Biochar's Influence on Soil Microorganisms: Understanding the Impacts and Mechanisms

Abstract

Biochar, the carbon-rich material produced from biomass pyrolysis, has garnered significant attention and research interest owing to its myriad of potential benefits for soil enhancement. These benefits range from increasing soil carbon storage, boosting soil fertility, to transforming and fixing pollutants in soil, all of which serve to ameliorate the overall soil environment. The impact of these improvements extends to the metabolic activities and community structure of soil microorganisms, either directly or indirectly, creating ripple effects on soil health. This paper embarks on a thorough review of biochar's effects on various soil aspects. These include the soil's physicochemical properties, such as its structure, composition, and reaction properties, and how biochar can influence these to improve the soil environment. It also explores how biochar affects enzyme activities in the soil that are crucial for various biochemical processes, as well as nutrients vital for plant growth and development. Importantly, the ability of biochar to interact with contaminants, rendering them harmless or less toxic, is examined, alongside an investigation into the related microbial activities that are influenced by these changes. This work also aims to summarise the potential mechanisms of interaction between biochar and microorganisms, providing a clearer understanding of how biochar influences the soil microbiome. It discusses the potential risks associated with biochar use, such as the release of harmful substances or unintended shifts in microbial communities, emphasizing the importance of a balanced view towards biochar application. Overall, the aim of this study is to lay a robust theoretical groundwork for future research in this field, contributing towards a better understanding and utilisation of biochar for soil enhancement and sustainable agriculture.

Keywords: *Biochar, Soil Enhancement, Microbiome, Contaminant, Sustainable Agriculture*

Introduction

Biochar, a carbon-dense byproduct arising from the pyrolysis of organic biomass, has seen a resurgence in interest within environmental and agricultural spheres. Pyrolysis, an ancient technique, refers to the thermal decomposition of organic substances in an oxygen-limited environment. This process not only generates biochar but also yields syngas and bio-oil (Lee *et at.*, 2020). Biochar, in particular, is typically produced from a variety of biomass sources, including wood, manure, and plant residue. This results in a material possessing distinctive qualities such as high porosity, expansive surface area, and substantial carbon content. These unique properties make biochar an attractive option for soil amendment. Owing to its distinctive physical and chemical characteristics, biochar has shown promise as a means to improve soil health and fertility. It's high porosity and large surface area facilitate the retention of water and nutrients, enhancing the soil's capacity to support plant growth. Its high carbon content, on the other hand, contributes to soil carbon sequestration, an important aspect of mitigating climate change (Powlson *et al.*, 2011).

Biochar's stability and resistance to decomposition contribute to its long-term effectiveness as a soil amendment. Unlike other organic materials that decompose and release stored carbon back into the atmosphere, biochar remains in the soil for longer periods. This not only promotes prolonged soil fertility but also ensures more stable carbon storage, making biochar an attractive strategy for sustainable agriculture and carbon sequestration (Osman *et al.*, 2022). The potential of biochar in soil enhancement and climate change mitigation has piqued the interest of researchers worldwide. Biochar's ability to enrich soil fertility, bolster crop yields, curtail greenhouse gas emissions, and capture carbon is well documented (Manga *et al.*, 2023). Its capabilities extend to detoxifying pollutants in the soil, leading to its prominence in the domain of soil and environmental sciences. Moreover, due to its inherent stability and resistance to decomposition, biochar holds promise as a durable medium for long-term carbon storage in soils. In this context, the current review aims to delve into the myriad ways biochar contributes to soil health, microbial activity, and overall environmental quality. The potential hazards associated with biochar usage, as well as the mechanisms underlying biochar-microbe interactions, will also be thoroughly examined. The objective is to provide a comprehensive, balanced, and up-to-date understanding of biochar's role in sustainable agriculture and environmental preservation, thereby laying the foundation for future research in this promising field. This review aims to provide a comprehensive understanding of the potential benefits of biochar for soil enhancement. We begin with an overview of the fundamental properties and production process of biochar, followed by an exploration of its beneficial effects on soil properties, microbial activities, and overall soil health. We will also delve into its interactions with soil contaminants, potential mechanisms of action, and possible risks associated with its use. Throughout the review, we highlight current research findings, identify knowledge gaps, and propose directions for future research in the field of biochar and soil science.

