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Biochar's Role in Sustainable Water and Soil Management Practices

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INTRODUCTION

Soil degradation has become increasingly prevalent due to modern agricultural practices. These practices introduce various pharmaceutical ingredients such as lead, zinc, and cadmium into the soil, which in turn lead to soil acidification, alkalinity, and the depletion of organic matter. Moreover, these chemical inputs release ammonium and methane, contributing to global warming and severe water pollution.

Biochar represents a promising solution to enhance soil fertility. Biochar is produced through pyrolysis, resulting in a porous carbonaceous structure with a variety of functional groups (Lehmann J, 2009). The carbon content of biochar increases with pyrolysis temperature, ranging from 300 to 800 °C, while nitrogen and hydrogen content decreases. Incorporating biochar into soils can improve soil structure, increase porosity, reduce bulk density, enhance aggregation, and improve water retention (Baiamonte et al., 2015; Sharma et al., 2023).

Understanding the mechanisms behind changes in soil fertility following the application of biochar is crucial. This article examines the changes in soil properties, including physiochemical and biological properties, after biochar application. Biochar can be classified into three categories: 1) feedstock with lower carbon ash (3–5%), such as bamboo and nut shells; 2) feedstock with ash (3–5 to 10–13%), such as tree bark, agricultural residues, and green wastes; and 3) feedstock with ash (>13%), such as waste paper, manures, industrial effluent, and municipal solid wastes. Because of its many qualities, biochar has recently been a hot issue in interdisciplinary research. The most common woody feedstock for biochar formation is oak sawdust, which is employed as a sustainable media. The usage of biochar is growing quickly in order to increase food security and produce agricultural products in a sustainable manner.

Biochar as fertilizer

Biochar is composed of organic matter and inorganic salts like humic-like and fluvic-like substances, as well as NPK in readily available forms, which function as fertilizers. According to Lin et al. (2012), biochar derived from Acacia saligna at 380°C and sawdust at 450°C contained humic substances (humic-like and fluvic-like materials) at rates of 17.7% and 16.2%, respectively. Masto et al. (2013) found that biochar produced from Lantana camara at 300°C contained available P (0.64 mg kg−1), K (711 mg kg−1), Na (1145 mg kg−1), Ca (5880 mg kg−1), and Mg (1010 mg kg−1).

Biochar's effects on the physical characteristics of soil

Biochar has been shown to enhance soil porosity, increase water storage capacity, and reduce bulk density (Chen et al., 2007; Abel et al., 2013). Peake et al. (2014) found that biochar application could raise available water holding capacity by more than 22%, decrease bulk density from 1.47 to 1.44 mg m−3, and increase porosity from 0.43 to 0.44 m3 m−3 (Nelissen et al., 2015). Overall, the use of biochar has improved soil physical properties such as bulk density, water holding capacity, and aggregation ability, contributing to enhanced soil fertility.

Biochar's effects on the chemical composition of soil

The application of biochar to soil enhances its chemical properties, such as pH, organic carbon content, cation exchange capacity (CEC), and nitrogen fertilizer use efficiency (NUE) (Agegnehu, G., A. K. Srivastava, and M. I. Bird, 2017). According to Novak et al. (2009), applying biochar to acidic coastal soil increases soil pH, organic matter, manganese, and calcium, while decreasing sulfur and zinc. Table 1 presents a summary of the changes in soil chemical properties resulting from various levels of biochar application: 0, 10, 15, and 20 t ha-1 (Uzoma et al., 2011).

Effects of Biochar Application on Biological Properties of Soil

Biochar serves as a habitat for small beneficial organisms, including symbiotic mycorrhizal fungi, which penetrate the soil and enhance enzymatic activity. Symbiotic organisms like Rhizobium are activated in biochar-treated environments, promoting increased nodulation and nitrogenase activity. Additionally, free-living bacteria such as Azotobacter sp. and Azospirillum benefit from the surplus habitat and adequate oxygen supply in biochar-amended soils (Gabhane et al., 2020).

