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Application and Mechanisms of Biochar in Wastewater Treatment: A Comprehensive Review

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Abstract:

With the increasingly serious water pollution problem, traditional wastewater treatment technologies are facing the double challenges of performance and cost. Biochar, as a porous material prepared by pyrolysis of biomass, has gradually become a research hotspot in the field of wastewater treatment due to its rich pore structure and diverse surface functional groups. In this paper, the raw material source, preparation process and physicochemical properties of biochar are systematically reviewed, and its main mechanisms in wastewater treatment are analyzed, including adsorption, surface complexation and ion exchange, microbial carrier function and catalytic redox reaction. Combined with typical application cases, the effects and advantages of biochar in the removal of heavy metals, organic pollutants and nutrient salts are introduced. Finally, the future development trends and research directions are discussed with respect to the problems of insufficient long-term stability and difficulty in scaling up the functionalization in the application of biochar, aiming to provide references for the research and application in the related fields and to promote the sustainable development of biochar technology.

Keywords: Biochar; Wastewater Treatment; Adsorption; Catalytic Oxidation.

1. Introduction

In the past ten years, research on biochar in the field of wastewater treatment has become a major focus [1]. With the continuous advancement of technology and ongoing product innovation, the pathways of pollution will continue to expand. Both new and existing pollutants will increasingly contaminate water resources. Water pollution has already become a key global concern, and its further expansion will lead to a reduction in the availability of usable water resources. According to research, in 2015, the global production of wastewater was approximately 359.4 billion cubic meters, of which about 63%, approximately 225.6 billion cubic meters, was collected and 52%, about 188.1 billion cubic meters, was treated [2]. In addition, around 48% of the wastewater was discharged directly into the environment without any treatment [2]. As the scale and complexity of water pollution grow, current treatment technologies are facing increasing challenges in both performance and cost.

The global discharge of wastewater is continuously increasing with the growth of the global population and the process of industrialization. This has led to a worsening of water pollution. As a result, the rate at which wastewater is treated cannot keep up with the rate at which pollution is generated. As a result, the speed at treat wastewater is treated cannot keep up with the speed at which water pollution is generated. Therefore, quickly identifying and developing more effective, environmentally friendly, and lower-cost wastewater treatment methods is something that should be paid close attention to.

In response to these limitations, researchers are turning their attention to alternative materials with high efficiency and low environmental impact. Biochar is a porous material produced by pyrolyzing biomass under oxygen-limited conditions. It features a rich pore structure and diverse surface functional groups. In recent years, due to the increasing severity of water pollution, scientists have begun to focus on the application of biochar. Biochar can not only purify water quality but also remove greenhouse gases from the atmosphere, which greatly contributes to addressing current global environmental issues. The production cost of biochar is also very low, and its raw materials are widely available, giving it great potential for sustainable development.

Furthermore, the affordability and accessibility of treatment technologies vary globally, influencing implementation strategies. Countries with rapid and slow economic development differ in how they treat wastewater. The level of economic development to some extent determines a country's approach to wastewater treatment. Further research on biochar may very well change the current situation, as the cost of producing biochar is lower compared to most existing wastewater treatment methods. Moreover, because biochar can be applied to various types of water pollution, it has gained widespread attention.

Biochar is currently widely applied in soil improvement, water treatment, energy storage, carbon sequestration, and biomass conversion. The production temperature of biochar, residence time, feedstock composition, and activating agents (such as KOH) significantly affect the physical and chemical properties of biochar, such as porosity, pH value, and specific surface area [3]. According to current research, biochar can effectively adsorb antibiotics, heavy metals, and organic pollutants in wastewater treatment; it can also be applied to carbon dioxide adsorption and agricultural carbon sequestration [3]. At present, research on biochar has advanced to combining it with other technologies and developing new biochar-based composites [4]. With continued advancements in materials science and policy frameworks, the scope of biochar applications is expected to broaden significantly. In the future, the global application of biochar will become increasingly widespread, not only covering agriculture, wastewater treatment, and energy storage, but also expanding into more areas to address the global environmental crisis. Exploring the role of carbon trading and policy support in promoting economic feasibility and implementation will be an important direction for advancing the future development of biochar.

