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REVIEW ARTICLE

A REVIEW ARTICLE ON THE EFFECT OF BIOCHAR ON SOIL PROPERTIES

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ABSTRACT

Soil fertility is declining due to the increased use of synthetic fertilizers and monocropping practices. Intensive farming, mining, and heavy metal contamination have caused numerous adverse effects on soils. To boost crop growth and keep soil fertile, it's vital to protect soil's physical, chemical, and biological makeup by ensuring sufficient organic content. Biochar is gaining recognition as a sustainable soil enhancer across various fields, including agriculture, environmental science, and energy. This article provides a comprehensive overview of biochar, covering its production, characterization, and impact on soil application. The review concludes that biochar application decreases soil bulk density, reduces soil N_2O emissions, and mitigates soil salinization by increasing soil porosity and cation exchange capacity. Additionally, biochar improves soil conditions by increasing water absorption, water retention, organic matter, nitrogen content, acidity, nutrient-holding capacity, and microbial activity. The mechanisms behind these improvements include biochar's high porosity, adsorptive properties, ash content, negative surface charge, slow nutrient release through chelation, provision of habitat for microorganisms, and increased total soil organic carbon. However, the effectiveness of biochar in enhancing soil properties is influenced by the soil's nature, the type of biochar used (based on feedstock and pyrolysis conditions), and the application rate of biochar.

KEYWORDS

Biochar, Organic carbon, Soil microbial population, Soil properties

1. INTRODUCTION

Biochar is also known as "black gold". Biochar is produced through the intense aromatization and stabilization of organic waste materials like agricultural straw, chicken manure, and municipal sludge, subjected to high temperatures and oxygen-free conditions. This process not only reduces pollution but also optimizes the use of resources (Marris, 2006; Parmar et al., 2014; V. Nguyen et al., 2019). Researchers defined "Biochar is a carbon- and energy-rich porous material created through the slow pyrolysis of biomass, and it has been proposed as an effective long-term strategy for sequestering carbon in soils." (Shackley et al., 2012). A study in 2013 stated that any organic residues can be transformed into biochar by the pyrolysis process (Xu et al., 2013).

Numerous studies have demonstrated that biochar exhibits characteristics such as high surface areas, high charge densities, low bulk densities, stable porous structures, and high organic carbon contents (Rajapaksha et al., 2016; Jain et al., 2017; Liu et al., 2018; Jones et al., 2010; Singh et al., 2010; Herath et al., 2013). The use of biochar in the field reduces the bulk density of soil and increases the water-holding capacity of coarse-textured soils due to their large surface area (Villagra-Mendoza and Horn, 2018). Biochar can have positive influences on soil biological properties microbial activity and chemical properties like pH and cation exchange capacity (CEC) (Abujabhah et al., 2016; Lehmann et al., 2003).

Biochar has many benefits including enhancing soil fertility, structure, water holding capacity, organic carbon content, increasing microbial performance, and thus sustainably increasing crop yields (Ebhin Masto et al., 2013). It is also a superior substitute for other organic fertilizers as it is functionally equivalent to FYM and other organic fertilizers. Surplus crop residues left in fields after harvesting can be efficiently utilized to create biochar. Research has shown that using various biochar forms together with organic and inorganic fertilizers can dramatically improve soil quality, crop growth, and nutrient access (Glaser et al., 2002; Graber et al., 2010; Lehmann et al., 2006; Silber et al., 2010). Biochar-treated soils produced higher crop yields because they had more available nutrients and essential minerals (Uzoma et al., 2011). Furthermore, biochar has carbon components that are easily degradable. The soil receives mineralized biodegradable carbon, which is readily consumed by microorganisms (Roberts et al., 2015). The majority of biochar remains stable in the soil for centuries (Keith et al., 2011). It is stated that using biochar to sequester carbon and reduce emissions could sequester 7.6 tons of CO_2 per year, and it is claimed that by 2100, the planet could sequester about 9.5×10^4 tons of carbon (Kuppusamy et al., 2016).

