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Application of Biochar in the Remediation of Heavy Metal Pollution in Agricultural Soils

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Abstract

As industrialization progresses, heavy metal contamination in agricultural soils has become a pressing concern, threatening the safety of food crops, the balance of ecosystems, and human well-being. This environmental issue has garnered significant attention due to its widespread impact. Major contributors to soil contamination include the release of industrial effluents, air emissions, solid waste, and the excessive application of chemical fertilizers and pesticides. The ongoing accumulation of heavy metals compromises soil health and hinders plant development. Biochar, an emerging soil amendment, has demonstrated great potential in addressing heavy metal pollution in agricultural environments. Its distinctive characteristics—such as high porosity and extensive surface area—enable it to effectively adsorb and stabilize heavy metal ions. Moreover, biochar contributes to improving soil fertility, enhancing moisture retention, optimizing soil structure, and promoting microbial diversity, thereby supporting healthier crop growth. This study investigates the role of biochar in remediating heavy metal-contaminated agricultural soils and aims to provide innovative and sustainable strategies for environmental restoration.

Keywords

Biochar; Agricultural Soil; Heavy Metal Pollution.

1. Brief Explanation of Relevant Concepts

1.1. Biochar

Biochar is a carbon-rich, stable substance derived from the thermal decomposition of biomass—such as agricultural residues and forestry by-products—under limited oxygen conditions. Produced through high-temperature pyrolysis, biochar differs from traditional fuel charcoal in both composition and application. It is widely utilized in agriculture as a soil amendment, enhancing plant growth, improving soil quality, and serving as a tool for carbon sequestration [1–3].

Similar to regular charcoal in its production process, biochar primarily consists of carbon. Scientific interest in biochar surged following studies on the fertility of Amazonian black soils. In countries like Japan, the agricultural use of biochar has been practiced for decades. With growing awareness of climate change driven by greenhouse gas emissions such as CO_2, N_2O, and CH_4, researchers have increasingly emphasized the environmental value of biochar. It offers a promising approach to capturing and stabilizing atmospheric greenhouse gases in soils, where they can remain inert for thousands of years.

In addition to its environmental benefits, biochar can enhance crop yields by up to 20%, improve water quality, and decrease dependence on synthetic fertilizers. The feedstocks for biochar production are varied, including not only agricultural and forestry waste but also municipal biosolids and livestock manure. Depending on factors such as pyrolysis temperature, residence time, and heating rate, biochar can be prepared using three primary methods, as outlined in Table 1. At present, its application in the remediation of heavy metal-contaminated soils is drawing increasing interest in environmental and agricultural research.

Table 1. Common Biochar Production Methods

Methods	Temperature (℃)	Residence time	Heating rate (℃/min)
Slow pyrolysis	300-650	5min-12h	10-30
Hydrothermal carbonization	180-260	5min-12h	5-10
High temperature vaporization	600-900	10-20s	50-100

1.2. Agricultural Soil

Agricultural soil, also known as cultivated soil, is formed based on natural soil and through human production activities such as plowing, fertilizing, irrigation, and improvement, as well as natural influences. Examples include soils found in farmland, orchards, and tea plantations. Agricultural soil serves as the foundation for crop growth. However, the current state of soil pollution in China's agricultural land is alarming.

In recent years, large-scale land use and the extensive application of fertilizers and pesticides for agricultural development have increasingly contributed to soil pollution. To improve crop yields, farmers often overuse chemical fertilizers and pesticides, leading to their accumulation in the soil[4-5]. Prolonged excessive use of agrochemicals has caused issues such as heavy metal accumulation and pesticide residues in soil, significantly affecting both crop quality and the environment.

With the adoption of modern agricultural practices such as large-scale operations and mechanized farming, the precision in fertilizer and pesticide use has declined. Excessive and improper applications have led to non-point source pollution in farmlands. The overuse of chemical inputs has further increased the risk of soil contamination, placing great pressure on the ecological environment.

1.3. Heavy Metal Pollution

Heavy metal pollution refers to environmental contamination caused by heavy metals or their compounds. The term “heavy metals” typically refers to metals with a density greater than 4.5 g/cm^3, including gold, silver, copper, iron, and lead. Unlike organic pollutants, many of which can be naturally degraded through physical, chemical, or biological processes, heavy metals are difficult to degrade in the environment and have a strong tendency to accumulate.