Although the application of biochar in wastewater treatment has made significant progress, there are still some challenges and research gaps. For example, there is a lack of long-term application studies, the interaction mechanisms in real wastewater remain unclear, the functionalization process is costly and difficult to scale up, and biochar is hard to recover and reuse [5-8].

The purpose of this paper is to summarize the practical functions and applications of biochar in wastewater treatment, analyze the future development trends of biochar, and provide references for related research to promote the global advancement of biochar.

2. Basic properties and preparation technology of biochar

2.1 Source of raw materials

Biochar feedstocks are highly diverse, encompassing agricultural residues, forestry or wood waste, animal manure, municipal or industrial waste, as well as aquatic plants and algae. Due to the varied nature of these raw materials, each type of biochar exhibits distinct characteristics. Biochar derived from agricultural waste typically contains high levels of cellulose and lignin, which contribute to stable carbon structures, favorable porosity, and moderate ash content. In contrast, biochar from forestry or wood waste is notable for its high carbon content, abundant porosity, and low ash levels. Animal manure-based biochar is rich in nitrogen and contains biologically available carbon. Biochar produced from municipal and industrial waste shows considerable variability and may include heavy metals and micropollutants. Meanwhile, biochar from aquatic plants and algae generally features high nitrogen content, a microporous structure, and numerous functional groups, making it particularly effective for adsorption applications. This wide range of feedstocks is matched by an equally varied array of production methods, each designed to optimize specific biochar properties.

2.2 Preparation process

The production processes of biochar have continuous-

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ly evolved over the past decade, with currently mature technologies mainly including pyrolysis, hydrothermal carbonization, and torrefaction. These three methods are further subdivided due to differences in temperature, pressure, and specific conditions. For example, torrefaction is categorized into dry and wet types. Technologies still in the research stage such as microwave pyrolysis are not yet widely used in general environmental or agricultural applications because of higher technical complexity or equipment costs and are currently suitable only for specific targets. In addition, the current stage of biochar research also includes post-treatment processes such as mechanical modification and chemical activation.

2.3 Physical and chemical properties of biochar under different conditions

Table 1 summarizes the key properties of biochar derived from different raw materials, highlighting their characteristic features and suitable applications. Agricultural waste-based biochar is rich in fiber and lignin, offering good carbon stability and porosity, making it ideal for waste reduction, soil fertilization, and carbon sequestration. Biochar from forestry residues and wood waste contains high carbon content with low ash levels and shows strong adsorption potential, suitable for high-end carbon products, building fill, and adsorption materials. Animal feces-derived biochar is characterized by high nitrogen and ash content, beneficial for nutrient adsorption and soil fertility improvement, although odor and toxicity require management.

Table 2 presents the influence of pyrolysis temperature on the physical and chemical properties of biochar. As temperature increases from low (300°C) to high (600–800°C), the specific surface area expands significantly from 2–50 m²/g up to over 800 m²/g, accompanied by changes in porosity from predominantly micropores to a combination of micropores and mesopores. Functional group abundance decreases with rising temperature, shifting from acidic groups such as COOH and OH at low temperatures to mainly aromatic carbon structures at high temperatures.