Biochar is thought to serve as a long-term carbon sink, which lowers greenhouse gas emissions, and mitigates the effects of global warming on food production (Colantoni et al., 2016; Fahad et al., 2016). Simultaneously, biochar can enhance soil quality, boost agricultural crop production, and offer increased ecological and economic benefits (Ouyang et al., 2016; Plaza et al., 2016). Therefore, Biochar can be employed as an environment-friendly soil amendment to reduce greenhouse gas emissions, manage pollution, enhance agricultural carbon sequestration, and support sustainable agricultural land management (Pérez-Cruzado et al., 2011; Chimento et al., 2014; Tsz et al., 2017). Adding biochar to soil is considered a promising approach for sequestering carbon, which can help mitigate the impacts of climate change (Lehmann, 2007). Compared to other common sources of organic matter, its stability and slow degradation in the soil allow it to have a more everlasting impact on the physical, chemical, and biological properties of the soil (Atkinson et al., 2010).

The quality of produced biochar during pyrolysis is determined by the type of biomass utilized and its manufacturing temperature. The application of biochar as a soil amendment improves soil properties, helping to resolve various soil-related challenges (Singh et al., 2012).

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Biochar is more stable in soils and has long-term benefits than other kinds of organic matter. Biochar is unique because it retains a large portion of the nutrients used and provides more to plants than other organic materials such as conventional farm leaf litter, compost, or manure (Schulz et al., 2013).

Previous studies on biochar have mainly concentrated on how it interacts with soil, influences crop growth, or cleans up pollution. However, they often ignore the potential downsides of using biochar. Additionally, there's a significant gap in understanding how to best use biochar to improve poor soil quality. This review aims to provide a comprehensive evaluation of recent research findings and theoretical advancements in biochar applications. The review also examines the use of biochar as a beneficial agricultural product to enhance its application and mitigate environmental and economic impacts. Specifically, this work aims to: (i) analyze the physical, chemical, and biological properties of biochar; (ii) investigate the effects of biochar addition on soil properties; and (iii) identify future research directions related to biochar in agriculture

2. Effect of Biochar on Soil Physical Properties

2.1 Soil Porosity and Surface Area

Biochar is porous and loose and the pores determine its surface area. The use of biochar increases the overall porosity of the soil, but the porosity depends on the type of biochar used and the type of soil where the biochar is applied (Herath et al., 2013). The higher soil porosity was due to the porous nature of biochar (Mukherjee and Lal, 2013).

During the preparation of biochar, as the temperature of pyrolysis increases, volatile matter decreases the pores diameter and hence porosity and the surface area increase (Chen and Yuan, 2011; Gul et al., 2015). The large surface area improves microbial activity and root growth in soil pores by increasing the number of microorganisms in the soil. On the other hand, tree roots loosen the soil and indirectly affect the porosity of the soil. Sandy soil has large pores that reduce the water retention capacity. (Liang et al., 2006) reported that in comparison to soil organic matter, biochar possesses a greater surface area, a negative surface charge, and a higher charge density, which enhances its ability to adsorb cations (Nduka et al., 2019). Due to the higher specific surface area of biochar, which improves the water-holding capacity of soil, the addition of biochar as an amendment was found to increase the total specific surface area of soil. (Woolf et al., 2010) implied that the soil density, particle size distribution, porosity, structure, and texture are all affected by biochar addition, which improves soil nutrient and microbial status, air content, water holding capacity, and root zone condition. The addition of biochar significantly enhanced the soil's porosity, permeability, and water-conducting capacity (Oguntunde et al., 2008). The incorporation of biochar varies soil porosity between 5 and 25 μm (Rasa et al., 2018).

Enhancing soil structure and porosity can be achieved through the addition of biochar, which leads to an increase in surface area, pore size distribution, and a reduction in soil bulk density (Major et al., 2010). Researchers manifested that many different factors, including particle size, pore size distribution, connectivity, mechanical strength, and interactions between biochar particles, can influence overall soil porosity (Jeffery et al., 2011). Adding biochar to clay and poorly aggregated soils has been shown to reduce compaction, improve aeration, and enhance the soil's ability to preserve moisture (Mukherjee and Lal, 2013b; Wang et al., 2016).

2.2 Bulk Density of Soil

Bulk density is a measure of the force with which soil particles press against each other. It is the ratio of the mass of the oven-dried soil to its apparent volume (volume of soil particles + volume of voids).

Soil bulk density significantly influences soil quality and plant growth. For instance, soils with high bulk density (> 1.6 Mg cm^{-3}) have reduced water absorption capacity and increased resistance to root penetration, which can impact both soil properties and plant growth (Goodman & Ennos, 1998). Soil bulk density is a critical measure of soil's physical characteristics and is inversely connected to soil compaction. Reducing soil bulk density can enhance soil structure, aid in nutrient release and retention, and significantly decrease soil compaction.

