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Discussion on the Mechanisms and Applications of Biochar in Antibiotic Adsorption and Degradation

Yujie Liu

Faculty of Resources and Environmental Science, Hubei University, Wuhan, China
lyj1931684298@outlook.com

Abstract. As a common emerging pollutant, antibiotics persist in water and soil worldwide, promoting the spread of resistance genes and threatening ecosystems and human health. Traditional methods are costly, inefficient, and prone to secondary pollution, creating an urgent need for green, efficient alternatives. Biochar, made from agricultural and forestry wastes via pyrolysis, features a porous structure, abundant functional groups, and good tunability, making it highly promising for antibiotic pollution remediation.This paper systematically reviews the preparation, modification methods and key physicochemical properties of biochar, and deeply analyzes its adsorption and degradation mechanisms toward antibiotics. It confirms that the synergistic effects of pore filling, π-π conjugation, electrostatic attraction, hydrogen bonding and other interactions, as well as catalytic oxidation by reactive oxygen species, are the key to efficient antibiotic removal, especially for tetracycline antibiotics. The application effects of biochar in wastewater treatment, soil remediation and other scenarios are also summarized, and the challenges in practical application are pointed out, including matrix interference, material stability and intermediate toxicity. This review provides support for the theoretical improvement and engineering application of biochar-based technologies, and promotes the coordinated development of resource utilization of agricultural and forestry wastes and green remediation of antibiotic pollution.

Keywords: Biochar, antibiotics, adsorption mechanism, degradation mechanism

1. Introduction

In recent years, the frequent detection of antibiotics in environmental media such as water and soil has become a regional environmental issue, particularly with residues in aquaculture wastewater, pharmaceutical effluents, and municipal sewage being the most prominent. These pollutants are persistent in the environment and bioaccumulative, and long-term residues can accelerate the spread of resistance genes, disrupt ecological community structures, and threaten the safety of drinking water and the quality of agricultural products. In traditional treatment technologies, physical adsorption is easily saturated, chemical oxidation consumes a large amount of reagents, and biological methods have limited removal of hard-to-degrade antibiotics, making it difficult to meet pollution control requirements in complex scenarios. The development of green and efficient remediation materials and technologies is urgent. Biochar, prepared from agricultural and forestry

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waste, has characteristics such as well-developed porosity, abundant functional groups, and strong stability, showing significant advantages in the treatment of antibiotic pollution and becoming a research hotspot in this field [1, 2].

Currently, researchers both domestically and internationally have carried out various studies on the preparation, modification and adsorption removal of antibiotics by biochar which has confirmed that pyrolysis processes and modification methods can effectively control the microstructure and surface properties of biochar and greatly increase its adsorption and catalytic removal of antibiotics [3, 4]. Nevertheless, the majority of available research only discusses the adsorption or degradation process, without a systematic description of the inherent mechanism of their synergistic effect; on the other hand, the researches on such issues like the performance of applications in the actual environmental system, stability of the material, or the risks of intermediate products are in the deficit, and it is hard to justify the engineering promotion of biochar technology.

The two main aspects reviewed in this article are the synergistic mechanisms of biochar in the adsorption and degradation of antibiotics, and the engineering applications of biochar in practice. It has methodically described the relationship between biochar preparation modifications and the physicochemical properties, critically examined the combined processes of adsorption and degradation, summarized its use efficiency in real-life situations like water treatment and soil cleanup, and has given the cutting edges in research and future development trends. The purpose of this review is not only to supplement the theoretical setting of the studies on the mechanistic of biochar-based antibiotic pollution control technologies but also to also offer practical references in the large-scale application of the technologies in the treatment of the actual pollution as well as contribute to the organization of the use of agricultural and forestry waste resources and the restoration of the ecological environment.

2. Basic properties and preparation of biochar

Biochar is a carbon-rich porous material obtained by pyrolyzing biomass such as agricultural and forestry waste under limited oxygen conditions. Its physicochemical properties directly determine its adsorption and degradation efficiency for antibiotics, while the preparation process and modification methods are the core aspects in regulating its structural performance.

2.1. Basic physical and chemical properties

Biochar is a solid material with a carbon element as its backbone, typically maintaining a carbon content of 40%–75%, while also containing hydrogen, oxygen, nitrogen, and mineral elements such as calcium, magnesium, and potassium [1]. Influenced by the enrichment of alkaline minerals during the pyrolysis process, biochar is generally weakly alkaline, with a pH value mostly between 7 and 10. This characteristic makes it more likely to generate electrostatic interactions with acidic or dissociated antibiotic molecules, enhancing adsorption affinity.