The primary source of heavy metal pollution is industrial pollution, followed by traffic emissions and household waste. Industrial pollution often releases heavy metals into the environment through solid waste, wastewater, and exhaust gas, which accumulate in humans, animals, and plants—causing significant harm to both health and ecosystems. Pollution from industrial sources can be controlled through technical and managerial interventions to meet national emission standards.

Traffic-related pollution mainly comes from vehicle exhaust emissions. To mitigate this, governments have implemented various regulations, such as the use of ethanol-blended gasoline and the installation of exhaust purification devices. Domestic pollution primarily comes from household waste such as used batteries, broken lamps, leftover cosmetics, and glazed ceramics. Heavy metal pollution can be significantly reduced by controlling it at the source.

2. The Significance of Biochar Application in the Remediation of Heavy Metal-Contaminated Soils

2.1. Improvement of Soil Physicochemical Properties

Due to its alkaline nature, biochar can improve the physicochemical properties of soil when added to it. As an efficient soil amendment, biochar plays an important role in the remediation of heavy metal-contaminated soils. In practical applications, its alkalinity helps raise soil pH levels, thereby alleviating soil acidification and creating a favorable growth environment for plants[6-7].

Additionally, the porous structure and abundance of functional groups in biochar enhance the soil's nutrient adsorption and retention capacity, reducing nutrient loss. Given its strong water-retention capacity, appropriate use of biochar can also increase the soil's water-holding ability, helping to alleviate drought stress and ensure sufficient moisture for plant growth.

2.2. Reduction of Remediation Costs

Traditional methods of soil heavy metal remediation, such as chemical leaching and electrokinetic remediation, require significant financial investment, involve complex operations, and take extended periods—making it difficult to meet remediation demands efficiently. In contrast, biochar, as a new soil amendment and remediation material, has wide availability. It can be produced from agricultural waste, forestry residues, municipal solid waste, and other low-cost sources.

Compared to conventional approaches, the application of biochar is relatively simple. It can be directly incorporated into the soil, mixed with soil, or made into composite materials, thus eliminating complex intermediate steps. This reduces resource input and offers a feasible solution for remediating heavy metal-contaminated soils.

3. Interactions Among Soil, Biochar, and Heavy Metals

3.1. Alteration of Soil Physicochemical Properties

Biochar can significantly reduce the bioavailability of heavy metals in soil and improve soil conditions, thereby creating a more favorable environment for plant growth. Its effect on heavy metal uptake is evident in the reduced content of heavy metals, especially the soluble forms. Although biochar has a limited effect on the availability of iron (Fe) and manganese (Mn), it effectively reduces the accumulation of heavy metals in different parts of rice plants when applied to contaminated paddy soils.

For maize grown in lead (Pb)-contaminated soils, biochar treatment reduced the bioavailability of Pb by 71% and almost completely eliminated the content of exchangeable Pb. Compared to untreated soils, the toxicity of Pb to maize was significantly reduced. Overall, biochar improves soil quality, lowers pollutant bioavailability and toxicity, and creates optimal conditions for crop growth.

3.2. Immobilization of Heavy Metals in Soil

Conventional agricultural soil remediation techniques encompass physical, chemical, and biological methods, as illustrated in **Table 2**. These methods play critical roles in managing heavy metal pollution. Physical methods, such as deep plowing and soil replacement, aim to remove or dilute contaminants directly. Chemical methods involve adding reagents to alter soil properties, causing heavy metal ions to precipitate or solidify. Biological methods use the metabolic activities of microorganisms or plants to degrade or absorb heavy metals[8].

Over time, the effectiveness of these techniques has been validated through practice, not only reducing soil heavy metal pollution but also ensuring the safety of agricultural products. In recent years, the application of biochar as a soil amendment for the in situ immobilization of heavy metals has shown tremendous potential in remediating agricultural soils. The incorporation of biochar into heavy metal-contaminated soil holds significant practical importance.