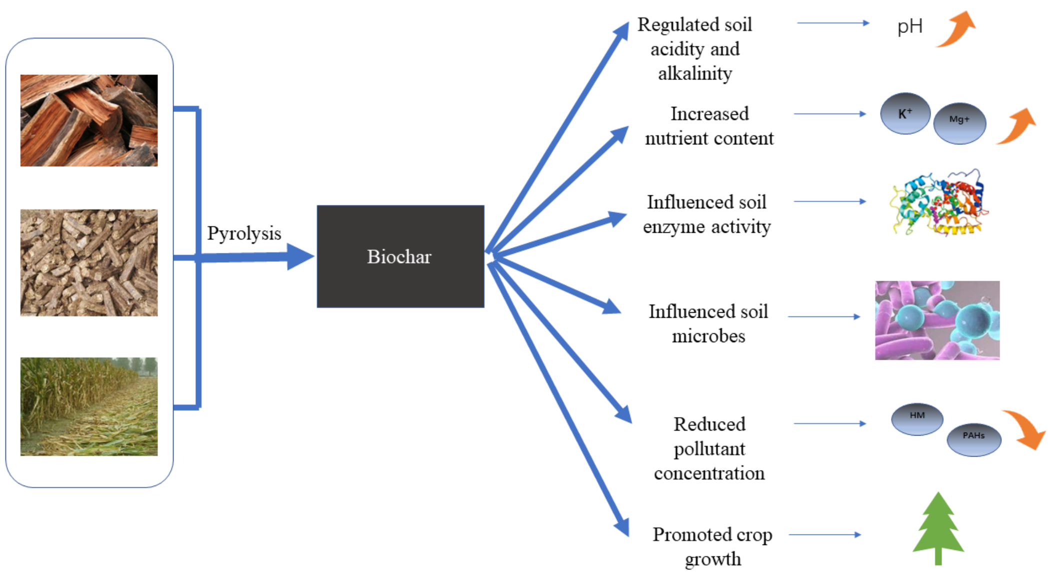

Fig.1 - Environmental effect of biochar on soil (**Source -** Huang *et al.*, 2023)

Benefits of Biochar in Soil Enhancement

Biochar has been recognized as an effective soil amendment that can contribute to multiple dimensions of soil enhancement, including increasing soil carbon storage, improving soil fertility, and reducing soil pollution. Each of these benefits is closely linked to the unique properties of biochar and its interactions with soil components. One of the most significant and widely recognized benefits of biochar application to soil is the enhancement of soil carbon storage. Biochar is primarily composed of carbon, up to 70-80% by weight, which is stabilized in a form that is highly resistant to decomposition (Dias *et al.,* 2010). When applied to soil, this carbon-rich material can remain stable for hundreds to thousands of years, thereby serving as a long-term sink for atmospheric carbon dioxide and contributing to climate change mitigation. Furthermore, by enhancing the capacity of soils to store carbon, biochar also improves soil health and productivity, as soil organic carbon plays a crucial role in maintaining soil structure, water-holding capacity, and nutrient cycling (Rahman *et al.,* 2020). In addition to carbon storage, biochar also exerts a positive influence on soil fertility. Several studies have shown that biochar can increase the availability of essential nutrients in the soil, such as nitrogen, phosphorus, and potassium, thereby promoting plant growth and productivity (Teotia *et al.,* 2016). This is mainly due to biochar's large surface area and high cation exchange capacity, which can adsorb and retain nutrients, preventing their leaching from the soil (Laird *et al.,* 2010). Moreover, biochar can also raise soil pH, particularly beneficial in acidic soils, which can further enhance nutrient availability and boost soil fertility (Jeffery *et al.,* 2017).

