Application of Biochar in Soil Improvement and Heavy Metals Remediation

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Abstract: With porous structure, large surface area and rich oxygen-containing functional groups, biochar has been concerned widely as a soil conditioner for its potential use in soil improvement and remediation. In this paper, the characterizations of different biochar were firstly studied, then the application of biochar in improving soil fertility and repairing heavy metal pollution were summarized. Finally, future perspectives of biochar were also proposed. It was found that effects of biochar on soil improvement mainly included soil properties increasement, such as pH, cation exchange capacity (CEC) and nitrogen content, plant growth and crop yield enhancement, and microbial community improvement. In soil remediation of heavy metals pollution, biochar prepared from different raw materials could immobilize heavy metal ions by direct functions of electrostatic adsorption, ion exchange, complexation, precipitation, and indirect reactions with plant uptake and soil microorganism. Through this study, it can provide a reference for the application of biochar in soil improvement and pollution remediation, and give alternative method for resource utilization of solid wastes.

1 INTRODUCTION

With the rapid development of industry and agriculture, soil environment faces increasingly serious challenges. According to the investigation report of soil pollution by the Ministry of Ecology and Environment, the over-standard rate of heavy metals in cultivated land in China reached 19.4%, and the pollution of heavy metals in soil was 82.4% (Guo 2020, Xing 2021). Therefore, it is urgent to carry out remediation of farmland soil to ensure the safety of agricultural products. Biochar is regarded as an excellent material for soil improvement and remediation because of its strong adsorption of heavy metals and porous structure (Xing 2021, Peng 2020). Besides, the preparation of biochar from biomass by pyrolysis can realize resource utilization of solid wastes and avoid environmental pollution caused by burning of solid wastes.

At present, many studies have made explorations on the preparation, effect and mechanism of different biochar, as well as its application in soil improvement and heavy metal passivation (Guo 2020, Peng 2020, Lyu 2020). However, due to different characteristics of biochar and various soil conditions, there is still lack of comprehensive study of biochar from different sources and its complex application in soil. Therefore, on the basis of summarizing the characterization of biochar in recent years, this paper reviewed the effect and mechanism of biochar in improving soil fertility and repairing heavy metals pollution, aiming to provide a reference for biochar application and soil remediation.

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2 DEFINITION AND CHARACTERIZATION OF BIOCHAR

Biochar is a kind of carbon-rich product obtained by pyrolysis of various biomass materials, such as agricultural and forestry wastes, livestock and poultry manure, municipal sludge, under the oxygen-limited atmosphere (Xing 2021). On the one hand, biochar has the characteristics of porosity, large specific surface area, abundant chemical functional groups, strong ion exchange capacity, and thus has a strong adsorption of many pollutions, which can reduce the availability of heavy metals in soil (Xing 2021, Peng 2020, Lyu 2020).

On the other hand, biochar contains various components such as fixed carbon, soluble organic matter, ash and minerals, which is beneficial for the improvement of carbon content, soil water holding capacity and soil structure, providing nutrients for plant growth and microorganism activity (An 2020).This effect was similar to that of chemical fertilizers, but biochar had the advantage not only of providing nutrients, but also of enhancing their efficiency and controlling their release (Kookana 2011, Ren 2017). In addition, most biochar was alkaline, so its application into acidic soils can alter the acid-alkaline environment, thus affecting the ionic status of various nutrients, and ultimately improving plant uptake of these substances (Zhang 2017). Studies also have confirmed that biochar can change the exchangeability of soil salt by increasing soil pH value, strengthen the plant availability of soil nutrients, and thus ensure plant growth in good condition (Kookana 2011, Nie 2018, Ren 2017, Zhang 2017).

3 APPLICATION OF BIOCHAR IN SOIL IMPROVEMENT

Biochar has been widely used in environmental protection, especially in soil improvement and remediation, as a cheap and simple carbon material (Xu 2014, Baquy 2019, Vidya Vijay 2019). Studies founde that biochar contained large amounts of organic matters that could be released into the soil for plant growth, so it can be added directly to the soil as a nutrient (Beesley 2011, Gaskin 2010). At the same time, biochar added to soils can enhance soil fertility by altering the physical, chemical property, and structure of the soil (Aller 2016).

The greatest advantage of biochar lied in its wide range of materials, such as agricultural and forestry wastes (Kloss 2012), from which biomass with certain organic components can be used as biochar raw materials, including straw, twigs and leaves, as well as sewage sludge from wastewater treatment (Zhang 2016). Because there were many kinds of raw materials of biochar and most of the wastes can be used to produce the product, resource recovery became another great advantage of biochar. At present, crop straw was one of the major problems in the disposal of agricultural wastes in China, so it was an effective way to make the crop straw into biochar and use it for soil conditioner or pollution remediation. However, the physical and chemical properties and function of biochar made from specific raw material were not always in line with the actual needs, therefore, in the process of developing biochar, it was necessary to improve the quality of biochar by means of modification, so that it can played its role efficiently.

