Applications, potential, and challenges of biochar in carbon sequestration

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Abstract. Biochar has great potential for carbon sequestration and has become a hot area of scientific research in recent years. Biochar can not only effectively fix atmospheric carbon dioxide in the soil, but also has multiple ecological benefits, such as improving soil structure, increasing soil fertility, and reducing greenhouse gas emissions. However, the technology still faces some challenges in practical industrial applications. In this paper, the characteristics of biochar are first described in detail, including types and properties, preparation methods, and carbon sequestration mechanisms. Subsequently, the challenges faced by biochar in the carbon sequestration process are discussed. Finally, the article proposes future directions and optimization measures for biochar, suggesting that by optimizing the raw material selection, improving the production process, assessing the long-term environmental impact, and reducing the cost. Through these measures, biochar technology is expected to further realize its carbon sequestration potential and play a more important role in the global response to climate change.

Keywords: Biochar, Carbon sequestration.

1. Introduction

Biochar is an important carbon sequestration technology that plays a positive role in improving climate change and soil health. Biochar produces carbon-rich materials under anoxic conditions by pyrolyzing biomass, such as crop residues. With the help of its porous structure and chemical stability, carbon can be stored for a long time, and the physical and chemical properties of the soil will be effectively improved [1]. Biochar can not only effectively reduce greenhouse gas emissions, but also improve soil fertility to promote plant growth, thereby achieving the dual role of agricultural production and environmental protection [2]. In addition, the application effect of biochar in different soil types (sandy, clay) and climatic conditions (tropical, temperate) has also been widely verified [3]. With the continuous advancement of technology and the expansion of its application scope, the potential of biochar in carbon sequestration will be further explored and utilized [4]. This article summarizes the current technology of biochar in carbon sequestration, points out the shortcomings, and proposes suggestions for optimizing future technologies.

2. Characteristics and preparation of biochar

2.1. Biochar Type

There are five main types of biochar, namely wood biochar, herb biochar, livestock and poultry manure biochar, sludge biochar, and mixed biochar. Wood biochar is mainly composed of wood materials such as wood, bark, sawdust, etc., which has a well-developed pore structure and high mechanical strength, and is suitable for soil improvement and water treatment. The main components of herb biochar include herbaceous plant residues such as rice straw, wheat straw, and corn stalks, which have large specific surface area and high porosity, and are suitable for improving soil structure and fertility. The components of livestock and poultry manure biochar include livestock and poultry manure such as cow dung, pig manure, and chicken manure. This type of biochar is rich in nutrients, especially nitrogen, phosphorus, potassium, and other elements, and is suitable as an organic fertilizer and soil conditioner. Sludge biochar includes municipal sludge, industrial sludge, etc., which is rich in organic matter and trace elements, and is suitable for soil remediation and pollutant adsorption. Mixed biochar is a mixture of multiple biomass, such as wood and herbaceous plants, livestock and poultry manure and crop residues, etc., which combines the advantages of different raw materials, has versatility, and is suitable for various application scenarios.

2.2. Nature

Biochar has several remarkable properties that make it valuable for application in environmental management and soil improvement. Firstly, biochar has a large specific surface area, which provides a wide surface area for material exchange with the surrounding environment, and the size of the particular surface area usually depends on the raw material and pyrolysis conditions of biochar. In addition, biochar has a well-developed pore structure, and this porosity not only enhances its adsorption capacity but also increases its water-holding capacity, which helps to improve soil moisture conditions. Biochar is also highly thermally stable, allowing it to persist in the soil for a long period and perform continuous ecological functions. The alkaline qualities of biochar help to neutralize acidic soils, thus improving the acid-base balance of the soil. Besides, the good adsorption capacity of biochar enables it to effectively adsorb organic pollutants in the soil, reducing the migration and spread of pollutants [5]. Finally, biochar typically has a carbon content of up to 60% to 90%, depending on the raw material and pyrolysis conditions, and the high carbon content ensures excellent stability and durability of biochar for environmental applications.