Another remarkable benefit of biochar lies in its potential to fix and transform pollutants in the soil. Owing to its high porosity and large surface area, biochar can adsorb various contaminants, including heavy metals and organic pollutants, and reduce their bioavailability and toxicity (Zhang *et al.,* 2013). This pollutant immobilization mechanism not only protects soil organisms and plants from harmful substances but also decreases the risk of contaminant leaching into groundwater (Padhan *et al.,* 2021). The cumulative effect of these improvements results in an enhanced soil environment that supports sustainable agriculture and contributes to environmental conservation. The addition of biochar to soils enhances soil physical properties, such as water-holding capacity and soil structure, promotes biological activity, and reduces nutrient leaching and greenhouse gas emissions. Together, these changes foster a healthier, more productive, and more resilient soil system, providing a solid foundation for sustainable agriculture and ecosystem services (Koohafkan *et al.,* 2012).

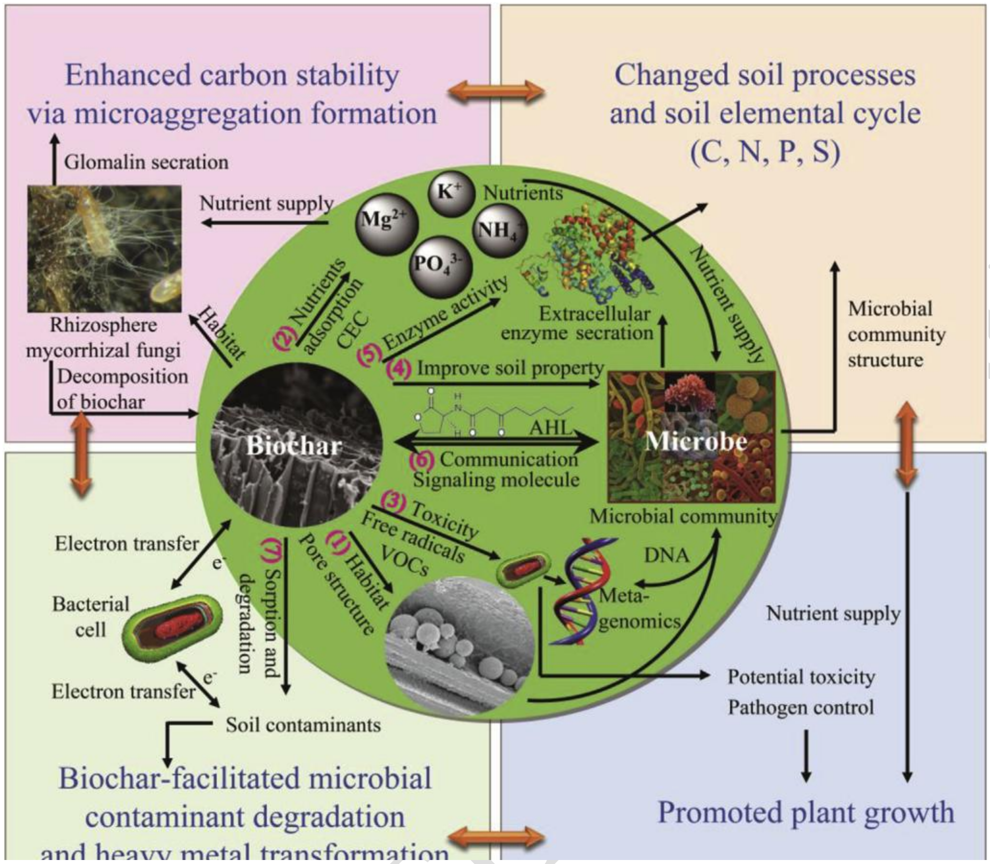

Fig.2 Proposed mechanisms of biochar-microbe interactions and the environmental effects of biochar. Source- (Waqas *et al*., 2021)

Impact of Biochar on Soil Microorganisms

Biochar's influence on soil extends beyond its physical and chemical properties; it also exerts substantial impacts on the biological component of the soil – the microorganisms. These microscopic entities, comprising bacteria, fungi, archaea, and others, play critical roles in nutrient cycling, organic mat ter decomposition, and disease suppression in soils (Buee *et al.*, 2009). Understanding how biochar influences these microorganisms can provide critical insights into its broader effects on soil health and productivity. It affects the metabolic activities of soil microorganisms both directly and indirectly. Directly, the porous structure and high surface area of biochar provide an ideal habitat for microorganisms, offering protection and nutrients for their growth (Palansooriya *et al.*, 2019). The high carbon content of biochar can serve as an energy source for heterotrophic microorganisms, stimulating their activity (Gomez *et al.*, 2014). Additionally, the high pH of biochar can promote the growth and activity of alkaliphilic microorganisms (Hung *et al.*, 2023). Indirectly, biochar enhances soil conditions by improving soil structure, water-holding capacity, and nutrient availability, all of which can indirectly benefit microbial metabolic activities (Atkinson *et al.*, 2010).