Due to its porous structure, large surface area, high carbon and mineral contents, and rich functional groups, the effects of biochar on soil improvement mainly include enhancement of soil physical and chemical properties, such as pH, cation exchange capacity (CEC) and nitrogen content, increasement of plant growth and crop yields, and improvement of microbial community, as shown in Figure 1.

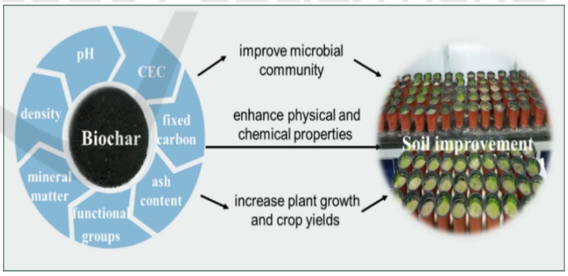

Figure 1: Effects of biochar on soil improvement.

3.1 Effect of Biochar on Enhance Physical and Chemical Properties

Biochar can directly provide nutrients such as nitrogen and carbon, which mainly depends on the raw materials for preparation. Meanwhile, properties of biochar, such as pH, CEC, porosity and specific surface area, can affect its function in soil. Studies found that biochar prepared by pyrolysis at high temperature was more efficient and feasible for reducing soil acidity and promoting nutrients retention (Guo 2020, Peng 2020, An 2020). The functional groups on the surface of biochar, especially oxygen-containing functional groups (e.g. -COOH, -OH), made outstanding contributions to soil CEC improvement and contaminants adsorption. It was found that the negative charge functional groups of biochar could increase soil CEC from 88.4 mmol/kg to 211.3 mmol/kg, which was important for soil fertility (An 2020).

3.2 Effect of Biochar on Improve Microbial Community

The porous structure on the surface of biochar can provide favorable conditions for the growth of soil microorganisms. At the same time, biochar can stimulate the metabolic activities of microorganisms and optimize the microbial community structure by increasing soil aeration, water holding capacity and providing nutrients for microorganisms (Peng 2020). Nie found that the number of soil microorganisms (i.e. rhizosphere bacteria, ammoniated bacteria, actinomycetes, fungi, nitrogen-fixing and denitrifying bacteria) increased with the increase of biochar proportion in spinach soil (Nie 2018). It's worth noting that the influence of biochar on soil microorganisms was very complex and different microorganisms may need different specific growth environments.

3.3 Effect of Biochar on Increase Plant and Crop Yields

Many researchers demonstrated that biochar can strengthen the long-term effect of soil fertility, release nutrients slowly into the soil, promote plant growth and crop yield by participating in nitrogen transformation (Peng 2020, An 2020). It was found that applying eucalyptus biochar in sandy soil could increase corn yield by more than one time. The results of pot experiment showed that pine sawdust biochar could increase sorghum yield by 18%-22% (Peng 2020). The promotion of biochar on plant growth and crop yield was mainly achieved indirectly by improving soil fertility and related physical and chemical properties, such as soil pH, CEC, nutrient content and availability (Guo 2020, An 2020). The improvement effect was also related to the physical structure and chemical composition of soil itself, characteristics of biochar, the adding form, action period and type of crops, and so on (Nie 2018).

4 APPLICATION OF BIOCHAR IN SOIL REMEDIATION OF HEAVY METALS POLLUTION

There are a variety of remediation techniques for heavy metal pollution in soils, it can be mainly devided into two methods: in situ remediation and ectopic remediation from the perspective of remediation methods (Derakhshan 2017). According to the types of adopted technologies, it can be divided into physical remediation, chemical remediation and bioecological methods. Physiccal and chemical methods generally used leaching, adsorption, transformation, transfer and other methods to achieve the removal of heavy metal pollution components, or to make it more stable in the soil, which enabling the heavy metals couldn't be transferred with water, while it was also difficult for organisms to absorb and use (Ko 2006). The bio-ecological method was more concerned with avoiding the risk of secondary pollution and reducing the cost of treatment, and was based on animals, plants and microorganisms, building an ecosystem of contaminated soils and enhancing their removal or fixation of heavy metals components (Babu 2013).

How to select appropriate treatment technology to remediate heavy metal pollution of soil in practical engineering application, factors such as technology maturity, economic cost input, treatment efficiency, risk of secondary pollution and duration period of effect need to be considered. Therefore, it was urgent to explore a technically reliable and economically feasible solution. Biochar can not only recycle many kinds of biomass wastes, but also be used as a kind of adsorption material for heavy metals.

