Role of Biochar in carbon sequestration and soil physical, chemical and biological properties

Abstract

Biochar, a stable, carbon-rich material derived from the pyrolysis of organic matter under limited oxygen conditions, has emerged as a sustainable solution for addressing climate change and enhancing soil health. This study explores the multifaceted role of biochar in carbon sequestration and its impact on soil physical, chemical, and biological properties. The unique structural and chemical characteristics of biochar enable it to store carbon for centuries, effectively mitigating greenhouse gas emissions and contributing to a negative carbon footprint. Additionally, biochar alters soil physical properties by improving porosity, aeration, and water retention, which enhances root growth and soil resilience against erosion and extreme weather conditions.Chemically, biochar enhances soil fertility through its high cation exchange capacity and alkaline nature. It retains essential nutrients, prevents leaching, and ameliorates soil acidity, creating a favorable environment for plant growth. Biologically, biochar supports microbial diversity and activity by providing a habitat for beneficial microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi. Despite its numerous benefits, the effectiveness of biochar is influenced by factors such as feedstock type, production conditions, and soil characteristics. Challenges such as economic feasibility, potential nutrient imbalances, and environmental trade-offs must be addressed to optimize its application. Future research should focus on tailoring biochar properties to specific soil and crop needs, scaling up production, and integrating biochar into sustainable land management practices.By sequestering carbon and enhancing soil properties, it offers a scalable solution for building resilient agricultural systems and achieving environmental sustainability.

Keywords: Environment, Nitrogen, Sequestration, Fertility, Alkaline

Introduction

Biochar, a carbon-rich material produced through the pyrolysis of organic matter under oxygen-limited conditions (Luo et al., 2023) and at relatively low temperatures (<700°C), has emerged as a versatile and sustainable solution to contemporary environmental challenges**(Yadav et al., 2017)**. With a unique combination of physical, chemical, and biological properties, biochar has the potential to address critical issues such as climate change, soil degradation, and agricultural sustainability. The uses of biochar fall into four main categories: climate change mitigation, soil conditioning, waste management, and energy **(Mašek., 2013)**. The rising concentration of greenhouse gases in the atmosphere is the maine cause of global warming **(Gupta et al., 2020)** and it has intensified the urgency to develop effective strategies for mitigating climate change. Carbon sequestration is the long-term storage of carbon in soils, and other reservoirs. It has potential role in sustainable agricultural practices **(Chagas et al., 2024)**. It is a key component of global efforts to reduce atmospheric carbon dioxide (CO_2) levels**(Wu et al., 2018)**. Biochar can be use as a tool to sequestering Carbon in soil **(Mukherjee and Lal., 2013)**. Biochar offers a promising pathway for achieving this goal due to its remarkable stability and resistance to decomposition. Unlike traditional organic amendments, which decompose relatively quickly and release CO_2 back into the atmosphere, biochar remains in the soil for centuries, effectively locking away carbon and contributing to a negative carbon footprint.Furthermore, biochar's ability to adsorb heavy metals inorganic and organic pollutants makes it a valuable tool for soil remediation **(Elkhlif et al., 2023)**. In addition to its role in carbon sequestration, biochar significantly improve the soil physical, chemical, and biological properties **(Layek et al., 2022)**. creating a synergistic effect that benefits both the environment and agricultural productivity. Soil is the foundation of terrestrial ecosystems, and its degradation poses a severe threat to food security and biodiversity. Biochar enhance the yield potential of highly degraded soil **(Lorenz & Lal., 2014)**. The application of biochar can restore degraded soils by improving their structure, fertility, and microbial activity**(Mitchell et al., 2015, Agegnehu et al., 2017)**.From a physical perspective, biochar improves soil porosity, aeration, and water retentionparticularly in sandy and compacted soils. Chemically, biochar acts as a reservoir for essential nutrients due to its high cation exchange capacity (CEC) and alkaline nature. It can retain nutrients that might otherwise be lost to leaching, making them available for plant uptake over extended periods. The biological benefits of biochar are equally significant. By providing a stable habitat for soil microorganisms, biochar fosters microbial diversity and activity. Beneficial microbes, such as nitrogen-fixing bacteria and mycorrhizal fungi, thrive in the presence of biochar, enhancing nutrient cycling and plant growth. Despite these benefits, the use of biochar is not without challenges. Its effectiveness varies depending on factors such as feedstock type, production conditions, and soil characteristics. Its integration into sustainable land management practices offers a pathway to enhancing agricultural resilience while contributing to global efforts to combat climate change. It is reduces the decomposition of soil organic carbon **(Yin et al., 2022)**. Biochar has gained significant attention in recent years as a sustainable solution for mitigating climate change**(Shirzad et al., 2023)** and enhancing soil health. Derived from the pyrolysis of organic materials in an oxygen-limited environment, biochar has a porous structure, a high carbon content, and a diverse range of physical and chemical properties that make it suitable for various agricultural and environmental applications.