These can also reshape the community structure of soil microorganisms. Several studies have shown that biochar amendment can alter the composition and diversity of soil microbial communities (Palansooriya *et al.,* 2019). This alteration is often associated with the enhancement of beneficial microorganisms and the suppression of pathogenic ones. For example, Nzanza *et al.* (2012) found that biochar amendment increased the abundance of mycorrhizal fungi, which can form mutualistic relationships with plants and enhance plant nutrient uptake. Meanwhile, biochar has been shown to suppress soil-borne plant pathogens, likely due to its ability to enhance the antagonistic capacity of beneficial microorganisms (De Corato, 2020). At a broader level, biochar's impact on soil microorganisms contributes to the overall health of the soil microbiome - the collective community of microorganisms in soil. A healthy soil microbiome is characterized by high diversity and functionality, which confer resilience against disturbances and promote soil processes (Sharma *et al.,* 2011). By enhancing microbial activity and diversity and promoting beneficial microbial interactions, biochar can foster a more robust and resilient soil microbiome.

Biochar's Effects on Soil's Physicochemical Properties

Biochar, as a soil amendment, has significant implications for the soil's physicochemical properties. These properties, encompassing soil structure, composition, and reaction properties, dictate the soil's capacity to support plant growth and contribute to ecosystem services. Understanding how biochar interacts with and influences these properties can help maximize the potential benefits of biochar application. Its effects on soil structure are multifaceted. Firstly, biochar can improve soil aggregation by enhancing the activities of soil microbes and earthworms, which play crucial roles in soil aggregate formation (Zhang *et al.,* 2021). Improved aggregation can enhance soil porosity and water infiltration, leading to a reduction in runoff and erosion (Franzluebbers, 2002). Secondly, the porous structure of biochar can increase soil porosity directly, improving soil aeration and water-holding capacity. This is particularly beneficial for sandy soils, which often suffer from low water retention capacity.

These can also significantly alter soil composition, particularly its organic matter and nutrient content. As a carbon-rich material, biochar contributes to the soil organic carbon pool, which is vital for soil health and productivity (Rahman *et al.,* 2020). Moreover, biochar contains various nutrients, such as nitrogen, phosphorus, and potassium, which can become available to plants upon its decomposition (Biederman & Harpole, 2013)). Besides, the large surface area and high cation exchange capacity of biochar can adsorb and retain nutrients, preventing their leaching from the soil and enhancing their availability to plants (Major *et al.,* 2012). These also influences the soil's reaction properties, notably soil pH. Biochar, particularly produced at high temperatures, often has a high pH due to the presence of basic minerals, such as potassium and calcium (Singh *et al.,* 2010). When applied to soil, biochar can raise soil pH, ameliorating soil acidity, which is a common problem in many agricultural soils. Additionally, the high pH of biochar can induce changes in soil microbial communities and nutrient availability, further influencing soil processes and plant growth (Xu *et al.,* 2014). The resultant improvement in the soil environment is multifaceted and substantial. The enhanced soil structure can lead to better water management, reducing water stress for plants and decreasing water wastage. The improved nutrient content and availability can support plant growth and productivity, potentially leading to higher crop yields. The ameliorated soil acidity can favor the growth and activity of beneficial soil microbes, fostering a healthier soil microbiome. Overall, these changes can create a more favorable soil environment for plant growth and microbial activity, contributing to agricultural sustainability and environmental conservation.

