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Research Progress on Biochar Remediation of Cd Contaminated Soil

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Abstract

With the acceleration of urbanization and industrialization, the problem of heavy metal pollution in soil has become increasingly prominent. Especially Cd contaminated soil has become the focus of public attention. As a promising environment-friendly amendment, biochar has shown great potential in the remediation of soil heavy metal pollution. We reviewed the research progress of biochar remediation of Cd contaminated soil, including the modification methods of biochar and the effects of raw materials and pyrolysis temperature on the remediation of Cd contaminated soil by biochar, aiming to provide scientific basis for the treatment of heavy metal contaminated soil and support for ecological environment protection.

Keywords

Biochar; Soil; Remediation; Cadmium; Heavy Metal Pollution.

1. Introduction

Human activities such as mine development, metal smelting, factory construction, wastewater treatment and landfill release a large amount of lead, mercury, cadmium, chromium, zinc and other heavy metal substances into the environment[1], causing severe contamination of the atmosphere, water, and soil. Heavy metal pollution is a global environmental challenge due to their high toxicity, persistence, non-degradability, and bioaccumulation potential, posing significant threats to ecosystems and human health. Among these, cadmium (Cd) is widely distributed and exhibits carcinogenic, mutagenic, genotoxic, and immunotoxic effects. Cd is more readily absorbed by plants compared to other heavy metals, leading to amplified ecological risks. According to the World Health Organization (WHO), approximately 80% of global Cd emissions originate from non-ferrous metal smelting and refining industries. The 2014 report on the national general survey of soil contamination of China revealed that heavy metals were the primary inorganic pollutants in the soil, with 16.1% of soil sampling sites exceeding national standards. Notably, Among them, the exceeding standard rate of cadmium pollutant point was 7.0 %. Agricultural practices, including the use of fertilizers, pesticides, and animal manure, also contribute to heavy metal accumulation in soil. Studies have shown that agricultural activities are the main cause of cadmium pollution in farmland soils in China. About 20 % of farmland soil cadmium content in China is higher than the national standard[2].

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Addressing Cd pollution has become an urgent priority for the high-quality development in China.

Biochar is a stable, porous, and aromatic-rich carbonaceous material produced through the pyrolysis of biomass under oxygen-limited conditions [3]. Compared to traditional adsorbents like activated carbon, biochar possesses a highly porous structure, large specific surface area, and abundant stable aromatic functional groups, enabling strong adsorption and immobilization of Cd and other heavy metal ions. In recent years, biochar has been widely applied as an eco-friendly amendment for remediating heavy metal-contaminated soils. It improves soil properties by enhancing cation exchange capacity (CEC), pH, and electrical conductivity, thereby indirectly reducing the bioavailability and mobility of heavy metals. Additionally, biochar directly immobilizes heavy metals in soil through mechanisms such as complexation, electrostatic attraction, precipitation, and ion exchange.

2. The Modification Methods of Biochar

Biochar has the characteristics of large specific surface area, high carbon content, stable structure and strong adsorption capacity [3], and has been widely used as a soil amendment. However, the surface area and functional groups of biochar itself are low, and the removal capacity of heavy metals by biochar alone is limited. In order to further improve the metal adsorption efficiency of biochar, more and more studies have modified biochar to improve its physical and chemical properties, so as to achieve better remediation effect on soil heavy metal pollution. In particular, modified biochar shows good potential in the remediation of cadmium and arsenic combined pollution, and which is the hot material for simultaneous remediation of cadmium and arsenic. The common methods of biochar modification mainly include physical, chemical and biological methods. Among them, chemical methods include acid-base modification, metal modification, redox modification, etc., which are also commonly used methods at present.

2.1. The Physical Method

Physical modification is to improve the ability of biochar to adsorb heavy metals by physical methods, such as steam, ultraviolet irradiation, ultrasonic, electromagnetic and other methods. The study found that the use of CO2 to modify sludge-based biochar can increase its specific surface area and increase the polar functional groups on the surface. In addition, the distribution and species of iron on iron-containing wood biochar composites were observed by various X-ray analysis techniques[4], and the adsorption experiments of As^{5+}, As^{3+}, Cr^{6+} and Hg^{2+} were carried out. It was found that Fe was detected during pyrolysis at 600 °C or 900 ℃. The removal rate of modified biochar was 99.9%, which was caused by the impregnation of iron.

2.2. The Chemical Method

Chemical modification refers to the use of strong acids, strong bases, organic solvents or supported metal oxides to improve the adsorption efficiency of biochar on heavy metals by affecting the carboxyl and hydroxyl groups in the biochar group. The chemical methods include acid-base modification, metal modification, redox modification, etc., which are also commonly used methods at present.

The surface of biochar can be significantly optimized by strong acid treatment, thereby forming more active functional groups. These new functional groups not only enrich the surface chemical properties of biochar, but also significantly enhance the affinity of biochar to heavy metal ions through efficient adsorption mechanisms such as ion exchange and complexation.

The alkali treatment of biochar can obviously increase the surface area, pore volume and surface functional groups of biochar, thus promoting the adsorption effect of heavy metals. Guo et al. [5] found that the adsorption effect of modified biochar on heavy metals Cd and Pb was significantly better than that of unmodified biochar by modifying biochar with NaOH. Oxidation modification is also an effective method to significantly enhance the adsorption capacity of biochar. Among many oxidants, H2O2 is favored because of its high economic value and environmental friendliness. In addition to the introduction of oxygen-containing groups, the oxidation of H2O2 can also further improve the physical and chemical properties of biochar by finely regulating the surface structure of biochar, thereby optimizing its adsorption performance [6].