The pore structure is the most core physical property of biochar. According to IUPAC standards, it can be divided into micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). Antibiotics are mostly small organic molecule pollutants, and micropores and mesopores are the main sites for their adsorption. Biochar usually has a specific surface area of 50–1500 m^2/g, and a high specific surface area means more adsorption sites, which is the physical basis for achieving efficient antibiotic removal [2-6].

The surface chemical properties determine the chemical adsorption and catalytic activity of biochar. Biochar prepared at low pyrolysis temperatures (300–500°C) has a surface rich in oxygen-

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containing functional groups such as hydroxyl, carboxyl, and carbonyl groups, which can bind to antibiotic molecules through hydrogen bonding. As the pyrolysis temperature increases, the content of oxygen-containing functional groups decreases, the degree of aromatization increases, and π-π conjugation gradually becomes the dominant adsorption force. In addition, the mineral components in biochar can not only regulate the surface charge but also enhance antibiotic immobilization through coordination and surface precipitation; some minerals can even provide active sites for catalytic degradation.

2.2. Preparation process

The raw materials for biochar are mainly agricultural and forestry waste, including straw, rice husks, wood chips, and fruit shells. These raw materials are widely available and inexpensive, aligning with the concept of resource utilization. The mainstream preparation methods include slow pyrolysis, fast pyrolysis, hydrothermal carbonization, and gasification. Among them, slow pyrolysis (300~700°C, residence time of several hours) is the most widely used method, with biochar yields reaching 25%~35%. The products have a high degree of aromatization, making them suitable for antibiotic pollution control scenarios [4]. Fast pyrolysis aims at producing bio-oil, resulting in low biochar yields; hydrothermal carbonization is suitable for high-moisture raw materials, producing products rich in functional groups but with underdeveloped porosity.

Pyrolysis temperature is a key parameter for regulating the properties of biochar. Low-temperature (<400°C) biochar has a high yield and abundant functional groups but an imperfect pore structure; medium-temperature (400–600°C) biochar balances specific surface area and functional group content, making it the optimal temperature range for treating antibiotics; high-temperature (>600°C) biochar has a high degree of graphitization and large specific surface area, but a large amount of oxygen-containing functional groups is lost [7].

To enhance adsorption and catalytic performance, researchers have developed various modification strategies: physical activation using CO_2 or steam as activators, increasing the number of micropores through gasification; chemical activation using reagents such as KOH or $ZnCl_2$, which can rapidly build a well-developed pore structure [8]; loading modification by incorporating materials like nano zero-valent iron, Fe_3O_4, or MnO_2, endowing biochar with magnetic separation ability and catalytic activity; doping with heteroatoms such as nitrogen or sulfur can adjust the electronic structure and improve the efficiency of persulfate activation [3, 9]. These diverse modification methods provide technical support for the targeted application of biochar.

3. Mechanisms of biochar adsorption and degradation of antibiotics

3.1. Adsorption mechanism

The adsorption of antibiotics by biochar is a process that involves the synergy of physical and chemical actions. Physical adsorption focuses on pore filling, where antibiotic molecules are trapped in the micropores and mesopores of biochar through diffusion, and the adsorption efficiency is directly related to the match between molecular size and pore size.

Chemical adsorption includes multiple non-covalent interactions: electrostatic attraction is regulated by the solution pH, and the adsorption strength is determined by the match between the surface charge of biochar and the dissociation form of antibiotics, with dissociable antibiotics like tetracyclines being significantly affected; π-π conjugation is the main adsorption driving force for aromatic antibiotics, as the polycyclic aromatic structure of high-temperature biochar can form

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electron donor-acceptor interactions with the aromatic rings of antibiotics; hydrogen bonding mainly occurs between the oxygen-containing functional groups of medium- and low-temperature biochar and the polar groups of antibiotics, which is an important factor for enhancing adsorption stability; additionally, coordination complexation and hydrophobic interactions can also assist adsorption under specific conditions.

3.2. Degradation mechanism

Biochar can achieve complete degradation of antibiotics through catalytic activation, with the core being the generation of reactive oxygen species to oxidize pollutants. In persulfate activation systems, the persistent free radicals, defect sites, and graphite structure of biochar can activate PDS/PMS, producing active species such as sulfate radicals, hydroxyl radicals, and singlet oxygen. Among them, the selective oxidation ability of singlet oxygen is minimally affected by water matrix interference, making it suitable for practical wastewater treatment [9-12].

Fenton-like systems are common degradation pathways, and biochar loaded with iron-based materials can achieve Fe^{2+}/Fe^{3+} cycling under the action of H_2O_2, continuously generating hydroxyl radicals to achieve antibiotic ring-opening and mineralization [13]. Photocatalytically modified biochar can generate photogenerated electron-hole pairs under light, producing reactive species to degrade antibiotics.