According to a study in 2013, the use of biochar reduces the bulk density of soil because biochar is highly Poriferous and when applied to soil, it reduces the bulk density by increasing the pore volume (Mukherjee and Lal, 2013). Researchers concluded that increasing the biochar use rate significantly reduced the bulk density (Githinji, 2014). Soils promote aggregation after charcoal addition; In addition, root and mycelial growth affects the apparent density of the soil (Steiner et al., 2007).

After biochar utilization, the Material properties of sandy soil were improved (Głąb et al., 2016). By accelerating the deployment of biochar, the bulk density of the soil decreased and the overall porosity of the soil increased. Red gram stalk biochar applied at a rate of 5 t ha^{-1} to the control plots had a lower bulk density of 1.36 g cm^{-3} and a greater void space (47.5%) than the control (Pandian et al., 2016). Zhang et al., (2012) concluded that adding biochar to the soil at a rate of 40 t ha^{-1} consistently lessened soil bulk density from 1.01 to 0.89 g cm^{-3} compared to the control where the control had 1.01 g cm^{-3}.

2.3 Water Holding Capacity

The water-holding capacity of soil is the maximum amount of water that soil can hold. This is an important characteristic from the farmer's perception and the point of view of plant growth. When soil can hold a large amount of water, the frequency of irrigation of crops is reduced and plants also grow well on this type of soil.

Soils amended with biochar retained 15% more moisture than the control treatment, as biochar oxidized, its surface became hydrophobic and increased its water-holding capacity (Laird et al., 2010). Researchers insisted that the use of biochar enhanced the soil's water retention capacity due to increased soil porosity and the adsorptive characteristics of biochar (Herath et al., 2013). Due to its high porosity and specific surface area, biochar slows down the movement of water through the soil, enhances the soil's water absorption, and modifies the residence time and flow pathways of water within the soil (Major et al., 2012; Abrol et al., 2016). Research revealed that the use of biochar boosted the soil's available water content by as much as 97% and its saturated water content by up to 56%. It was also noted that hydrophilic functional groups were available on the surface of the biochar's graphene sheets and within its pores (Uzoma et al., 2011). The incorporation of biochar enhances the levels of nutrients, air, and water in the soil. Rather than applying crop residues directly, returning them as biochar allows for improved water retention in the soil (Nduka et al., 2019). Its ability to retain more water facilitates the use of biochar in regions susceptible to drought. The application of biochar derived from sugarcane bagasse increased the amount of plant-available soil moisture, resulting in higher sugarcane yield and sugar content (Chen et al., 2010). Soil treated with biochar exhibited an 11% higher water-holding capacity, significantly enhancing soil fertility (Karhu et al., 2011). Eteng et al., (2014) observed that maize in the coconut shell biochar applied plot had a water use efficiency (WUE) of 9.44 kg mm^{-1} and 9.24 kg mm^{-1} for the cattle dung biochar. (Gururaj and Krishna, 2016) highlighted the idea that adding biochar would help the soil retain more water. When compared to the control, the soil with biochar added had a low water evaporation rate.

Integrating biochar into the soil raises its water retention capacity, although this effect is dependent on soil texture. Biochar application notably improves water retention in sandy soils, while it has minimal or no impact on loamy and clay soils (Tryon, 1948). In sandy loam soils, the addition of biochar boosted maize yields and enhanced water use efficiency. (Aslam et al., 2014).

2.4 Soil Aggregation

Soil aggregation is the adhesion together of colloidal soil particles due to the net force of gravity. From an agricultural point of view, this property is very important. Well-aggregated soils have good structure and support the movement of nutrients and water through the soil and their uptake by plants. Multiple mechanisms of aggregation exist, one of which is the hierarchical theory of aggregation, the concentric theory, the formation of hydroxides, oxides, phosphates, and carbonates, combined with the bridging action of cations between clay and organic matter particles, leads to increased soil aggregation or aggregates may form as a result of a combination of these processes (Le Bissonnais, 1996; Santos et al., 2014; Bronick and Geoderma, 2005; Juriga and Zootech, 2018; Bronick and Lal, 2005). After the application of biochar into the soil, all of these mechanisms started in the formation and stabilization of soil structure. Multivalent ions bound to biochar can enhance soil organic matter (SOM) stability by interacting with negatively charged components of soil and organic matter (Mukome et al., 2013). Researchers found that these ions, particularly iron, can facilitate the attachment of SOM to clay particles (Feng et al., 2005). In addition, certain positively charged ions can create links between biochar and soil mineral structures (Lin et al., 2012).