Table 2. Overview of Traditional Agricultural Soil Remediation Techniques

Type of technology	MethodDescription	Mechanism of action
Physical method	Deep soil tillage, soil change, etc	Direct removal or dilution of contaminants
Biological approach	Using the metabolic activity of microorganisms or plants	Change soil properties so that heavy metal ions precipitate or solidify
Biological approach	Using the metabolic activity of microorganisms or plants	Degradation or absorption of heavy metals

3.3. Changes in Crop Uptake of Heavy Metals

The effectiveness of biochar in remediating heavy metals in agricultural soil varies depending on the type of raw material used, as different feedstocks influence biochar's properties and remediation performance.

For example, in cabbage experiments, peanut shell-derived biochar improved acidic soil conditions, enhanced nutrient availability and soil pH, and minimized aluminum (Al) toxicity, promoting healthy cabbage growth. Biochar derived from sugarcane residues pyrolyzed at 500°C reduced the bioavailability of cadmium (Cd) by 63%, increased microbial activity in mung bean rhizospheres, enhanced symbiotic relationships, and boosted crop yield.

Similarly, biochar produced from maize straw residues at 500°C significantly improved soil nutrient content and pH while reducing the bioavailability of chromium (Cr). Rice husk biochar pyrolyzed at 500°C increased soil pH and enhanced the adsorption of heavy metals such as Cd, Cu, Pb, and Zn. Consequently, lettuce plants absorbed significantly lower levels of these metals. These findings demonstrate the recognized potential of biochar in remediating heavy metal-contaminated agricultural soils.

4. Effective Strategies for Biochar-Based Remediation of Heavy Metal Pollution in Agricultural Soils

4.1. Strict Control of Coating Thickness

In the process of soil remediation, to maximize the benefits of biochar, it is essential to strictly control the thickness of the biochar soil layer to ensure optimal adsorption and immobilization of heavy metals. For this purpose, proportionally formulated soil layer preparation methods can be employed, such as spray drying, impregnation, and sol–gel techniques, to ensure the uniformity and thickness of the biochar coating meet the desired standards [9].

Additionally, the ratio of coating materials and additives should be dynamically adjusted to optimize performance and improve coating quality and stability. Enhanced coating quality monitoring can effectively prevent the problem of overly thick layers. Techniques such as optical microscopy, electron microscopy, and X-ray diffraction can assist specialists in examining the structure, morphology, thickness, and uniformity of biochar coatings.

4.2. Rational Use of Acidic Materials

The combined use of acidic materials may reduce remediation effectiveness or cause adverse reactions. On the one hand, when mixing biochar with acidic materials, it is necessary to select appropriate types—avoiding excessively strong acids or those containing large quantities of harmful substances. The selection should also consider soil heavy metal content and type; suitable options may include sulfuric acid, hydrochloric acid, and acetic acid. Proper selection can minimize negative interactions and prevent reduced remediation performance when mixed with biochar.

On the other hand, the mixing ratio of acidic materials and biochar must be carefully controlled. Excessive acid content can lead to overly acidic soils, negatively affecting plant growth and disturbing the soil ecological balance. Therefore, practitioners must manage the mixing ratio to achieve optimal remediation results.

4.3. Conducting Environmental Assessments

As a complex material, biochar exhibits a range of physical and chemical properties—such as specific surface area, pore size distribution, microstructure, adsorption capacity, and carbon sequestration ability. Before using biochar for agricultural soil heavy metal remediation, these properties must be thoroughly understood to better evaluate potential environmental risks[10-12].

Moreover, applying biochar in remediation may impact soil microorganisms and ecological systems. Thus, relevant authorities and practitioners must conduct comprehensive environmental risk assessments to scientifically and systematically evaluate and predict potential environmental effects. This includes identifying appropriate usage conditions, determining safety precautions, and formulating environmental protection measures.