Table 1. Biochar Raw Materials Properties Comparison Table

Raw material type	Summary of biochar characteristics	Suitable applications	Raw material type
Agricultural waste	High fiber and lignin source, good carbon stability and porosity	Waste reduction, soil fertilization, carbon sequestration	Agricultural waste
Forestry residues and wood waste	High carbon, low ash, high stability and adsorption potential	High-end carbon products, building fill, adsorption materials	Forestry residues and wood waste
Animal feces	High nitrogen, high ash, adsorption of nutrients but need to deal with odor and toxicity	Soil fertility improvement, bioreactor media	Animal feces

Table 2. Effects of different conditions on the physical and chemical properties of biochar

Pyrolysis temperature	Specific surface area (m²/g)	Porosity	Functional group performance
Low temperature (300°C)	2-50	Mostly micropores	Acidic functional groups such as COOH and OH are more
medium temperature (400-500°C)	50-200	Micropores + mesopores	Functional groups gradually decrease
High temperature (600-800°C)	200-800+	Most micropores + mesopores	Few functional groups, mainly aromatic carbon structure

3. Mechanism of action of biochar in wastewater treatment

3.1 Adsorption

Biochar adsorbs pollutants primarily through physical and chemical mechanisms. The differences between these two types of adsorption are primarily reflected in their adsorption mechanisms, types of forces involved, adsorption strength, specificity, selectivity, reversibility, temperature influence, adsorption layers, and application scenarios. Physical adsorption refers to pollutants such as metal ions being attached to the surface and pores of biochar through van der Waals forces and pore interactions. This type of adsorption is usually reversible, has a fast rate but weak binding strength, and is significantly affected by specific surface area and pore volume. Chemical adsorption mainly involves electron transfer and covalent bond formation, where pollutants form stable coordination bonds or complexes with functional groups. This is the main mechanism for the removal of heavy metals and certain organic pollutants. Chemical adsorption is typically monolayer, mostly irreversible and difficult to desorb, has a slower rate but stronger binding strength, is greatly influenced by temperature and surface functional groups, and exhibits high selectivity and specificity. In addition, adsorption capacity is closely related to the density of functional groups and cation exchange capacity.

3.2 Surface complexation and ion exchange

Chemical adsorption mainly includes surface complexation and ion exchange. Among these, surface complexation plays a dominant role in most metal adsorption processes. It involves coordination reactions between metal ions and surface functional groups such as carboxyl, hydroxyl, and amino groups, resulting in the formation of stable complexes. Ion exchange, as the name suggests, refers to the exchange between positively charged metal ions and negatively charged functional groups on the biochar surface. Although it is a common mechanism during adsorption, its capacity is relatively limited.

These two mechanisms often interact with physical adsorption and precipitation, collectively influencing the overall adsorption outcome. For instance, calcium/aluminum-modified biochar can enhance the removal efficiency of U(VI) and Eu^{3+} through ion exchange and co-precipitation mechanisms [5].

3.3 Microbial carrier function

Techniques for immobilizing microorganisms on biochar mainly include adsorption, entrapment, cross-linking, and covalent bonding. Biochar has a high specific surface area and porous structure, making it an excellent habitat for microbial attachment. This promotes biofilm formation, community stability, and biodegradation. The porous structure offers physical habitats where microorganisms can attach and grow on the surface and within the internal pores, forming stable biofilms. Microbial communities within these biofilms are more tolerant of toxic pollutants and hydraulic shear forces, which enhances the stability of the treatment process [6].

After microorganisms gather on the biochar surface, they can facilitate cell-to-cell communication which named quorum sensing, enhancing synergistic degradation effects. In addition to providing space, biochar can also improve the microenvironment, such as regulating pH and enhancing oxygen transfer. This promotes the degradation efficiency of organic pollutants. Surface functional groups on biochar adsorb pollutants, increasing their local concentration around microorganisms and ultimately improving degradation rates. For example, biochar can stimulate the activity of enzymes such as β-glucosidase and acetyl-CoA synthase, and regulate key enzymes in the TCA cycle, which affects the carbon mineralization pathway [9]. In one case, immobilizing Pseudomonas stutter on biochar for Ni^{2+} removal achieved a removal rate of 83 percent and simultaneously enhanced microbial activity and stability [6]. Immobilizing microorganisms in biochar can enhance their tolerance to toxicity, increase reaction efficiency, and improve reusability. This approach is widely used for the removal of heavy metals, organic dyes, and nutrients.