Applied biochar can either integrate with mineral particles in the soil or become part of the soil aggregates (Juriga and Zootech, 2018). According to researchers, biochar includes base cations that can form cationic bridges with clay and organic particles to improve the soil's structural conditions, hydrophobic organic matter components contribute more to soil aggregate stability than hydrophilic components and biochar can improve aggregation by aiding in the binding of native SOM, increasing the resistance of soil aggregates to water, and making aggregates more resistant to physical disturbance due to its highly aromatic C structure (e.g., wet-dry cycles) (Rajkovich et al., 2012; Bronick and Lal, 2005; Piccolo and Mbagwu, 1999). Additionally, biochar significantly influences microbial properties, and microorganisms produce polysaccharides that enhance soil aggregation (Ding et al., 2016; Angers et al., 1997).

2.5 Soil Color and Temperature

Biochar is a dark, granular substance. When applied in large amounts to soil, it causes the soil to become darker. This change in color affects how the soil reflects sunlight and absorbs heat, ultimately influencing soil temperature. Research in Ghana has shown that soil near charcoal production sites is noticeably darker than soil in other locations. (Y. Zhang et al., 2021). Compared to other areas, surface reflectance decreased by 37%, while the average surface temperature rose by 4 degrees Celsius. Changes in soil color were noted after biochar was added, revealing that the Munsell color value shifted with increasing biochar application rates. At an application rate of 10 g kg^{-1}, the Munsell color value was 5.5, but it decreased to 3 when the rate was increased to 50 g kg^{-1}. The impact of biochar on soil temperature is influenced by soil thickness. The dark color of biochar enhances the soil's color, leading to higher soil temperatures, which promotes seed emergence and boosts crop yields (Oguntunde et al., 2008; Oguntunde et al., 2004).

(Ventura et al., 2012) demonstrated that Adding biochar to the soil caused the soil surface to become warmer. Compared to untreated soil, biochar-treated soil was 0.6 degrees Celsius hotter during winter and 0.8 degrees Celsius hotter during summer. Biochar's capacity to modulate seasonal and daily fluctuations in soil temperature is mainly driven by alterations in soil thermal conductivity and reflectance (Zhang et al., 2013). Biochar can reduce the amount of sunlight reflected by soil and slow down heat transfer within the soil. The main reason for slower heat transfer is the increased organic matter content caused by the biochar (Abu-Hamdeh & Reeder, 2000).

Biochar's dark color not only altered the soil's visual aspect but also increased its ability to hold water (Tryon,.1948). The primary factors affecting soil-specific heat are soil color and moisture content. The incorporation of biochar increases soil temperature in areas with low moisture content, providing a noticeable soil heat retention effect. This effectively suppresses harmful weed seeds in agricultural fields while enhancing crop quality and yield (Oz, 2018).

3. Effect of Biochar on Soil Chemical Properties

3.1 Organic Matters

Elevated levels of soil organic matter can significantly influence crop yields(Liang et al., 2014). The soil environment is essential for plant growth, and the prolonged use of biochar can improve soil nutrient availability and enhance the efficiency of nutrient uptake by plants (Jeffery, et al., 2011). While biochar can boost Organic substance concentration, this effect depends on the amount and stability of the biochar used (Glaser et al., 2001; Zygourakis, 2017).

Biochar is rich in mineral nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, especially when derived from livestock and poultry manure. When applied to soil, these nutrients can improve soil fertility and productivity. Biochar significantly increases the availability of essential cations like potassium, magnesium, calcium, manganese, zinc, and copper, enhancing soil nutrient availability (Zhang et al., 2020). It also fosters the conversion of small organic molecules into more complex soil organic matter. through surface catalytic activity, while soil macropores adsorb these molecules (Liang et al., 2010). This process is primarily due to increased soil porosity, improved nutrient accessibility, and decreased soil bulk density (Akhtar et al., 2014; Asai et al., 2009).

Biochar can enhance crop yields by stimulating root microorganism activity and increasing root absorption of organic materials. Its effect on nutrient retention in soil is influenced by factors such as biochar type, application rate, and soil texture. However, applying biochar does not always result in increased crop yields. In some cases, it can impair soil productivity and reduce yields, depending on the amount used and soil texture (Zhang et al., 2020). A study was conducted a three-year field experiment with biochar on corn and soybean rotation soil, finding no yield increase in the first year after applying 20 t·ha-1 of biochar, but subsequent years saw yield increases of 28%, 30%, and 140% (Major et al., 2010).