In addition, metal modification is also an effective modification method. By introducing metal ions, it can not only increase the pore structure of biochar, and form more oxygen-containing functional groups, but also provide more adsorption sites, further enhancing the adsorption capacity of biochar to heavy metals. Chen et al. [7] modified biochar with manganese and applied it to heavy metal contaminated farmland. It was found that this method can more effectively reduce the number of available heavy metals than single application of biochar, reduce the absorption rate of heavy metals by crops, and significantly alleviate heavy metal pollution in farmland and increase crop yield.

2.3. The Biological Method

Biological modification refers to the immobilization of microorganisms with tolerance or adsorption capacity to heavy metals as microbial agents on biochar to remediate heavy metal contaminated soil. Biochar can improve soil fertility and biological community composition through physical adsorption. The porous structure of biochar provides space and nutrition for the growth and reproduction of microorganisms, and resists the influence of external environmental factors on microbial growth. Zhu et al.[8] used Bacillus and cotton straw biochar to repair Cd contaminated soil, which improved soil enzyme activity and the abundance of dominant bacteria.

3. The Remediation Effect of Biochar from Different Raw Materials

The differences in the physical and chemical properties and structure of biochar prepared by different raw materials and modification methods lead to some differences in the passivation and fixation mechanisms of different biochars on heavy metals, which leads to the instability of the passivation effect of different biochar materials on heavy metals. At the same time, different types of biochar have different effects on soil fertility regulation and crop growth. Biomass raw materials mainly come from agricultural waste, forestry waste, municipal waste, etc., which are cheap and easy to obtain, and can provide organic matter for soil.

3.1. The Straw Biochars

The main sources of straw biochar raw materials are rice, corn, wheat, soybean, cotton and other crop straws. Yin et al. [9] prepared 1 % ~ 2 % rice straw biochar to passivate the farmland soil in the mining area, and found that the Cd concentration in the rhizosphere pore water of the soil was significantly reduced. Gao et al.[10] used corn straw biochar to reduce the extractable Cd in farmland soil by 91 %. After the application of biochar, the efficiency of the transformation of the soluble state of Cd and Pb in the soil to the organic bound state was improved. Some studies have found that the application of wheat straw biochar to farmland can control the low level of Cd and Pb extractable state in three years, accompanied by the increase of soil pH. Sun et al.[11] used rice straw, wheat straw, corn straw and cotton stalk as raw materials to prepare biochar by slow pyrolysis at 600 ℃. It was found that although the specific surface area of cotton stalk biochar was the smallest, and the adsorption capacity of Cd^{2+} was higher than that of other biochars.

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3.2. The Bamboo and Wood Biochar

The main sources of bamboo biochar raw materials are bamboo, branches and so on. Studies have found that biochar prepared from hardwood can effectively reduce the available Cd in soil [12]. Bamboo biochar promoted the accumulation of copper, cadmium and zinc in the tissues of Salix psammophila. Especially the accumulation of cadmium and zinc was more obvious[13]. Dai et al.[14] studied the adsorption characteristics of Pb^{2+} and Cd^{2+} in wastewater by pear branch biochar before and after NaOH modification. It was found that NaOH modification increased the number of surface pores and surface functional groups of pear branch biochar, and improved its ion exchange performance.

3.3. The Fecal biochar

The raw materials of biochar are mainly derived from the feces of various animals. Kim et al. [15] prepared biochar from cow dung to adsorb Pb and Cd in soil. It was found that the extractable Pb and Cd contents were significantly reduced and transformed in the form of carbonate minerals. It has been found that the Cd^{2+} adsorption capacity of pig manure biochar is 10-15 times that of wheat straw biochar due to its more polar functional groups and ash [16].

3.4. Other Biochars

The main sources of other types of biochar are rice husk, coconut shell, sludge and so on. Lin et al.[17] found that the bimetal oxide enhanced sludge biochar prepared by the combination of Mg^{2+} and Fe^{3+} had better adsorption capacity for Cd(II) and Pb(II) than other metal combinations. Liu et al. [18] found that 5 % coconut shell biochar could increase the adsorption rate of heavy metal Cd by 17.9 %.

4. The Remediation Effect of Biochar Prepared at Different Temperatures

The biochar shows alkaline properties, which is because plants produce some inorganic minerals such as alkali salts during high-temperature pyrolysis. This is mainly due to during the pyrolysis process, with the gradual increase of temperature, the volatile substances in biochar, especially those containing acidic substances, will be completely decomposed. With the complete decomposition and volatilization of these acidic substances, the pH value of biochar is worth gradually increasing, thus showing a trend positively correlated with the preparation temperature. Cao et al.[19] found that the higher the pyrolysis temperature of cow dung biomass, the larger the specific surface area of cow dung biochar.

5. Conclusion

The preparation of biochar has a wide range of raw materials, low cost, and green production process. Biochar can not only realize the comprehensive utilization of waste resources, but also repair heavy metal contaminated soil, and has broad application prospects. This green economic restoration method has promoted the research of environmental pollution restoration to a deeper level. Future studies should optimize the modification methods of biochar, and produce high-quality biochar with high efficiency and low cost, and determine the best utilization path according to the characteristics of biochar to improve the remediation effect of biochar on soil heavy metal pollution.

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