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Study on the Influence of Different Raw Materials and Pyrolysis Conditions on the Performance of Biochar in Remediating Heavy Metal-Contaminated Soils

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Abstract:

The issue of soil heavy metal pollution is becoming increasingly severe, posing a critical environmental challenge that threatens ecological security and human health. Biochar-based soil remediation technology has drawn significant attention due to its potential advantages, and it is of great significance for improving soil environmental quality. This paper focuses on using biochar to remediate heavy metal-contaminated soils and explores the influence mechanisms of different raw materials and pyrolysis conditions on its remediation performance. Through a systematic analysis of three practical cases, the action patterns of key factors such as biochar raw material types, pyrolysis temperatures, and heating rates on the remediation effect of soil heavy metals are deeply understood. The research results provide a practical basis for the engineering application of biochar-based soil remediation technology and reveal the interaction mechanism among biochar, soil, and heavy metals from a theoretical perspective. This is of great significance for promoting the development of more efficient and sustainable strategies in the field of soil pollution remediation.

Keywords: Biochar; Raw Material Type; Pyrolysis Conditions; Soil Heavy Metal Pollution;

1. Introduction

Soil, a pivotal component of the terrestrial ecosystem, is integral to ecological stability and food security. However, exacerbated by extensive industrial undertakings such as mining and smelting, and intensive agricultural practices like excessive chemical fertilizer and pesticide use, soil heavy metal pollution has become a grave concern. Heavy metals, including cadmium, lead, and mercury, accumulate in the soil and infiltrate the human body via the food chain, jeopardizing human health and potentially causing ailments such as kidney failure and neurological disorders.

Traditional soil heavy metal remediation methods, including physical (e.g., electrokinetic remediation, soil washing) and chemical (e.g., chemical stabilization, leaching) techniques, have inherent limitations. Physical methods generally entail high energy consumption and thus high costs; for example, electrokinetic remediation requires a continuous electricity supply, escalating overall expenses. Chemical methods may induce secondary pollution. Chemicals used in leaching can contaminate groundwater if mismanaged and disrupt the soil's natural structure, undermining its fertility and biological activity[1].

Biochar, produced through biomass pyrolysis under anaerobic or oxygen-restricted conditions, holds promise in soil heavy metal remediation. Its unique features, such as a large specific surface area, abundant surface functional groups, and high cation - exchange capacity, enable effective heavy metal adsorption. Despite prior research on biochar applications, knowledge gaps remain regarding the combined effects of different raw materials (e.g., woody biomass, agricultural waste, sewage sludge) and pyrolysis parameters (temperature, heating rate, residence time) on its remediation performance. Moreover, studies on its real - world applications across diverse soil types and pollution levels are scarce[2].

This paper aims to thoroughly explore the influence mechanisms of different raw materials and pyrolysis conditions on biochar's performance in remediating heavy metal - contaminated soils. First, in - depth case studies of biochar remediation in various polluted areas are conducted, involving biochar prepared from different raw materials and under distinct pyrolysis conditions. Then, a detailed comparative analysis is performed to precisely determine the impacts on biochar's properties and remediation efficiency. Finally, the research findings are comprehensively discussed, covering their generality across different regions and soil conditions, their limitations, implications for practical biochar - based soil remediation, and prospects for future research [3].

2. Case Studies

2.1 Case 1: The Influence of Pyrolysis Temperature on the Hydrological Properties of the Biochar-Soil System

This study investigates the influence of pyrolysis temperature on biochar properties and their subsequent effects on soil hydrological characteristics. Wheat straw - derived biochars pyrolyzed at 350°C, 450°C, 550°C, and 650°C were characterized for physical (porosity, specific surface area) and chemical (elemental composition, pH) properties, then applied to soil to evaluate aggregate stability and water - holding capacity.

Increasing pyrolysis temperature enhanced biochar specific surface area and pH, while altering elemental composition. Biochar addition improved soil aggregate stability, with 450 - 550°C - produced biochars demonstrating optimal performance [4]. All biochars increased soil water - holding capacity, with the peak observed at 550°C [4].

The pyrolysis temperature during biochar synthesis significantly impacts its properties. Substantial evidence indicates that a pyrolysis temperature range of 450 - 550 °C optimizes the interactions between biochar and soil. Employing biochars produced within this temperature regime can enhance soil quality, fortify the remediation of heavy - metal - contaminated soils, and advance sustainable agricultural practices by improving soil structure and water management processes[4].

2.2 Case 2: Biochar Effects on Mining Soil Heavy Metals

Heavy metal contamination in mining - affected soils poses significant threats to the ecological environment and human health. As a soil amendment, biochar has attracted considerable attention, and understanding its impact on the availability and speciation of heavy metals in mining - polluted soils is of great significance.

This study employed incubation experiments, adding biochar at different rates to investigate its effects on the speciation and bioavailability of heavy metals in mining - contaminated soils. Results showed that heavy metal concentrations in the mining - affected soils exceeded background levels and relevant regulatory standards. Biochar application increased the proportion of residual fractions while reducing the acid - soluble fractions of heavy metals, indicating a transformation towards more stable forms. For instance, with a 10% biochar addition, the calcium chloride - extractable concentrations of copper, zinc, and cadmium decreased by 57.26%, 51.37%, and 42.04%,[5] respectively, compared to the control. However, no significant change was observed in the extractable concentration of arsenic.