3.2 Organic Carbon

Biochar, a stable form of carbon, can retain carbon in the soil for extended periods and act as a material to reduce carbon emissions. Nonetheless, its excessive application may lead to an increase in greenhouse gas emissions (Purakayastha et al., 2019).

Biochar enhances soil conditions, encouraging crop growth, boosting yields, and diminishing nutrient loss (Kameyama et al., 2012). By reducing nutrient runoff, biochar improves soil nutrient utilization and retains water and nutrients in the rhizosphere. It effectively increases the organic carbon content in temperate zone soils, making it a valuable improvement for soils with particular deficiencies (Laird et al., 2017). (Liu et al., 2011) Biochar can significantly reduce CH_4 emissions when added to soil, with a study showing a 96% reduction in CH4 emissions (Karhu et al., 2011). However, researchers found that when biochar application exceeded 5 mg ha-1, N_2O release decreased (Alho et al., 2012.).

Amending soil with biochar not only improves soil fertility and health but also sequesters carbon. Biomass recycling in the form of biochar is a straightforward and appealing idea for carbon sequestration. To reduce greenhouse gas emissions, biochar should sequester carbon by enhancing soil carbon storage. Long-term tests and modeling show minimal carbon loss from biochar, reducing atmospheric carbon emissions (Mathews., 2008). Applying biochar can increase total soil carbon by 41% to 65% on average (Rafi et al., 2015). In a research by Coumaravel et al., applying different types of biochar increased levels of organic carbon in the soil to 4.4-4.8 g kg^{-1} measured to 3.6 g kg^{-1} in the control. Therefore, future studies should focus on determining the appropriate amount of biochar to use (2015).

3.3 Hydrogen Ion Concentration (pH) and Electrical Conductivity

Biochar generally has a pH range of 4 to 12, and Its alkaline properties can directly influence soil pH when applied. It helps regulate soil pH and increase base saturation. When added to soil, biochar interacts with H^+ and $Al3^+$ ions, working with water to reduce ion concentration (Glaser et al., 2002).

Research found that basic cations like potassium, calcium, and magnesium in biochar can adsorb and reduce exchangeable aluminum and hydrogen ions, improving soil pH (Zwieten et al., 2010). Also biochar treatment increased soil pH for wheat cultivation from 4.5 to 6.0, boosting yield from 3924 kg ha^{-1} to 6219 kg ha-1 (Galinato et al., 2011). The inclusion of alkali and alkaline earth metal carbonates in biochar significantly raises soil pH. Soils amended with 10 t ha^{-1} biochar had the highest pH values, while control plots had the lowest (Nigussie and Kissi, 2012). Active oxygen groups like COOH or OH on biochar's surface counter with metal cations and H^+ ions in the soil, altering the pH (Gan et al., 2015). Applying 10 t ha-1 of biochar raised acidic soil pH from 4.62 to 5.87 and mitigated aluminum's harmful effects (Lima et al., 2019). Researchers reported that over 90 days, biochar inclusion increased soil pH, demonstrating its potential to reclaim acidic soils (Wang et al., 2015).

Soil electrical conductivity (EC) is crucial for the growth and quality of upland crops (Han et al., 2020). An experiment by (Zafar Ullah et al., 2018) found that after 120 days, soil treated with 10 t/ha of sugarcane bagasse biochar had a maximum EC of 0.72 dS/m, 24% higher than the control, indicating that higher biochar application rates significantly increase soil EC. High concentrations of soluble salts in saline soils reduce crop yields, but biochar can help mitigate this. For instance, tomato plants grown in saline irrigation conditions showed significantly improved growth and yield after biochar application (Usman & Al-Wabel, 2016).

3.4 Cation Exchange Capacity (CEC)

Soil cation exchange capacity (CEC) measures the soil's capacity to bind and retain essential nutrients (cations) for plant uptake while preventing them from leaching into ground and surface waters. Cations are electrostatically bound and exchanged at negatively charged sites on biochar's reactive surface area (Verheijen et al., 2010).

CEC is a vital indicator of soil quality, and soil amended with biochar shows a higher CEC. An elevated CEC indicates an enhanced ability to fix nutrients, which is essential for plant growth. The negatively charged oxygen active groups on the biochar's surface enhance its CEC (Karthik et al., 2020). Increasing biochar application rates raises CEC, helping to regulate soil salinization in agricultural fields (Abbruzzini et al., 2017).