Jiang conducted field experiments on lead (Pb) and cadmium (Cd) contaminated farmland near the mine, and the remediation of Pb and Cd pollution by litchi biochar was investigated. It was found that litchi biochar could significantly improve soil properties, such as pH, organic matter and CEC, it was also found to reduce heavy metals accumulation in crop plants (Jiang 2020). Luo conducted a sequential batch experiment to study the effects of soil samples contaminated with cadmium and arsenic (As) in corncob biochar (COB) (Luo 2020). It was found that the COB had good fixation effect on the two heavy metal pollutants, they were transformed into forms that were difficult to migrate or utilize due to biochar's physical and chemical characteristics such as specific surface area, total pore volume, average pore size and C/O ratio. Biochar also provided nutrients such as carbon and nitrogen for soil and soil microbial communities.

4.1 Effect of Biochar on Soil Remediation of Heavy Metals Pollution

Biochar also had good properties for remediation of heavy metal contamination in soils, stabilizing heavy metal ions in soils and reducing their bioavailability (Awasthi 2016, Huang 2017, Meng 2018, Wang 2019). A large number of studies demonstrated that biochar made from different feedstocks (e.g. municipal sludge, hardwood, straw) had excellent adsorption effects on heavy metals and reduced the toxicity of heavy metals in soil and plant (Gascó 2019), as shown in Table 1. Wang conducted field experiments in farmland polluted by lead and cadmium, and found that litchi biochar significantly improved the soil properties, such as pH, organic matter and CEC, and alleviated the accumulation of lead and cadmium in crops (Gascó 2019). The adsorption efficiency of biochar was determined by its pore structure, specific surface area and functional groups, thus affecting its adsorption and fixation of heavy metals (Chen 2020, Gascó 2019, Wang 2021).

Table 1: Effects of different biochar on soil remediation of heavy metals pollution.

Feedstock	Pyrolysis Temp.	Remediation effect	Ref.
Sewage sludge	500 ºC	increased pH and decreased available heavy metal in soil	(Xing 2021, Chen 2020)
Livestock manure	450 ºC	decreased heavy metal content in Brassica napus	(Guo 2020, Gascó 2019)
Rice husks	450 ºC	reduced the toxicity of heavy metals in soil and increased plant productivity	(Guo 2020, Xing 2021)
Hardwood	600 ºC	Ni, Zn contents in soil declined by 83%-98% in three years	(An 2020)
Straw	500 ºC	decreased Cd content in soil	(Guo 2020, Peng 2020)
Bagasse	450 ºC	Cd decreased by 76%, Pb decreased by 49.1% in plant	(Nie 2018)
Maize straw	400 ºC	available Cd in soil decreased by 21%-56%	(Xing 2021)
Litchi	500-550 ºC	improve soil properties, reduce Pb and Cd accumulation	(Jiang 2020)

4.2 Mechanism of Biochar in Soil Remediation

At present, various studies have made efforts for the explanation of biochar adsorption of heavy metals and the mechanism could be mainly divided into the following aspects (Nie 2018, Chen 2020, Gascó 2019, Wang 2021): (i) electrostatic adsorption: biochar was generally electronegative, so it can adsorb cations when adding to soil; (ii) complexation: the metal ions can be fixed by forming complexation with functional groups on the surface of biochar; (iii) precipitation: mineral components (such as carbonate and phosphate) can transform heavy metals into more stable forms by coprecipitation and reduced their pollution risks; (iv) ion exchange: by increasing soil CEC, biochar can improve the ion exchange and adsorption of heavy metals. Oxygen-containing functional groups also played an active role in ion exchange of heavy metals; (v) indirect effect: biochar can also immobilize heavy metals in soil through the complex, simultaneous and interact functions among soil, animals, plants and microorganisms (Nie 2018, Antonangelo 2021). Thus, we can not only use biochar to remove and fix the metal pollutants in the soil, but also can select different kinds of raw materials according to the different kinds of metal pollution, to ensure optimal repair effect.

5 CONCLUSION AND PROSPECTS

Biochar has promising application in soil improvement and remediation for its comprehensive effects on soil fertility, microbial activity, plant and crop growth, and heavy metals immobilization. Although biochar can improve soil fertility and repair polluted soil, the mechanisms of biochar on soil remediation of heavy metal pollution and other emerging pollutants (Antonangelo 2021), especially the interact role of microorganisms, are still unclear. The different performances of biochar in different types and properties of soil, long-term stability and toxicity of biochar, as well as field application, all need in-depth researches in the future.

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