3.4 Catalytic oxidation and reduction reactions

Due to the diversity of biochar preparation methods, modified biochar's have garnered increasing research interest. Modified biochar's, such as those loaded with nZVI or modified with metal oxides, possess redox catalytic abilities and can actively participate in the degradation and transformation of pollutants [10],[7]. In wastewater treatment, common reactions involving modified biochar include Fenton reactions, reduction reactions, and oxidation reactions. Each type of reaction can influence the overall treatment process under different conditions. The graphite structure of biochar and its catalytically active sites, such as Lewis's acid sites and metal-binding sites, contribute to its role as a heterogeneous catalyst. This is one of the key mechanisms enabling biochar to function effectively in catalytic processes [7]. For example, Fe-modified biochar can efficiently catalyze H_2O_2 to generate hydroxyl radicals (•OH), which degrade organic pollutants [11].

4. Application examples and treatment objects of biochar

4.1 Heavy metal ions

Biochar can effectively remove various heavy metals, including lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}), nickel (Ni^{2+}), copper (Cu^{2+}), and arsenic (As). The primary mechanisms involve surface complexation, ion exchange, electrostatic interactions, and precipitation. For example, cow dung biochar has demonstrated removal capacities of up to 40.8 mg/g for Pb (II) and 24.2 mg/g for Cd(II) [7]. Different modification techniques can also enable biochar to achieve various desired effects. For instance, the addition of MgO or bioactivation can further enhance selectivity and adsorption capacity.

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4.2 Organic pollutants

Biochar can effectively remove dyes such as methylene blue and Congo red, pharmaceutical residues such as tetracycline and sulfamethoxazole, and volatile organic compounds like benzene. The removal mechanisms include π–π interactions, electrostatic attraction, hydrophobic interactions, and pore filling. For example, microalgae-based biochar (Spirulina) has shown a removal rate of 85.47 percent for methylene blue (MB) with a maximum adsorption capacity of 113 mg/g. For Congo red (CR), the removal rate reached 95.61 percent with a maximum adsorption capacity of 164.35 mg/g. For tetracycline (TC), the maximum adsorption capacity was 147.9 mg/g [12]. Biochar/TiO_2 composites have also achieved a removal rate as high as 99.2 percent in the degradation of textile dyes [3].

4.3 Nutrients

Biochar can adsorb nitrogen, such as NH_4^+ and NO_3^-, and phosphorus (PO_4^{3-}), making it suitable for phosphorus removal from wastewater and nutrient recovery in agriculture. The adsorption mechanisms include electrostatic adsorption, ion exchange, and precipitation reactions. Key examples include ZFCO-BC biochar, which reduced phosphorus concentrations from 1660 mg/L to 0.06 mg/L, achieving a removal rate of 99.9 percent [7]. Microalgae-derived biochar has shown an ammonia nitrogen removal efficiency of up to 72 percent [12]. In addition, biochar can be modified into nutrient-enriched biochar for use as a slow-release fertilizer in agriculture.

4.4 Analysis of typical cases

Biochar has been widely applied in industrial wastewater, domestic sewage, and agricultural settings, offering numerous case studies for analysis. For instance, algal biochar has been used to treat textile wastewater containing Cr (VI), achieving an adsorption capacity of 187 mg/g and a removal rate of 97.84 percent [7]. Biochar can also remove benzene, nitrogen, and phosphorus from wastewater. Additionally, it has antibacterial and deodorizing properties and can serve as a biofiltration material to improve water quality. In agriculture, biochar is mainly used to remove pesticides and metal contaminants, making it suitable for the reuse of irrigation water. Literature References

5. Conclusion

With its low cost, sustainability and multifunctionality, biochar shows a broad application prospect in the field of wastewater treatment. It can effectively remove a variety of pollutants through physical adsorption, chemical adsorption, microbial synergy and catalysis. However, biochar still faces the challenges of high cost of functionalization, difficult recycling and insufficient evaluation of long-term effects in practical applications. Future research should focus on improving the performance of biochar, lowering the preparation cost, developing composite materials, and exploring the mechanism of its environmental behavior to achieve large-scale promotion and application. Meanwhile, the combination of policy support and carbon trading mechanism will also promote its economic feasibility and environmental benefits.