2.3. Method for preparing biochar

Biochar can be prepared in a variety of ways, of which pyrolysis is the most common and easily reactive. Pyrolysis is the decomposition of biomass into biochar, gases, and liquid products in an anaerobic or anoxic environment under heating conditions ranging from 200°C to 900°C. Gasification is the conversion of biomass into syngas (mainly composed of CO and H_2) and biochar under high temperature and partially oxidizing conditions from 800°C to 1200°C. Hydrothermal carbonization also converts biomass to syngas and biochar at high temperatures (800°C to 1200°C) and under partially oxidized conditions. The microwave carbonization method heats the biomass by microwave and decomposes it under anaerobic conditions to produce biochar, which is uniformly heated, fast, and energy efficient. The chemical activation method involves adding chemical reagents (e.g. KOH, H_3PO_4, $ZnCl_2$, etc.) during the pyrolysis or carbonization process in order to activate the biochar and produce biochar with high specific surface area and high porosity, thus significantly improving its adsorption performance and catalytic activity [6]. Through these different preparation methods, the structure and properties of biochar can be adjusted according to the application requirements, enhancing its application value in environmental remediation and resource utilization.

3. Cabon sequestration of biochar

3.1. Carbon sequestration mechanism of biochar

The process of formation and application of biochar demonstrates its important role in the carbon cycle and environmental protection. First, through pyrolysis technology, biomass is heated under anaerobic or anoxic conditions to convert the carbon in it into a stable carbonized substance, i.e. biochar, while releasing volatile organic compounds and gases. The carbon in biochar exists in the form of stable aromatic carbon, a structure that facilitates long-term carbon sequestration and promotes the carbon sequestration effect of biochar in the environment [7]. In addition, the porous structure and good adsorption properties of biochar can capture greenhouse gases, including carbon dioxide, methane, and nitrous oxide, thus effectively reducing greenhouse gas emissions. In terms of soil sequestration, plants absorb atmospheric carbon dioxide through photosynthesis, and the biomass generated is converted into biochar, which fixes carbon in the soil and reduces the concentration of carbon dioxide in the atmosphere. At the same time, the porous structure of biochar can adsorb and retain water and nutrients, providing a habitat for soil microorganisms and improving soil health.

Therefore, biochar not only has significant advantages in carbon sequestration but also improves its ecological benefits by improving soil quality.

3.2. Factors affecting the carbon sequestration capacity of biochar

The carbon sequestration capacity of biochar is affected by a number of factors, including the type of raw material, the intermediary environment, the pyrolysis conditions, and the physicochemical properties of the biochar [8]. First, woody biomass usually contains high lignin and cellulose, generating biochar with high stability and carbon content, which is suitable for long-term carbon sequestration; whereas herbaceous plants contain high ash and minerals, generating biochar with lower carbon content and lower stability. In addition, suitable soil pH and higher soil organic matter content helped to improve the stability of biochar, thus enhancing its carbon sequestration effect. The pyrolysis conditions also have an important effect on the performance of biochar. Biochar generated by low-temperature pyrolysis (300-500°C) contains more volatiles and unstable carbon, and has lower carbon sequestration capacity, while biochar generated by high-temperature pyrolysis (500-700°C) has higher carbon content and stability, and has stronger carbon sequestration capacity. In addition, the high specific surface area and porosity of biochar help to improve its adsorption capacity and stability, while biochar rich in aromatic carbon has higher chemical stability and carbon sequestration capacity. Taken together, the carbon sequestration performance of biochar can be significantly enhanced by selecting suitable raw materials, optimizing pyrolysis conditions, and considering the influence of the intermediary environment.

4. Application and challenges of biochar in carbon sequestration

4.1. Application of biochar

The application of biochar in carbon sequestration has a wide range of prospects, mainly in agricultural applications, organic waste treatment, adsorption of pollutants, ecological restoration, and carbon trading.

Firstly, the application of biochar in agriculture mainly focuses on soil improvement and fertility enhancement. The porous structure of biochar can significantly improve the physical properties of the soil, enhance the structural stability of the soil, and then increase the water retention capacity and nutrient retention capacity of the soil. These properties make biochar an important application in agriculture, especially in reducing greenhouse gas emissions. Studies have shown that biochar can reduce methane (CH_4) and nitrous oxide (N_2O) emissions from soils, which is positive for mitigating climate change [9].

