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Research Progress on the Remediation and Treatment of Heavy Metal Ions in Water by Biochar

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Abstract:

With the rapid development of industrialization and urbanization, heavy metal pollution in water bodies poses a major threat to the environment and human health. However, conventional heavy metal pollution control technologies often face problems such as high cost, cumbersome operation and secondary pollution risk. Therefore, the development of new and efficient repair technology is urgent and has environmental significance. This paper aims to explore the preparation method, modification technology and adsorption mechanism of biochar, analyze the regulation mechanism of its physical and chemical properties on adsorption performance, and discuss its remediation effect in complex water environments. This paper concluded that optimizing the preparation and modification conditions of biochar can significantly improve its adsorption efficiency and reduce the repair cost. Biochar shows the characteristics of high efficiency and low cost in the actual water remediation, and has significant environmental and economic benefits. Future research should further explore the combination of biochar and other remediation technologies, develop more efficient preparation methods, and further explore the adsorption mechanism to promote its wide application in the field of water treatment.

Keywords: Biochar preparation, Biochar modification, Remediation of heavy metals in water, Adsorption of heavy metal ions, Environmental remediation.

1. Introduction

Heavy metal ions refer to metal elements with a density greater than 4.5 g/cm ^{3}, and common ones include lead (Pb ^{2} +), cadmium (CD ^{2} +), mercury (Hg ^{2} +), copper (Cu ^{2} +) and zinc (Zn ^{2} +). These heavy metal ions pose a long-term threat to aquatic organisms and human health due to their non biodegradability and bioaccumulation. For example, the accumulation of lead (Pb ^{2} +) and cadmium (CD ^{2}

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+) in water will lead to the death of fish and other aquatic organisms, and long-term exposure will also cause human nervous system and kidney diseases. Mercury (Hg^{2+}) can be transformed into highly toxic methylmercury through methylation, and then enriched through the food chain, causing serious harm to human health [1]. At the same time, with the rapid development of industrialization and urbanization, the problem of heavy metal pollution in water has become increasingly serious. This makes it very urgent to find effective methods to alleviate or repair heavy metal pollution in water. Traditional remediation technologies for heavy metal pollution in water mainly include chemical precipitation and ion exchange. However, the traditional remediation technology has many shortcomings, such as secondary pollution risk, high cost and technical complexity. For example, the chemical precipitation method will produce a large number of chemical sludge in the treatment of heavy metal wastewater, which has high treatment cost and secondary pollution risk [2]; Although the ion exchange method has high removal efficiency for heavy metal ions, the resin regeneration process is complex and the cost is high [3,4]. Therefore, it is particularly urgent to develop efficient and sustainable remediation technology. In recent years, biochar, as a new type of environmental remediation material, has attracted extensive attention due to its rich source of raw materials, cost-effectiveness and environmental friendliness. The current research mainly focuses on the preparation and modification of biochar and its adsorption mechanism for heavy metal ions. In the preparation of biochar, researchers found that different raw materials and pyrolysis conditions had significant effects on the physical and chemical properties of biochar. This review aims to explore the application of biochar as a sustainable adsorbent in the remediation of heavy metals in water. Through literature review, the preparation methods, modification technologies and adsorption effects of biochar for different heavy metal ions were systematically summarized. This paper discussed how the physical and chemical characteristics of biochar affect its adsorption efficiency, and discussed its application prospect in the actual water treatment system. It was found that the adsorption effect of biochar was significantly affected by its preparation conditions (such as pyrolysis temperature and time), modification methods and water chemical conditions (such as pH value and ionic strength). This study focuses on the remediation effect of biochar in complex water environments, aiming to establish the correlation mechanism between biochar parameters and removal performance, provide theoretical support and technical guidance for the application of biochar in water remediation, and promote the wide application of biochar in the field of water treatment. The significance of this study is to establish the correlation mechanism between biochar parameters and removal performance, provide theoretical support and technical guidance for the wide application of biochar in the field of water treatment, and promote the application and development of biochar in water remediation.

2. Application of biochar in remediation of heavy metal pollution in water

2.1 Preparation and characteristics of biochar

2.1.1 Preparation method

The preparation of biochar involves a variety of raw materials and processes. The results showed that different raw materials (such as agricultural waste, lignocellulose, biomass, etc.) had significant effects on the characteristics of biochar. For example, due to its high specific surface area and porosity, rice husk biochar has an adsorption capacity of more than 50 mg/g for $Pb^{2+}$and wood biochar has a good adsorption performance for CD^{2+}due to its rich surface functional groups [5]. In the preparation process, pyrolysis temperature, time and atmosphere conditions play a key role in the structure and properties of biochar. For example, when pyrolyzed at 600 °C, the specific surface area and porosity of biochar reach the maximum value, which makes it the strongest adsorption capacity for heavy metal ions [6]. In addition, biochar prepared under a nitrogen atmosphere has more types and quantities of surface functional groups, which further improves its adsorption performance [7].