References

[1] Wang, Y., Chen, L., Zhu, Y. et al. Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: a scientometric review. Environ Sci Eur 36, 25 (2024). https://doi.org/10.1186/s12302-024-00859-z

[2] Jones, E. R., Van Vliet, M. T. H., Qadir, M., & Bierkens, M. F. P. (2021). Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data, 13(2), 237–254. https://doi.org/10.5194/essd-13-237-2021

[3] Ahmed, S. F., Mehejabin, F., Chowdhury, A. A., Almomani, F., Khan, N. A., Badruddin, I. A., & Kamangar, S. (2024). Biochar produced from waste-based feedstocks: Mechanisms, affecting factors, economy, utilization, challenges, and prospects. GCB Bioenergy, 16(8), e13175. https://doi.org/10.1111/gcbb.13175

[4] Agyekum, E. B., & Nutakor, C. (2024). Recent advancement in biochar production and utilization – A combination of traditional and bibliometric review. International Journal of Hydrogen Energy, 54, 1137–1153. https://doi.org/10.1016/j.ijhydene.2023.11.335

[5] Liu, C., Bolan, N., Rajapaksha, A. U., Wang, H., Balasubramanian, P., Zhang, P., Nguyen, X. C., & Li, F. (2025). Critical review of biochar for the removal of emerging inorganic pollutants from wastewater. Chinese Chemical Letters, 36(2), 109960. https://doi.org/10.1016/j.cclet.2024.109960

[6] Saravanan, A., Swaminaathan, P., Kumar, P. S., Yaashikaa, P. R., Kamalesh, R., & Rangasamy, G. (2023). A comprehensive review on immobilized microbes - biochar and their environmental remediation: Mechanism, challenges and future perspectives. Environmental Research, 236, 116723. https://doi.org/10.1016/j.envres.2023.116723

[7] Yameen, M. Z., Naqvi, S. R., Juchelková, D., & Khan, M. N. A. (2024). Harnessing the power of functionalized biochar: Progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. Biochar, 6(1), 25. https://doi.org/10.1007/s42773-024-00316-3

[8] Zhang, X., Bhattacharya, T., Wang, C., Kumar, A., & Nidheesh, P. V. (2023). Straw-derived biochar for the removal of antibiotics from water: Adsorption and degradation mechanisms, recent advancements and challenges. Environmental Research, 237, 116998. https://doi.org/10.1016/j.envres.2023.116998

[9] Li, Y., Kumar Awasthi, M., Sindhu, R., Binod, P., Zhang, Z., & Taherzadeh, M. J. (2023). Biochar preparation and evaluation of its effect in composting mechanism: A review. Bioresource Technology, 384, 129329. https://doi.org/10.1016/j.biortech.2023.129329
[10] Phiri, Z., Moja, N. T., Nkambule, T. T. I., & De Kock, L.-A. (2024). Utilization of biochar for remediation of heavy metals in aqueous environments: A review and bibliometric analysis. Heliyon, 10(4), e25785. https://doi.org/10.1016/j.heliyon.2024.e25785
[11] Cao, J., Jiang, Y., Tan, X., Li, L., Cao, S., Dou, J., Chen, R., Hu, X., Qiu, Z., Li, M., Chen, Z., & Zhu, H. (2024). Sludge-based biochar preparation: Pyrolysis and co-pyrolysis methods, improvements, and environmental applications. Fuel, 373, 132265.
[12] Costa, J. A. V., Zaparoli, M., Cassuriaga, A. P. A., Cardias, B. B., Vaz, B. D. S., Morais, M. G. D., & Moreira, J. B. (2023). Biochar production from microalgae: A new sustainable approach to wastewater treatment based on a circular economy. Enzyme and Microbial Technology, 169, 110281.