Biochar's Influence on Enzyme Activities and Nutrients in Soil

Soil is a dynamic and complex environment, hosting a myriad of biochemical processes that are crucial for soil health and function. Many of these processes are catalyzed by enzymes, proteins that accelerate chemical reactions in soils. Biochar, as a soil amendment, can influence these enzyme activities, potentially altering soil biochemical processes and nutrient dynamics. Enzymes in soil play significant roles in nutrient cycling, organic matter decomposition, and detoxification processes. Biochar has been shown to influence a wide array of these soil enzymes, including those involved in the cycles of carbon, nitrogen, phosphorus, and sulfur (Anderson *et al.,* 2011). The high carbon content and porous structure of biochar can provide substrates and habitats for soil microbes, enhancing their metabolic activities, including enzyme production (Thies & Rillig, 2011). Moreover, the high pH of biochar can change the soil's chemical environment, affecting enzyme stability and activity (Zhu *et al.,* 2017). For example, biochar has been found to increase the activity of β-glucosidase, an enzyme involved in the decomposition of cellulose, the main component of plant residues (Awad *et al.,* 2012). This can accelerate the transformation of organic matter into humus, contributing to soil organic carbon sequestration. Similarly, biochar can enhance the activities of nitrogen-cycling enzymes, such as urease and nitrate reductase, which can improve nitrogen availability to plants and reduce nitrogen loss through leaching and gaseous emissions (Cameron *et al.,* 2013). It influence on soil nutrients is also substantial. As previously mentioned, biochar can contribute nutrients to the soil, such as nitrogen, phosphorus, and potassium, upon its decomposition (Osman *et al.,* 2022). However, biochar's impact on soil nutrients extends beyond its nutrient content. The large surface area and high cation exchange capacity of biochar can adsorb and retain nutrients, preventing their leaching from the soil and enhancing their availability to plants (Major *et al.,* 2012). Additionally, biochar can raise soil pH, particularly beneficial in acidic soils, which can enhance nutrient availability, as many nutrients are more available at neutral to slightly alkaline pH levels.

Biochar's Interaction with Soil Contaminants

Soil contamination poses serious threats to soil health, food security, and human health. Various substances, including heavy metals, pesticides, and petroleum products, can contaminate soils through anthropogenic activities. Biochar, due to its unique properties, can interact with these contaminants, potentially reducing their bioavailability and toxicity. Understanding these interactions can provide new insights into biochar's role in soil remediation. Biochar's interaction with soil contaminants is primarily driven by its high surface area and strong adsorption capacity. The porous structure of biochar is rich in functional groups, such as carboxyl, hydroxyl, and phenolic groups, which can form complexes with contaminants, reducing their mobility and bioavailability (Shakya *et al.,* 2020). Moreover, the basic minerals present in biochar can react with acid compounds, further enhancing its adsorption capacity (Cheng *et al.,* 2021). Heavy metals are a group of common soil contaminants that biochar can effectively interact with. Research shows that biochar can adsorb a variety of heavy metals, including lead, cadmium, and mercury, reducing their bioavailability and leaching potential (Bolan *et al.,* 2014). The adsorption of heavy metals onto biochar is facilitated by the surface functional groups and basic minerals in biochar, which can form stable complexes with the metals (Yin *et al.,* 2022). Organic pollutants, such as pesticides and polycyclic aromatic hydrocarbons (PAHs), can also be effectively adsorbed by biochar. The aromatic structure of biochar can interact with these organic pollutants through π-π interactions, trapping them in the porous matrix of bio char (Rong *et al.*, 2019). This adsorption can reduce the bioavailability and mobility of organic pollutants, mitigating their environmental risks. Its interaction with soil contaminants can influence related microbial activities. By reducing contaminant bioavailability, biochar can alleviate the toxic effects of contaminants on soil microbes, promoting their growth and activity (Xiang et al., 2022). This can accelerate the degradation of organic pollutants, as many soil microbes are capable of degrading these pollutants into less toxic or non-toxic substances (Mcguinness *et al.*, 2009).