Application of biochar in the environment

1. Using biochar to clean up contaminants, metals, and metalloids

Biochar produced via pyrolysis at temperatures ranging from 550°C to 750°C is beneficial for phytoremediation of metals such as zinc, lead, and cadmium. Due to its alkaline pH, biochar aids in increasing soil pH and stabilizing metals, potentially reducing the bioavailability and leachability of heavy metals and organic pollutants in soils through strong adsorption and various physicochemical reactions (Zhang et al., 2013).

2. The use of biochar to lessen water pollution

Biochar has been found to be effective in managing water pollution and treating contaminated wastewater. According to Hao et al. (2021), the use of coconut shell biochar can mitigate lead contamination in water due to its porous structure.

3. The role of biochar in reducing climate change and sequestering carbon:

Biochar is remarkably stable in soil, helping mitigate climate change by sequestering carbon. Studies have shown that applying biochar at a rate of 2% – 5% can significantly increase carbon sequestration by 46% – 58% in rice and beet fields (Lai et al., 2013). Additionally, research conducted in the Loess Plateau of China demonstrated that biochar derived from apple wood residues, when reapplied in apple orchards, can enhance soil organic carbon sequestration by 316.52% – 354.78% over a two-year period (Han et al., 2022).

4. Emerging hazardous wastes including organic pollutants and microplastics can be rectified with biochar:

The widespread use of plastic worldwide has significantly heightened soil and aquatic contamination. A promising method for removing microplastics from aquatic systems involves catalytic removal using magnetic biochar to activate oxidation processes (Ye et al., 2020). Another effective approach for removing microplastics from aqueous solutions utilizes magnesium and zinc-modified magnetic biochar through magnetic and thermal degradation methods (Wang et al., 2021).

5. Induces Microbial Activity in the Soil

Applying biochar modifies the soil's physical and chemical properties, enhancing its ability to serve as a carrier for microorganisms. Soil microbial activity is crucial for the decomposition of organic matter, nutrient cycling, and improving the nutrient availability and production capacity of crops. Research has shown that biochar stimulates microbial growth by providing a favorable medium for microbes (Parmar et al., 2014). Biochar application has been found to influence the activity and habitat of beneficial organisms like mycorrhizal fungi, leading to improved soil health and quality. Studies have also documented that biochar, particularly from fresh biogas, positively impacts soil microbiota by modulating the suppression of harmful ions such as arsenic and ferric ions.

6. Agronomical Importance (Crop Improvement)

Biochar has significant agronomical benefits, particularly in enhancing crop yield and productivity. It improves nutrient availability and increases nutrient-use efficiency by crops. Literature reports a 10% increase in crop yields following biochar application. Biochar also reduces soil salinity, thereby improving nutrient accessibility and supporting higher yields (Akhil et al., 2021). Furthermore, biochar has demonstrated potential in managing plant diseases and pests. A 3–5% biochar application can inhibit the growth of fungal pathogens and reduce pest activity (Parmar et al., 2014). Numerous field and pot experiments have revealed that biochar application enhances the growth and yield of various crops, including *Phaseolus vulgaris*, *Cucumis sativus*, *Fragaria × ananassa*, *Solanum lycopersicum*, *Zea mays*, *Citrullus lanatus*, and *Piper nigrum* (Das et al., 2020). Additionally, studies indicate that rice husk biochar applied to wheat crops boosts yield and water retention capacity, further emphasizing biochar's agronomical importance.

CONCLUSION

The use of biochar is expected to improve soil fertility, plant growth, and crop yield. Biochar's unique properties, such as its high surface area, well-defined pore structure, and concentrations of exchangeable cations and nutrient elements, are influenced by factors like the type of biomass used and the temperature during pyrolysis. These physiochemical attributes contribute to enhanced soil fertility and support the proliferation of beneficial soil microorganisms after biochar application. This review offers a structured examination of the importance of biochar application in soil management, water treatment, and wastewater treatment to reduce contamination in natural ecosystems.

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