Secondly, in terms of organic waste treatment, the production process of biochar can effectively treat wastes such as agricultural residues, livestock and poultry manure, and municipal organic waste. Through the pyrolysis process, these organic wastes can not only be converted into a stable form of carbon, biochar, but also reduce the volume of the waste and realize the sequestration of organic carbon [10]. In this way, organic waste, which might otherwise release large amounts of carbon dioxide due to natural decomposition, can be converted into a stable product with long-lasting carbon sequestration capacity, thus reducing carbon emissions and promoting the utilization of waste resources.

In terms of pollutant adsorption, biochar has demonstrated excellent capabilities, especially in the treatment of heavy metal pollutants. The porous structure and chemical stability of biochar enable it to effectively adsorb and immobilize heavy metal pollutants in the soil, reducing the bioavailability of these pollutants and thus reducing their harm to the environment. Additionally, biochar can also assist in ecosystem restoration by improving phytoremediation capacity, thus restoring the health and ecological function of damaged soil.

In ecological restoration, biochar is widely applied as a soil amendment. Since biochar can improve the physical and chemical properties of soil and enhance the health of soil, it plays an important role in ecological restoration projects. Especially in damaged ecosystems, the application of biochar helps to restore the function of the soil, enhance the plant growth environment, and promote the sustainable development of the entire ecosystem [11].

Finally, the potential of biochar in carbon trading should not be overlooked. Through biochar projects, enterprises and organizations can obtain carbon credits to offset their carbon emissions. This mechanism not only provides carbon-emitting enterprises with a new way to offset their carbon emissions, but also provides a market impetus for the promotion and application of biochar, which promotes the process of carbon neutrality on a global scale.

The application of biochar in carbon sequestration has demonstrated multiple environmental and economic benefits, and its wide application in agriculture, waste treatment, pollution management, ecological remediation, and carbon trading signifies its great potential in combating climate change and promoting sustainable development.

4.2. Research challenges and future optimization directions

Biochar is a potential carbon sequestration technology. However, there are still some challenges in the research and application of biochar. In terms of raw material diversity, biochar has a wide range of components, and the physical and chemical properties of different raw materials vary significantly, which will lead to biochar with different performances. Therefore, researchers need to analyze the characteristics of various biomass materials to select raw materials with high carbon content and pyrolysis efficiency. In addition, the performance of biochar can also be improved by mixing raw materials [12].

In terms of production technology, in the complex production process of biochar, factors such as the pyrolysis process, temperature, and time control will affect the properties of the produced biochar. The production process needs to optimize pyrolysis conditions including time, temperature, and atmosphere, and explore new pyrolysis technologies such as microwave pyrolysis to improve the stability and production efficiency of biochar. Besides, In addition, adding chemical modifications or functional materials during the production process can help enhance the adsorption capacity and stability of biochar [13].

In terms of environmental impact, due to the lack of long-term field trials and environmental monitoring, the environmental impact and long-term stability of biochar in soil cannot be determined. The full life cycle of biochar and the carbon footprint generated during production and application need to be quantified and evaluated.

In terms of cost, the high costs of production and application limit the large-scale application and promotion of biochar. Thus, low-cost production and application technologies need to be developed. In addition, policy and market support is also necessary, including carbon credits, carbon subsidies, and unified biomass carbon quality standards and certification systems.

5. Conclusion

In conclusion, biochar is an effective carbon sequestration technology that can store carbon for a long time and improve soil quality by converting biomass into stable carbon forms through pyrolysis. Biochar properties, medium properties, and environmental factors all affect the carbon sequestration capacity of biochar. In terms of carbon sequestration, biochar can be effectively applied to agriculture, organic waste treatment, adsorption of heavy metal pollutants, ecological restoration, carbon trading, etc. However, biochar has raw material diversity, high production costs, lack of long-term research data, and unified carbon sequestration quality standards and specifications, and is currently difficult to use on a large scale. In the future, the research direction of biochar should focus on optimizing the preparation process, improving carbon sequestration efficiency and unifying standards, and promoting its large-scale application in agriculture and environmental remediation. The research on biochar in carbon sequestration provides a sustainable carbon emission reduction technology for mitigating climate change, improving soil health, increasing agricultural productivity, reducing waste treatment pressure, and ultimately promoting the sustainable development of the circular economy.

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