Role of Biochar in Carbon Sequestration

One of the primary benefits of biochar is its potential to sequester carbon**(Sheng et al., 2016, Nan et al., 2021)**. It is an eco-friendly approach for soil carbon sequestration **(Sarfraz et al., 2019)**. The C sequestration capability of biochar is depend on the solid carbon retention and the stability of this carbon in biochar after pyrolysis (Nan et al., 2022). Biochar (BC) is regarded as an important way of carbon sink (Zhang et al., 2020).Unlike other forms of organic matter, biochar is highly stable and resistant to microbial decomposition, allowing it to remain in the soil for hundreds to thousands of years**(Yadav et al., 2017, Rodrigues et al., 2023)**. The characteristics of biochar depend on pyrolysis conditions viz. oxygen, highest temperature, pressure, heating period and rate, etc**(Igalavithana et al., 2017)**. Biochar is black carbon, but not all black carbon is biochar (Spokas et al., 2012).The application of biochar to soils not only stores carbon but also reduces emissions of greenhouse gases such as methane (CH_4) and nitrous oxide **(Wang et al., 2023)**. Studies have shown that biochar can suppress methane emissions from anaerobic soils by enhancing oxygen diffusion and promoting the activity of methanotrophic bacteria. Similarly, biochar reduces nitrous oxide emissions by altering soil microbial processes, such as nitrification and denitrification, due to its high adsorption capacity and the modulation of soil pH.Additionally, biochar production itself can contribute to climate change mitigation**(Mekuria & Noble., 2013, Lal., 2016)**. By converting biomass into a stable carbon form**(Majumder et al., 2019)**, biochar production reduces the amount of organic matter that would otherwise decompose and release carbon dioxide (CO_2) into the atmosphere. Moreover, the pyrolysis process can generate bioenergy**(Matovic., 2011)**, which serves as a renewable energy source and offsets fossil fuel use.

Role of Biochar in Soil Physical Properties

1. Soil Structure

Biochar significantly enhances soil structure by modifying its aggregation and stability. When applied to soil, biochar interacts with soil particles such as sand, silt, and clay, promoting the formation of stable aggregates. It is positively influencing the aggregate formation **(Makó *et al.*, 2020, Blanco-Canqui., 2017).**This process improves soil aeration and root penetration, fostering better plant growth. The porous nature of biochar also acts as a microhabitat for soil microbes, whose activity further contributes to aggregate stability. Additionally, biochar's resistance to decomposition ensures that these structural benefits persist over time. Improved soil structure also reduces the risks of compaction and erosion, leading to more sustainable land management practices.

2. Water Retention

Water retention properties of the soil was enhanced by the application of biochar**(Głąb*et al.*, 2016, Paneque *et al.*, 2016, Xiao *et al.*, 2016).** This is particularly beneficial in sandy soils because biochar increased soil water retention **(Aslam *et al.*,2014).** By absorbing and holding water within its structure, biochar reduces water percolation and evaporation losses. This can be crucial in arid and semi-arid regions where water availability is a limiting factor. Moreover, biochar's ability to retain water ensures consistent moisture levels, supporting plant growth and reducing irrigation needs. It also enhances the soil's capacity to withstand drought stress.

3. Soil Bulk Density

The incorporation of biochar into soil reduces its bulk densitybecause porosity of biochar is very high **(Mukherjee *et al.*,2013**,**Zhang *et al.*,2013, Głąb*et al.*,2016)**. This reduction is particularly useful in heavy clay soils, which are prone to compaction and poor drainage. A lower bulk density improves soil aeration and root growth, enabling better nutrient uptake. Additionally, reduced soil density minimizes the energy required for tillage, leading to lower operational costs and reduced soil degradation.

4. Impact on Soil Porosity

Biochar increases soil porosity due to high porous nature of biochar **(Mukherjee *et al.*, (2013**) and **Singh *et at.*, (2022)**. This enhancement in porosity improves aeration, movement and retention of nutrient as well as waterwithin the soil**(Aslam *et al.*, (2014)**. The interconnected pore network also helps prevent waterlogging in poorly drained soils while retaining sufficient moisture for plants. Enhanced porosity further facilitates nutrient retention and transport, contributing to overall soil fertility.

5. Thermal Properties

Biochar influences the thermal properties of soil by altering its heat conductivity and storage capacity. Application of biochar reduced the thermal conductivity of soil as well as thermal diffusivity (**Zhao *et al.*, 2016, Usowicz *et al.*,2016)**. Its dark color and porous nature help in absorbing and retaining heat during the day, which can moderate soil temperature fluctuations. This thermal buffering effect is particularly beneficial in colder climates, where warmer soils promote early germination and root development. Additionally, biochar's thermal properties may protect soil microbial activity during extreme temperature changes, supporting a stable and productive ecosystem.