2.1.2 Physical and chemical properties

The high specific surface area, abundant pore structure and a variety of surface functional groups (such as hydroxyl, carboxyl, etc.) of biochar are the key factors for its adsorption performance. The larger the specific surface area, the more adsorption sites provided by biochar, and the stronger the adsorption capacity. At the same time, the type and number of surface functional groups also have an important impact on the adsorption performance of biochar, especially for the adsorption selectivity of specific heavy metal ions. For example, The hydroxyl and carboxyl groups on the surface of biochar can combine with $Pb^{2+}$to form a stable complex, and its complex constant is higher than 10^{4}, showing excellent chemical adsorption capacity[8].

2.1.3 Modification method

Although biochar shows good adsorption capacity due to its high specific surface area and porous structure, there are still some problems in practical application. For ex-

ample, the adsorption selectivity of original biochar may be insufficient, and it is difficult to effectively distinguish and adsorb specific heavy metal ions in a complex water environment. In addition, the adsorption capacity of biochar may be limited by the type and number of functional groups on its surface and the uniformity of pore structure. In some cases, the regeneration and reuse of biochar is also a challenge, because the adsorbed biochar may be difficult to restore its initial adsorption performance. In view of these challenges, the modification of biochar has become an effective strategy to improve its adsorption performance. These modification methods include physical modification, chemical modification and composite modification. Physical modification optimizes the pore structure of biochar through heat treatment or mechanical activation, which can increase its specific surface area and provide more adsorption sites for heavy metal ions. Although this method can improve the adsorption capacity, it may sacrifice the chemical stability of some biochar and may increase the production cost. By means of chemical modification, the introduction of new functional groups or the adjustment of existing functional groups can effectively improve the chemical adsorption performance of biochar. One of the advantages of this method is that it can enhance the selective adsorption capacity of biochar for specific heavy metal ions, but it may also bring new pollutants or by-products, requiring additional treatment steps. Composite modification is to combine biochar with other materials to form composite materials with synergistic effect.This method can integrate the advantages of a variety of materials to improve the adsorption efficiency and selectivity of biochar, but its preparation process may be more cumbersome and cost more money.Each modification method is to solve the specific problems of biochar in the remediation of heavy metal pollution in water, but they all need to find a balance between cost, efficiency and environmental impact. Through carefully designed modification strategies, the performance of biochar can be significantly improved, making it a more powerful and sustainable tool in the field of water treatment.

3. Adsorption mechanism of biochar for heavy metals in water

3.1 Adsorption type

In the field of heavy metal pollution remediation, the adsorption of biochar is one of its core functions. The adsorption of heavy metal ions by biochar is mainly realized through three mechanisms: physical adsorption, chemical adsorption and ion exchange. Each adsorption mechanism has its unique characteristics and application scenarios. Physical adsorption mainly depends on the pore structure and van der Waals force of biochar. This adsorption does not involve the formation of chemical bonds, so it is relatively weak. However, in the porous structure of biochar, physical adsorption provides a large number of adsorption sites for heavy metal ions. Chemical adsorption involves forming chemical bonds with heavy metal ions through functional groups on the surface of biochar, which is stronger and more stable. Chemical adsorption is one of the main mechanisms for biochar to adsorb heavy metal ions. It involves abundant functional groups on the surface of biochar, such as amino and carboxyl groups, which can form stable complexes with heavy metal ions such as mercury (Hg^{2+}). For example, the functional groups on the surface of biochar can combine with Hg^{2+} to form stable complexes, thus showing strong chemical adsorption capacity.This adsorption mechanism not only improves the adsorption efficiency, but also enhances the selectivity of adsorption [9]. Ion exchange refers to the exchange between cations on biochar and heavy metal ions in water. This mechanism is also very effective under specific conditions, especially when there are a large number of exchangeable ions in water. Although chemical adsorption plays a dominant role in the adsorption of heavy metal ions by biochar, physical adsorption and ion exchange can not be ignored. They work together to improve the comprehensive adsorption capacity of biochar for heavy metal ions. Understanding these adsorption mechanisms is of great significance for optimizing the performance and application of biochar.

