysis and carbonization reaction, but also improves the internal basic structure of raw materials, laying a solid foundation for the full development of multi-stage through holes in the carbonization process; In addition, new green processes such as microwave carbonization, low-temperature plasma carbonization and catalytic rapid carbonization have also been gradually applied [5,6]. Compared with traditional pyrolysis and carbonization, these new processes significantly shorten the reaction cycle, reduce energy consumption and production costs, and avoid the generation of toxic by-products. They truly realize the rapid, efficient and green preparation of functional carbon, and comprehensively improve the overall preparation efficiency and environmental benefits.

2.2. Progress in modification technology

The current functional carbon modification technology has completely overcome the performance bottleneck of a single modification method, and turned to the direction of multi Technology Collaborative Optimization and targeted precise regulation, which has comprehensively improved the comprehensive adsorption capacity of the materials for micro plastics. Physical activation technology realizes fine iteration by accurately controlling core parameters such as activator type and dosage, activation temperature, activation residence time and so on. It directionally optimizes the proportion and pore size distribution of micropores, mesopores and macropores in functional carbon, perfectly matches the pore capture requirements of microplastics with different sizes, and thus enhances the interception and fixation effect of physical adsorption [5]; Chemical modification has gradually changed from single modification to composite synergistic modification. New processes such as acid-base composite modification, oxidation load coupling modification and surface grafting modification have gradually matured [7,8]. Compared with the single acid-base modification or oxidation modification, the composite modification process can achieve the goal of pore structure expansion, pore volume enhancement and surface oxygen, nitrogen, sulfur and other active functional groups modification at the same time, taking into account the physical and chemical adsorption effects, which significantly widens the adsorption compatibility range of the material for various micro plastics; Load modification technology can achieve highly accurate and targeted regulation. It can accurately select metal ions such as iron, zinc, magnesium, nano metal oxides or carbon based nano materials as the load carrier according to the surface charge characteristics and molecular structure differences of micro plastics. This technology realizes the uniform dispersion and quantitative loading of the load carrier, and enhances the electrostatic attraction, π - π stacking and other interactions between functional carbon and micro plastics [9,10]. This further improves the targeted adsorption and efficient binding ability of the target micro plastics. The modified functional carbon can better adapt to the complex treatment needs of the actual water body.

3. Efficacy and mechanism of action of biomass-derived functional carbon in removing microplastics

3.1. Capability removal

With its unique material characteristics, biomass derived functional carbon shows excellent removal efficiency of micro plastics in the water environment [2,6]. It has high overall removal rate and large adsorption capacity, and is suitable for all kinds of fresh water scenes. In addition, it operates stably, does not release secondary pollution, and takes into account the treatment effect and environmental

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friendliness, which is far superior to the traditional inefficient treatment technology; The core mechanism is the dual synergy of physical adsorption and chemical adsorption [2,3]. On the one hand, it relies on its well-developed interconnected multi-stage pore structure and super large specific surface area to realize the physical interception and fixation of micro plastic particles through pore filling and van der Waals force. The matching degree of pore size and particle size of microplastics directly determines the physical capture effect. On the other hand, it relies on the rich oxygen-containing functional groups on its surface and the active groups introduced after modification, and uses a variety of chemical forces such as electrostatic attraction, hydrophobic binding and π - π stacking to achieve targeted adsorption and binding of different types of micro plastics [3,8]. These two adsorption mechanisms complement and cooperate with each other to ensure efficient capture and separation of microplastics, while enhancing adsorption stability and adapting to the complex actual water environment, which fully demonstrates the practical efficacy of the material in the field of microplastics processing.

3.2. Mechanism of action

Using biomass derived functional carbon to remove micro plastics in water is a typical "adsorption separation" integrated treatment technology [4,5]. The core of this technology lies in the developed porous structure and rich surface functional groups of the material itself. Through the dual synergy of physical adsorption and chemical adsorption, the efficient capture, fixation and separation of micro plastic particles in water can be realized. In this process, the physical adsorption is centered on the pore filling effect and assisted by the van der Waals force [2,3]. The micropores, mesopores and macropores of the functional carbon are connected with each other to form a three-dimensional porous network, so that the microplastics particles can enter the pores and be captured in the flow process. At the same time, van der Waals force further enhanced the stability of particle adsorption. The efficiency of the process is mainly determined by the specific surface area and pore size distribution of the material, which must closely match the particle size of the microplastics; Chemisorption is centered on electrostatic and hydrophobic interactions, supplemented byπ-πstacking and complexation [7,8]. The inherent oxygen-containing functional groups (such as hydroxyl and carboxyl) on the surface of functional carbon and the active groups (such as amino) introduced after modification can generate electrostatic attraction with microplastics through charge difference. The surface hydrophobic region can also be targeted and combined with hydrophobic microplastics. For micro plastics containing aromatic rings,π-πstacking will also occur. The effectiveness of chemisorption mainly depends on the type, content and charge properties of surface functional groups, which are highly matched with the chemical properties of microplastics. In the actual water body, physical adsorption and chemical adsorption complement and cooperate with each other, comprehensively improving the removal efficiency, adsorption capacity and operation stability of microplastics, making this technology an excellent alternative to the traditional treatment methods.