Role of Biochar in Soil Chemical Properties

1. Soil pH

Biochar often exhibits an alkaline pH**(Jemal & Yakob., 2021)**, making it an effective amendment for acidic soils (Dai et al., 2017). **Gonzaga et al., 2020** seen that the biochar was increase the pH of soil. Generally, biochar can induce changes in soil pH, CEC, and exchangeable Ca^{2+}, K^{+}, and Mg^{2+} with the effectiveness and magnitude of change closely related to the soil's original properties **(Hailegnaw et al., 2019)**.This pH adjustment improves nutrient availability, reduces the solubility of toxic elements like aluminum, and enhances microbial activity. By stabilizing soil pH, biochar creates a more favorable environment for plant growth and nutrient cycling.

2. Cation Exchange Capacity (CEC)

The porous structure and high surface area of biochar contribute to its remarkable ability to increase soil cation exchange capacity (CEC)**(Fu., et al., 2016, Ennis et al., 2012)**. This means that biochar can hold and exchange essential nutrients, such as potassium (K^{+}), calcium (Ca^{2+}), and ammonium (NH_4^{+}), making them more available to plants**(Munera-Echeverriey al., 2018)**. The improvement in CEC also reduces nutrient leaching, particularly in sandy soils, ensuring long-term soil fertility.

3. Nutrient Retention and Supply

Biochar acts as a reservoir for nutrients, adsorbing and retaining them within its structure**(Liu et al., 2018)**. The biochar is composed of C,H, N and also carries some of the other essential plant elements such as K, Ca, Mg, Na **(Elkhlif et al., 2023)**. Biochar's ability to store nutrients benefits crops by providing a consistent and slow-release source of essential elements. It increases nitrogen retention in soil by reducing leaching and gaseous loss, and also increases phosphorus availability by decreasing the leaching process in soil **(Hossain et al., 2020)**.Additionally, biochar can enhance the efficiency of applied fertilizers by reducing nutrient losses.

4. Organic Matter Stabilization

Biochar stabilizes organic matter in soil **(Dong et al., 2016)**by reducing the decomposition rates of labile carbon pools**(Kimetu& Lehmann., 2010)**. This leads to increased soil organic carbon levels over time, which is beneficial for soil fertility and structure. Biochar can actively promote soil C storage by promoting aggregation and the physical stabilization of SOM**(Wang et al.,**

2017). The interaction of biochar with organic matter also supports the formation of humus, a key component of healthy, fertile soils.

5. Heavy Metal Immobilization

Biochar has a high capacity for adsorbing heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As), thereby reducing their bioavailability in contaminated soils**(Khan et al., 2020)**. The increase in soil pH caused by adding biochar and apatite created more negative charge on the soil surface that promoted Pb, Zn and Cd adsorption **(Joseph et al., 2019)**. Biochar mineral composites enhanced heavy metals immobilization in soil **(Wang et al., 2022)**. Its functional groups, such as carboxyl and hydroxyl, bind these metals, preventing their uptake by plants and reducing toxicity risks. This property makes biochar a valuable tool in soil remediation efforts.

6. Nutrient Leaching

Biochar has been widely reported to reduce nutrient leaching in agricultural systems **(Gao & DeLuca., 2016)**. The adsorption properties of biochar help retain nutrients like nitrate (NO_3^-) and ammonium (NH_4^+) in the soil**(Alkharabsheh et al., 2021)**, preventing their leaching into groundwater. This is particularly important in sandy soils and regions with high rainfall, where nutrient losses can be substantial. Reduced leaching **(Laird et al., 2010)**not only improves nutrient use efficiency but also minimizes environmental pollution.

Soil Biological Properties

The biological properties of soil are profoundly improved by biochar application**(Taheri et al., 2024)**. By providing a habitat for microorganisms**(Gul et al., 2015, Kuryntseva et al., 2023)**, biochar enhances microbial diversity and activity**(Hossain et al., 2020)**. Its porous structure offers refuge and colonization sites for beneficial microbes, including nitrogen-fixing bacteria and mycorrhizal fungi, which are crucial for nutrient cycling and plant health.Biochar can stimulate soil microbial activity by serving as a source of labile carbon and by modifying soil pH and moisture content**(Murtaza et al., 2021)**. Enhanced microbial activity **(Zaheeret al., 2021)**promotes the decomposition of organic matter, nutrient mineralization, and the suppression of soil-borne pathogens.In addition to benefiting microbial communities, biochar can directly influence plant growth through its interactions with the rhizosphere. The improved nutrient availability, reduced phytotoxicity, and enhanced water retention associated with biochar create an optimal environment for root development and plant growth.

Conclusion

Biochar represents a promising tool for addressing the twin challenges of climate change and soil degradation. Its ability to sequester carbon, improve soil physical, chemical, and biological properties, and mitigate greenhouse gas emissions underscores its value as a sustainable soil amendment. However, realizing its full potential requires overcoming technical, economic, and logistical challenges through innovative research and policy support. By integrating biochar into holistic land management strategies, we can create resilient agricultural systems and contribute to a sustainable future.

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