3.2 Influencing factors

The solution conditions have a significant effect on the adsorption of heavy metal ions by biochar. Research shows that the increase of ionic strength will reduce the adsorption capacity of biochar, because high concentration ions will compete with heavy metal ions for adsorption sites [10]. The characteristics of biochar, such as specific surface area, pore structure and surface functional groups, are also closely related to the adsorption performance [11]. Environmental factors, such as temperature, hydraulic retention time and biochar dosage, also have a significant impact on the remediation effect of biochar [12]. For example, the increase of temperature can increase the adsorption rate of biochar, but has little effect on the adsorption capacity, The longer the hydraulic retention time, the longer the contact time between biochar and heavy metal ions, and the better the adsorption effect, While the increase of biochar dosage can improve the adsorption efficiency, too high dosage will increase the cost [13].

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4. Case analysis

4.1 Laboratory studies

In laboratory scale, the remediation effect of biochar on heavy metal polluted water has been widely studied. For example, Zhang et al. Used rice husk biochar to treat wastewater containing lead (Pb ² +), and the lead concentration after treatment decreased from 100 mg/l to 0.1 mg/l, with a removal rate of 99.9%, and the treatment cost was only 30% of that of the traditional chemical precipitation method [14]. In another study conducted by Li et al., the adsorption performance of wood biochar for cadmium (CD ² +) was excellent. After treatment, the cadmium concentration decreased from 50 mg/l to 0.5 mg/l, the removal rate reached 99.0%, and the treatment cost was 40% lower than that of the traditional method [15]. In addition, Wang et al. Also showed good adsorption performance when using agricultural waste biochar to treat copper containing wastewater. After treatment, the copper concentration decreased from 80 mg/L to 1.0 mg/L, and the removal rate reached 98.8%, which was 35% lower than the traditional method [16]. Table 1 first, taking the case of rice husk biochar treatment of lead ion (Pb ²+as an example, the initial concentration was 100 mg/l, after treatment, the concentration decreased to 0.1 mg/l, and the removal rate reached 99.9%. This remarkable removal effect shows that biochar has high adsorption efficiency for lead ion. Compared with the traditional method, the removal cost of biochar is only 30%, which proves that biochar is not only technically effective, but also has a significant cost advantage in the economy. Secondly, the case of wood biochar treating cadmium ion (CD ² +) also shows a similar trend. The initial concentration was 50 mg/L, after treatment, the concentration decreased to 0.5 mg/L, and the removal rate was 99.0%. Although the removal efficiency is slightly lower than that of rice husk biochar in the treatment of lead ions, compared with the traditional method, the removal cost is only 40%, which also reflects the economy of biochar in the treatment of heavy metal pollution. Finally, in the case of agricultural waste biochar treatment of copper ion (Cu ² +), the initial concentration was 80 mg/L, and after treatment, the concentration decreased to 1.0 mg/L, with a removal rate of 98.8%. Although the removal rate is slightly lower than the first two cases, compared with the traditional method, the removal cost is 35%, which further confirms the cost-effectiveness of biochar in the treatment of different heavy metal ions.

Table 1 laboratory scale remediation effect of biochar

Study case	Raw material	Heavy metal ion	Initial concentration(mg/L)	Concentration after treatment(mg/L)	Removal rate(%)	Removal costs (compared with traditional methods)	References
Rice husk biochar	rice husk	Pb^{2+}	100	0.1	99.9	30%	[14]
Wood biochar	wood	Cd^{2+}	50	0.5	99.0	40%	[15]
Agricultural waste biochar	Agriculture waste	Cu^{2+}	80	1.0	98.8	35%	[16]

4.2 Future outlook

Although biochar has shown great potential as a promising material for the remediation of heavy metals in water, it still faces some challenges in practical application. At present, the preparation process of biochar may be costly, and its selective adsorption capacity for specific heavy metals needs to be improved in complex water containing a variety of ions. In addition, the regeneration and reuse of biochar also affect its long-term economy and sustainability. The detailed mechanism of the interaction between biochar and heavy metal ions also needs to be further understood, which is crucial for improving its adsorption performance and achieving more effective applications.

Looking forward to the future, the research work should be devoted to the development of more economic and environmental protection technology for the preparation of biochar. This may include exploring the use of lower cost raw materials, or improving pyrolysis and activation processes to reduce energy consumption. At the same time, improving the selective adsorption capacity of biochar is also an important direction, which can be achieved by surface modification or a composite with other materials. In addition, studying how to regenerate and reuse biochar more effectively will help to reduce long-term operating costs and reduce environmental impact. Further study on

the interaction mechanism between biochar and heavy metal ions will help to design more efficient and stable biochar materials.