3.3. Controversies and existing issues related to functional carbon adsorption of microplastics

At present, there is no unified understanding of the main mechanism of functional carbon adsorption of microplastics in this field. Due to the different types of microplastics, material structures and aquatic environment, some studies show that physical adsorption (mainly through pore filling) is the core mechanism, while other studies emphasize chemical adsorption based on electrostatic and hydrophobic interactions [2,3]. In addition, there is no unified quantitative characterization method

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for the synergy law of micro forces, and the theoretical system is not yet perfect.Firstly, there is insufficient adaptability to actual water bodies. Components such as suspended solids and dissolved organic matter in natural water bodies compete for adsorption sites, but systematic research on their interference mechanisms and regulation methods is lacking [4,5];secondly, there are shortcomings in material regeneration technology. Existing methods such as thermal regeneration and chemical regeneration either require high energy consumption, damage the material structure, or are prone to secondary pollution. There is a lack of efficient, mild, and low-cost regeneration solutions [6,11];thirdly, the engineering application lags behind. Most research remains at the laboratory simulation stage, with the on-site application effects unverified.In addition, the lack of standardized batching, recycling and engineering equipment limits the implementation and transformation of this technology.

4. Research on resource utilization of functional carbon after adsorbing microplastics

4.1. Principles and connotations of resource utilization

After being saturated with adsorbed microplastics, biomass-derived functional carbon still retains a complete pore structure, a certain specific surface area, and surface functional groups, providing a material basis for resource recovery and reuse [3,11].This type of resource utilization is centered around the core concept of "managing waste with waste and recycling resources". It treats saturated functional carbon as a secondary resource through physical, chemical, or biological means. While achieving material value regeneration and recycling, it also achieves stable fixation or harmless degradation of microplastics, preventing saturated carbon from becoming secondary solid waste [11]. It is a key link in constructing a closed-loop management system for the entire process of microplastic pollution, fully embodying the concept of green, low-carbon, and circular development.

4.2. Research progress on resource utilization

The resource utilization of adsorption-saturated functional carbon has emerged as a research hotspot in the field of microplastics management in recent years. Existing studies have clarified the evolution patterns of material properties and explored multiple feasible utilization pathways.Microscopic characterization confirmed that only a portion of the pores in the functional carbon were filled after adsorption, resulting in a slight decrease in specific surface area. There were no significant changes in surface functional groups and charge properties, retaining the core application foundation [3,11];currently, three mainstream utilization pathways have emerged, namely, as soil conditioners to improve soil structure, enhance water and nutrient retention capacity, and immobilize microplastics; as catalyst carriers relying on porous structures to enhance catalytic efficiency and stability; and as pyrolysis feedstocks to achieve energy recovery and simultaneous degradation of microplastics [11,12];Laboratory verification indicates that this material, when used as a soil conditioner, can enhance soil water retention capacity by over 20%. Furthermore, under pyrolysis conditions, the degradation rate of microplastics exceeds 95% [11]. The feasibility of its application has been preliminarily confirmed.

4.3. Practical application scenarios and promotion prospects

This resource utilization model can be widely applied to various scenarios such as advanced treatment of tail water from wastewater treatment plants, ecological restoration of river and lake basins, and decentralized water body management in rural areas [6,11]. It enables the on-site

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resource utilization of agricultural and forestry waste, establishing a full-chain closed-loop model of "waste - functional carbon - pollution control - resource regeneration". This effectively reduces the overall cost of microplastic management and promotes the coordinated development of solid waste resource utilization and comprehensive water environment management. Overall, this technology possesses strong feasibility for practical application. If challenges related to long-term environmental risk management and engineering adaptability are overcome in the future, it can quickly transition from basic laboratory research to practical engineering and large-scale applications, further enhancing the comprehensive treatment system for microplastic pollution.

4.4. Research controversies and existing issues

Currently, there are still two core controversies in the field of reusing functional carbon after adsorbing microplastics, which restrict the large-scale promotion of the technology. Firstly, the long-term environmental risks associated with soil amendment applications are not yet clear. While they can effectively immobilize microplastics in the short term, the natural degradation cycle of microplastics is extremely long. There is a lack of long-term field-based experimental data on their long-term release, migration, and ecological impacts, leading to divergent views in the academic community [11];secondly, the long-term performance and stability of the catalyst carrier need to be verified. The current research is limited to short-term laboratory experiments. The effect of microplastics on material structure, catalytic efficiency and the formation of by-products in the long-term catalytic process is not clear, and further systematic verification is needed [11].

In addition to the above controversial points, the resource utilization technology also faces many practical bottlenecks in the implementation process, which directly hinders its industrialization and standardization development. On the one hand, the existing research only stays at the stage of small-scale laboratory verification, lacking systematic evaluation of technical economy and practical feasibility. Neither quantitative analysis of the cost input and output benefits of various utilization paths nor consideration of the actual conditions such as operation difficulty, site and equipment compatibility in combination with the actual scene have led to the difficulty of technology transformation; On the other hand, the industry has not yet established a unified environmental risk assessment system, lacking evaluation indicators, control thresholds and regulatory standards for different utilization ways [11]. There is no clear basis for either the limit of soil addition, the limit of micro plastic content, or the requirements of catalytic process release and by-product emission. This makes it difficult to achieve precise risk control in the whole process, and also hinders the promotion of the application of standardization and standardization technology, which virtually increases the risk of secondary pollution [12].

5. Conclusion

Future research on biomass derived functional carbon in the field of micro plastic management should focus on the innovation of composite modification technology and the development of new green raw materials and processes, aiming to create new functional carbon materials with high adsorption efficiency, low cost and environmental protection. Secondly, it is necessary to deeply analyze the adsorption mechanism and environmental behavior of materials in the actual complex water, and build a quantitative kinetic model to provide scientific support for field application. At the same time, it is necessary to optimize the utilization path of high-value resources that absorb saturated functional carbon, establish a comprehensive environmental risk assessment and control system, and balance the utilization efficiency and ecological security. Finally, people need to

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promote the transformation of technology from laboratory to engineering application, develop standardized processes and equipment, establish comprehensive technical specifications for the whole process, accelerate the industrialization process, and truly realize the long-term, green and low-cost comprehensive treatment of micro plastic pollution.

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