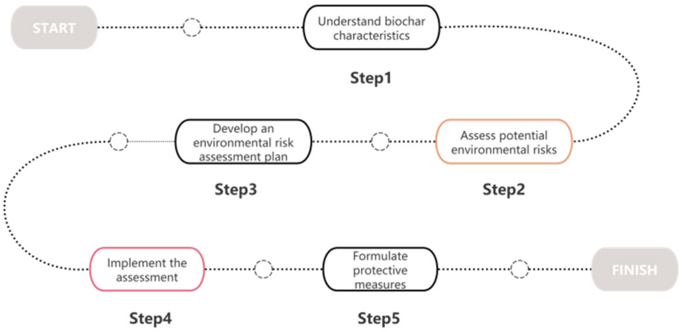

Figure 1. Biochar Environmental Assessment Workflow

5. Conclusion

As an effective soil amendment and material for heavy metal remediation, biochar shows significant potential for application in addressing heavy metal pollution in agricultural soils. Considerable progress has been made in converting agricultural biomass into biochar and in studying the mechanisms of metal accumulation and transfer in polluted soils.

Despite its positive effects, the application of biochar in the remediation of heavy metals in agricultural soils still faces certain limitations. Moving forward, further research should be devoted to optimizing biochar remediation technologies to achieve effective management and control of heavy metal contamination in agricultural land.

References

[1] Chen, C.; Yang, F.; Ma, Y.; Dai, L.; Zhang, Z.; Guo, H.; Ding, Y. Ball milling boosted magnetic cotton husk-derived biochar adsorptive removal of oxytetracycline and ciprofloxacin from water. Carbon Res. 2024, 3, 63.

[2] Ambaye, T.G.; Vaccari, M.; van Hullebusch, E.D.; Amrane, A.; Rtimi, S. Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. Int. J. Environ. Sci. Technol. 2021, 18, 3273–3294.

[3] Simiele, M.; Sferra, G.; Lebrun, M.; Renzone, G.; Bourgerie, S.; Scippa, G.S.; Morabito, D.; Scaloni, A.; Trupiano, D. In-depth study to decipher mechanisms underlying Arabidopsis thaliana tolerance to metal(loid) soil contamination in association with biochar and/or bacteria. Environ. Exp. Bot. 2021, 182, 104335.

[4] Wang, J.; Zhang, M. Adsorption characteristics and mechanism of bisphenol A by magnetic biochar. Int. J. Environ. Res. Public Health 2020, 17, 1075.

[5] Simiele, M.; Lebrun, M.; Miard, F.; Trupiano, D.; Poupart, F.; Forestier, O.; Scippa, G.S.; Bourgerie, S.; Morabito, D. Assisted phytoremediation of a former mine soil using biochar and iron sulphate: Effects on As soil immobilization and accumulation in three Salicaceae species. Sci. Total Environ. 2020, 710, 136203.

[6] Dong, X.; Chu, Y.; Tong, Z.; Sun, M.; Meng, D.; Yi, X.; Gao, T.; Wang, M.; Duan, J. Mechanisms of adsorption and functionalization of biochar for pesticides: A review. Ecotoxicol. Environ. Saf. 2024, 272, 116019.

[7] Edwin, T.; Mera, M.; Komala, P.S. Impact of pyrolysis temperature on the removal of nutrients using coarse rice-husk biochar. J. Ecol. Eng. 2023, 24, 247–257.

[8] Li, Z.; Niu, R.; Yu, J.; Yu, L.; Cao, D. Removal of cadmium from aqueous solution by magnetic biochar: Adsorption characteristics and mechanism. Environ. Sci. Pollut. Res. 2024, 31, 6543–6557.

[9] Manori, S.; Shah, V.; Soni, V.; Dutta, K.; Daverey, A. Phytoremediation of cadmium-contaminated soil by Bidens pilosa L.: Impact of pine needle biochar amendment. Environ. Sci. Pollut. Res. 2021, 28, 58872–58884.

[10] Iriarte-Velasco, U.; Sierra, I.; Zudaire, L.; Ayastuy, J.L. Preparation of a porous biochar from the acid activation of pork bones. Food Bioprod. Process. 2016, 98, 341–353.

[11] Karimi, M.; Tuesta, J.L.D.; Gonçalves, C.N.d.P.; Gomes, H.T.; Rodrigues, A.E.; Silva, J.A.C. Compost from municipal solid wastes as a source of biochar for CO2 capture. Chem. Eng. Technol. 2020, 43, 1336–1349.

[12] Wang, Q.H.; Lai, Z.Y.; Mu, J.; Chu, D.M.; Zang, X.R. Converting industrial waste cork to biochar as Cu (II) adsorbent via slow pyrolysis. Waste Manag. 2020, 105, 102–109.