It is worth noting that there is a significant synergistic effect between adsorption and degradation: biochar first enriches antibiotics on its surface and within its pores, increasing the local concentration of pollutants and shortening the diffusion distance of reactive oxygen species, greatly enhancing the degradation rate. This synergistic effect is particularly prominent in the removal of tetracycline antibiotics [14].

4. Application of biochar in antibiotic adsorption and degradation

Biochar, with the advantages of a green economy and adjustable performance, has already been explored for applications in scenarios of antibiotic pollution management, such as water treatment and soil remediation, gradually extending from laboratory research to actual engineering applications. In the field of water treatment, biochar can be used as an adsorbent or catalytic filler for the removal of antibiotics from municipal sewage, aquaculture wastewater, and pharmaceutical wastewater. In soil remediation, biochar can adsorb and immobilize antibiotics in situ, reducing their leaching and migration risks and bioavailability, while improving the soil microenvironment and inhibiting the spread of resistance genes. Additionally, biochar can serve as a functional filler in constructed wetlands and ecological buffer zones, enhancing the ability of green infrastructure to remove trace antibiotics.

4.1. Iron-modified corn straw biochar activated persulfate degradation of sulfamethoxazole

Zhang et al. Prepared [15] biochar using corn straw as raw material, modified it by in-situ loading of nanoscale zero-valent iron, and constructed a biochar/persulfate catalytic system to treat sulfamethoxazole in aquaculture wastewater. The core innovation of this study lies in using the pore structure of biochar to immobilize nanoscale iron, solving the problems of iron nanoparticle aggregation and oxidation, while combining the dual advantages of biochar adsorption and iron-based catalysis. Experimental results showed that the removal rate of sulfamethoxazole reached over 95% within 60 minutes, and after 5 cycles, the material still maintained a removal rate above 80%.

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This case confirms that loaded and modified biochar can achieve efficient synergy between adsorption and catalysis, with advantages of easy separation, strong stability, and high treatment efficiency, making it suitable for antibiotic removal in complex water bodies such as aquaculture wastewater.

4.2. Adsorption fixation of tetracycline by rice husk-based biochar and its application in soil remediation

Li et al. applied medium-temperature biochar prepared from pyrolyzed rice husks to tetracycline-contaminated soil to investigate its pollutant fixation effects and ecological impacts [14]. The innovation of the study lies in focusing on actual soil systems, clarifying the long-term fixation mechanism of biochar on antibiotics, and evaluating its regulatory effects on soil microbial communities. The results showed that applying 5% biochar could reduce the effective tetracycline content in soil by 62%, significantly inhibit the migration of antibiotics into plants, and increase the abundance of soil degradation functional microbes. This case demonstrates that biochar prepared from agricultural and forestry waste has dual value in in situ soil remediation by both controlling pollution and improving soil, providing a low-cost and feasible solution for managing antibiotic contamination in farmland.

Currently, the application of biochar still faces issues such as competitive adsorption in actual matrices, long-term material stability, and the toxicity of intermediate degradation products. However, the above case has confirmed its practicality and feasibility in antibiotic pollution management, laying the foundation for large-scale application.

5. Conclusion

This article systematically reviews the selection of raw materials for biochar, preparation processes, modification methods, and core physicochemical properties, and deeply analyzes its synergistic mechanisms of antibiotic adsorption and catalytic degradation. It summarizes the progress in the application of this material in antibiotic pollution control scenarios such as water treatment and soil remediation and points out the current key bottlenecks in research and practical application. In this experiment, through quenching experiments, pore size distribution analysis, and other techniques, the relationship between pore parameters and degradation rate was systematically established, further validating the functional patterns of the adsorption-catalytic degradation synergy. The results show that the developed pore structure, abundant surface functional groups, and tunable electronic properties of biochar are the core basis for its efficient antibiotic removal; pyrolysis temperature, activation method, and modification strategies can precisely regulate the material structure. Medium-temperature pyrolysis combined with loading, heteroatom doping, and other modification methods can simultaneously enhance adsorption capacity and catalytic activity. Biochar's removal of antibiotics relies on multi-mechanism synergy, where pore filling, electrostatic attraction, π-π conjugation, and hydrogen bonding jointly drive the adsorption process, while persulfate activation, Fenton-like reactions, and other pathways generate reactive oxygen species to achieve degradation. The synergistic effect of adsorption enrichment and catalytic degradation is key to the efficient mineralization of antibiotics, with the most significant enhanced removal effect on tetracycline antibiotics. In practical applications, biochar can effectively reduce the mobility and bioavailability of antibiotics in water and soil, proving feasible for livestock wastewater and farmland pollution remediation, while also enabling the resource utilization of agricultural and forestry waste. However, current research still faces issues such as interference from complex matrices, insufficient long-term

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stability of materials, unclear toxicity of degradation intermediates, and immature techniques for large-scale preparation and engineering applications, which require further breakthroughs.

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