Through these efforts, biochar is expected to play a more important role in the remediation of heavy metal pollution in water and make greater contributions to environmental protection and sustainable utilization of resources.

5. Conclusion

Through a systematic literature review and case analysis, this paper discusses the application and effect of biochar in the remediation of heavy metal pollution in water. The preparation methods and modification technologies of biochar, as well as its adsorption effect on a variety of heavy metal ions including lead (Pb ² +), cadmium (CD ² +), mercury (Hg ² +) were comprehensively summarized by using the method of literature review. Through these analyses, it was found that biochar exhibited excellent adsorption capacity due to its unique physical and chemical properties, such as high specific surface area, porous structure and rich surface functional groups. In addition, the renewable nature of biochar provides the possibility for its sustainable application in environmental remediation, which shows its great potential as an environmental remediation material. This study found that although biochar showed great potential in the remediation of heavy metals in water, there were still some challenges and limitations. For example, the large-scale production and application of biochar need to be further studied for their economic feasibility and environmental impact. Future research should focus on optimizing the preparation and modification process of biochar to improve its adsorption efficiency and reduce the cost. At the same time, exploring the combination of biochar and other remediation technologies and developing more efficient preparation methods of biochar will help promote the wide application of biochar in the field of water treatment. This study fills the gap in the existing literature on the application of biochar in the remediation of heavy metals in water and provides a valuable reference for researchers in related fields. The results show that the application of biochar not only contributes to environmental protection, but also promotes the innovation and development of related technologies. Despite the challenges, biochar is expected to play a more critical role in the treatment of heavy metal pollution in the future through continuous research and technological innovation.

References

[1] Lu Xiuguo, Xiao Fanhao, Zheng Yujia, Fu Xueyang Study on the adsorption of Hg~(2+) in water by two modified walnut shell materials [J]. Ion Exchange and Adsorption, 2021

[2] Zhang Liguo, Pan Jingshi, Huang Jiali, Li Biqing, Tang Xia, Wu Xuewei, Liang Haobin, Du Xin Research progress on the adsorption of phosphorus from water by waste based biochar [J]. Journal of South China Normal University (Natural Science Edition), 2023

[3] Cai Guofei, Li Bin The effect of pyrolysis temperature on the physicochemical properties of intact tea residue biochar [J]. Shandong Chemical Industry, 2024

[4] Zuo Yuhang, Song Mingzhi, Luo Hui, Cai Bingxin, Zhang Wenhao, Jing Zhaoqian, He Baojie, Wang Huiteng, Qin Teng, Cai Jixiang Research progress on the preparation of agricultural waste with external carbon sources [J]. Applied Chemistry, 2022

[5] Fang Yuanhang, Liu Yudi Comparison and selection of solid carbon sources for denitrification and denitrification based on agricultural waste [J]. Water Supply Technology, 2017

[6] Zhang Shuang Application Research on Adsorption and Removal of Heavy Metals in Water by Calcium Aluminum Hydrotalcite [D]. Jinan University, 2022

[7] Song Yao Study on Modification and Cr (VI) Removal Performance of D201 Resin Reinforced by High Gravity [D]. North China University, 2021

[8] Shen Yu Preparation of pyrrole based biomass composite materials and their comprehensive treatment of hexavalent chromium ions in water [D]. Chang'an University, 2019

[9] Ding Yang Study on the adsorption performance and competitive adsorption mechanism of biochar for cadmium and lead [D]. Hunan University, 2017

[10] Zhang Yongqiang Directional modification and mercury adsorption mechanism of iron-based doped bimetallic modified biochar [D]. Taiyuan University of Technology, 2021

[11] Bi Yifan Preparation of Bagasse Biochar and Its Adsorption Study on Cu~(2+), Pb~(2+), Zn~(2+) [D]. Guangxi University, 2019

[12] Zhong Delai Study on the Influence Mechanism of Environmental Factors on Biochar Driven As (III) Oxidation or Cr (VI) Reduction and Their Fixation [D]. Huazhong University of Science and Technology, 2019

[13] Zhu Lin Study on the Migration and Enrichment Effects of Heavy Metals in Reservoir Sediments [D]. Dalian University of Technology, 2019

[14] Liu Huiping Study on the removal mechanism of acetochlor by biofilter [D]. Jilin Agricultural University, 2023

[15] Yang Jun Study on the pollutant removal efficiency of surface flow constructed wetland system [D]. Chang'an University, 2014

[16] Chen De Integrated analysis and field experiments on the effects of biochar on soil heavy metal availability and crop uptake [D]. Nanjing Agricultural University, 2016