Overall, biochar effectively altered the speciation of heavy metals in mining - contaminated soils and decreased the bioavailability of certain heavy metals, offering a viable approach and theoretical basis for soil remediation. While this study demonstrated the positive effects of biochar on heavy metal speciation and availability in mining - impacted soils, several limitations exist. The research was confined to short - term incubation experiments, failing to account for the complex environmental factors in the field,

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such as climatic variations (precipitation, temperature fluctuations) and dynamics of soil biotic communities, which may influence biochar performance. Additionally, the study did not comprehensively cover all heavy metal species present in mining soils, suggesting that further research should expand the scope of investigation [5].

2.3 Case 3: Biochar Filtration for Stormwater Treatment

Stormwater runoff often contains various pollutants such as heavy metals (e.g., copper, zinc) and organic contaminants (e.g., polycyclic aromatic hydrocarbons, pesticides), posing risks to water bodies and ecosystems. Biochar - based filtration has emerged as a potential approach for stormwater treatment. Biochar, with its large specific surface area, abundant pore structure, and surface functional groups, demonstrates excellent adsorption capabilities for these pollutants. Multiple case studies in different regions have shown that the addition of biochar - based filtration media to stormwater collection systems can significantly increase the removal rate of pollutants in stormwater runoff, validating its feasibility and effectiveness in practical applications. However, challenges remain in the long - term operation of biochar - based filtration systems, such as the stability of biochar and its anti - clogging ability. Future research is needed to optimize this technology for wider application [6].

3. Comparative Analysis of Case Studies

3.1 Influence of Raw Materials on Biochar Performance

In the cases, wheat straw, replete with cellulose and hemicellulose, serves as a raw material. Biochar fabricated therefrom shows certain efficacy in enhancing soil aggregate stability and water - retention capacity. Biochars from disparate raw materials display variegated performances in soil remediation and other applications due to chemical composition differences. For example, agricultural straw - based biochars have advantages in modulating soil physical properties, like the positive impact on soil hydrological characteristics in this case. However, their heavy - metal sorption capacity is comparatively feeble because of structural and functional - group constraints. Biochars from raw materials such as wood, during lignin pyrolysis, tend to form well - developed pores and aromatic architectures. These structural features endow them with a large number of adsorption sites, enabling strong interactions with heavy - metal ions through mechanisms like ion exchange, surface complexation, and electrostatic adsorption. As a result, they exhibit excellent heavy - metal sorption capabilities, in stark contrast to agricultural straw - based biochars, which have relatively weak heavy - metal sorption due to their own structural and functional - group limitations.

3.2 Influence of Pyrolysis Conditions on Biochar Performance

Pyrolysis temperature significantly impacts biochar properties. For instance, wheat straw-derived biochar pyrolyzed at 450–550 °C optimizes soil aggregate stability and water-holding capacity. Low-temperature pyrolysis retains abundant organic functional groups, yet limits pore development and specific surface area. Increasing pyrolysis temperature enhances biochar aromatization and graphitization, enlarging specific surface area and porosity for superior pollutant adsorption. Although heating rate remains unemphasized in the document, studies indicate it affects pyrolysis reactions and biochar microstructure, thereby influencing performance[7].

3.3 Differences in Adsorption Mechanisms in Different Cases

In the mining - soil case, biochar transforms heavy metals from the acid - soluble to the residual fraction, reducing some heavy metals' bioavailability via surface complexation, ion exchange, etc. In the stormwater - treatment case, biochar adsorbs heavy metals and organic pollutants in stormwater using its large specific surface area, abundant pore structure, and surface functional groups. Adsorption mechanisms vary across cases due to raw - material, pyrolysis - condition, and pollutant - property differences, reflecting their complexity [8].

4. Discussion

4.1 Universality and Limitations of Case Results

The three cases illustrate biochar's application effects in diverse scenarios, yet the research has limitations. Differences in soil types, pollution levels, environmental conditions, and biochar application methods make it hard to apply the case results widely. The research mainly focuses on short - term effects, lacking studies on biochar's long - term stability in soil, its long - term interactions with the soil ecosystem, and potential secondary pollution risks. Long - term positioning experiments and in - depth mechanism explorations are needed.

4.2 Enlightenment for Biochar - based Soil Remediation

Based on the cases, in practical soil remediation, choose biochar raw materials and pyrolysis conditions considering soil pollution type, degree, and physicochemical properties. For single - heavy - metal - polluted and acidic soils, select wheat - straw - based biochar like in the case to precipitate heavy metals by adjusting soil pH. For multi - heavy - metal - polluted soils, consider biochars with good adsorption performance. For soils needing both pollution remediation and fertility improvement, weigh the environmental risks of biochars from materials like sewage sludge before use. Also, explore biochar's combined application with other remediation technologies to enhance the remediation effect [9].

4.3 Future Research Prospects

Future biochar - remediation research can be done in multiple ways. Expand biochar raw - material sources and study new - material biochars' remediation effects and environmental safety on different polluted soils. Explore the interaction mechanisms among biochar, soil, pollutants, and microorganisms to understand biochar's long - term changes in the soil environment and its ecological impacts. Innovate the preparation process to cut costs and improve product quality. Conduct large - scale field tests and engineering demonstrations, and establish a long - term monitoring and evaluation system to promote biochar remediation technology's wide application [10].

5. Conclusions

Through the systematic analysis of three practical cases, this paper has clarified the significant influence of different raw materials and pyrolysis conditions on the performance of biochar in remediating heavy metal - contaminated soils. The research results show that the type of biochar raw materials determines its basic properties and main remediation functions, and the pyrolysis temperature and heating rate significantly affect the physical and chemical properties and adsorption performance of biochar. Different biochars have their advantages and applicable ranges in actual soil remediation scenarios. This study provides practical guidance for the rational application of biochar remediation technology for soil heavy metal pollution, and also points out the direction for further research in this field. It has important theoretical and practical significance for promoting the development and application of biochar - based soil remediation technology.

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