Potential Mechanisms of Biochar-Microorganism Interaction

The interaction between biochar and soil microorganisms is multifaceted and dynamic, with multiple potential mechanisms involved. These mechanisms can influence the structure and function of the soil microbiome, shaping soil health and processes. Biochar can provide physical habitats for soil microorganisms. The porous structure of biochar creates a large surface area with many micro- and nano-scale pores, offering living spaces for microorganisms (Garcia *et al.*, 2020). Moreover, these pores can protect microorganisms from predation and environmental stresses, enhancing their survival and activity (Harvey *et al.*,2020). It can also provide substrates for microbial metabolism. Biochar contains a variety of organic compounds, such as volatile fatty acids, that can be used by microorganisms as energy sources (Kaur *et al.,* 2020). Additionally, the carbon-rich biochar can contribute to the soil organic carbon pool, which is vital for microbial growth and activity (Lin *et al.,* 2022). These can modify the soil's chemical environment, affecting microbial activities. The high pH of biochar can raise soil pH, potentially favoring the growth of alkaliphilic microorganisms (Zhou *et al.,* 2019). Also, the high cation exchange capacity of biochar can adsorb and retain nutrients, improving nutrient availability to microorganisms (Sanchez *et al.,* 2018).

These interactions between biochar and soil microorganisms can have significant impacts on the soil microbiome. By providing physical habitats and nutritional substrates, biochar can enhance microbial abundance and diversity, contributing to a healthier soil microbiome (Hartmann & Six, 2023). Moreover, by modifying the soil's chemical environment, biochar can shape microbial community structure and function, potentially leading to shifts in soil processes, such as nutrient cycling and organic matter decomposition (Wu *et al.,* 2016).

Risks Associated with Biochar Use

Biochar, while offering significant benefits in terms of soil improvement and carbon sequestration, also poses potential risks that need careful consideration. These risks encompass the potential release of harmful substances and unintended shifts in microbial communities. It is produced through pyrolysis of organic materials, a process that can generate a variety of substances, depending on the feedstock and pyrolysis conditions. Some of these substances can be potentially harmful. For example, polycyclic aromatic hydrocarbons (PAHs) and heavy metals, which are harmful to both humans and the environment, can be present in biochar, especially if the feedstock is contaminated or the pyrolysis temperature is high (Yang *et al.*, 2019). If these harmful substances are not properly managed, they can be released into the environment, posing risks to soil, water, and air quality.

Biochar's influence on soil microbial communities can be a double-edged sword. While biochar can enhance microbial abundance and diversity, it can also lead to unintended shifts in microbial community structure (Palansooriya *et al.*, 2019). These shifts can affect soil processes, such as nutrient cycling and organic matter decomposition, potentially leading to unforeseen consequences. For instance, biochar can enhance the activities of nitrogen-cycling bacteria, which can increase nitrogen loss through gaseous emissions, contributing to greenhouse gas emissions (Harindintwali *et al.*, 2021). The long-term effects of biochar in soils remain largely unknown. Biochar is highly stable and can persist in soils for hundreds to thousands of years (Gurwick *et al.,* 2013). The effects of biochar application today can influence soil health and function for generations to come. This requires a cautious and balanced view towards biochar application, considering both its benefits and risks.

Table 1: Hazards of endogenous biochar pollutants to soil microorganisms

Pollutant	**Examples**	**Hazards**
Heavy Metals	Pb, Cd, Zn	Inhibits microbial growth, reduces biomass, affects microbial enzyme activity
Organic Contaminants	Polycyclic aromatic hydrocarbons, volatile organic compounds	Mutagenic effects on microorganisms, inhibition of microbial activity, alteration of microbial community structure
EPFRs	Hydroxy, alkoxy	Reduces enzyme activity in cells, causes oxidative stress, affects the community structure of microorganisms
Other Pollutants	Perfluorinated compound, perfluorooctane sulphonate, pentadecafluorooctanoic acid	Alters the diversity and abundance of soil bacterial communities, inhibits enzyme activity

Conclusion

Biochar presents a promising avenue for soil enhancement, boosting soil fertility, managing pollutants, and indirectly influencing the soil microbiome. While the benefits are significant, potential risks such as the release of harmful substances and unforeseen shifts in microbial communities necessitate a balanced perspective. The review illuminates our current understanding of biochar's interaction with the soil environment and its microorganisms, highlighting the need for further research to explore the long-term impacts of biochar on soil health and function. The utilization of biochar as an agricultural tool could play a vital role in promoting sustainable agriculture and tackling climate change.

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