CEC measures soil's capability to absorb, withhold, and interchange cations. Increasing soil CEC involves enhancing the number of soil cation exchange sites. High CEC soils are better at adsorbing cations (NH^{4+}, K^+, Ca^{2+}, and Mg^{2+}), which improves nutrient use efficiency and reduces nutrient loss (Liang et al., 2006). The oxidation of acidic aromatic carbon on biochar's surface forms abundant functional groups (-OH, -COOH), mounting soil CEC (Atkinson et al., 2010; Gaskin et al., 2014).

Adding biochar to soil increases total soil charge and CEC by 20-40% Different from the control (Zhang et al., 2021) . Even small amounts of biochar can Substantially raise the levels of alkaline cations and nutrients in the soil (Hossain et al., 2010). Biochar addition to acidic or alkaline soils can enhance soil CEC due to increased surface anions (Chintala et al., 2014). However, Soils containing significant organic material, which already have high CEC, may not see further CEC increases with biochar addition (Schulz & Science, 2012). Peng et al., (2011) demonstrated that applying 2.4 t ha-1 of rice straw-derived biochar to soil for 11 days enhanced soil CEC from 4% to 17%, decreased the Stability of soil particles from 1% to 17%, and boosted maize crop dry matter yield.

4. Effect of Biochar on Soil Biological Properties

4.1 Influence on Microbial Population

The deployment of biochar enhances not only the physical and chemical properties of the soil but also its microbiological characteristics (Ding et al., 2016). Due to its extensive surface area and reactivity, biochar attracts ions and organic molecules, creating numerous possible sites for relationships between microbes and substrates (Gul et al., 2015). Consequently, biochar can modify the composition of the soil microbial community, impact microbial activity, and influence soil enzyme activity, thereby impacting various biogeochemical processes (Zhu et al., 2017). Biochar is an excellent organic amendment for improving the Carbon content of soil, water-holding, and microbial habitats (Mankasingh et al., 2011). According to researchers, the pores in biochar support the growth, spread, and protection of microbes from adverse environmental conditions, providing them with essential nutrients for growth and multiplication (Tan et al., 2017). The pore spaces in biochar serve as habitats for soil organisms and offer protection from predators (Warnock et al., 2010).

Research in 2009 revealed that biochar supplement affects soil microbial activity, biomass, and nutrient availability (Kolb et al., 2009). In soil, biochar acts as a storage facility for bacteria and arbuscular mycorrhizal fungi, Which enables the availability of soil nutrients for plant uptake (Fox et al., 2014). The porous nature of biochar supports numerous microorganisms, including mycorrhizal fungi, actinomycetes, and bacteria, promoting the growth of beneficial microbial populations essential for plant development (Lehmann et al ., 2009). Biochar influences soil microbial populations and soil biogeochemistry (Warnock et al., 2010). Moreover, biochar with symbiotic mycorrhizal associations in the soil ecosystem helps restore the ecosystem and sequester carbon, fostering long-lasting plant growth. Also, biochar enhances microbial growth and reproduction by providing carbon, energy, and mineral nutrition, increasing moisture retention, and improving soil quality (Meng et al., 2013). It was concluded by researchers that biochar's porous structure stores organic carbon and mineral nutrients, affecting soil microbial activity and populations (Lin et al., 2012). The microbial biomass in the soil varies depending on the biochar source, soil texture, and other soil ecosystem aspects.

Phosphorus-solubilizing microbes (PSM), which solubilize and trigger phosphorus for better plant root intake, can thrive with the aid of biochar, which also increases ammonia and phosphate ions in the soil (Deb et al., 2016). The combined utilization of biochar and PSM significantly boosted crop yields in phosphorus-deficient soils. It was reported that the augmentation of biochar led to a rise in bacterial diversity., with the increase correlating with the biochar amount (Wu et al., 2016). Additionally, biochar enhanced the soil's ability to retain water., increased microbial biomass, and enhanced bacterial community structure, reducing nitrogen leaching. Biochar improved conditions in the plant rhizosphere, facilitating better crop establishment by increasing populations of *Pseudomonas, Mesorhizobium, Brevibacillus, and Trichoderma* (Graber et al., 2010). In addition biochar increased the readiness of boron and molybdenum, leading to greater biological nitrogen fixation in common beans (Phaseolus vulgaris) (Rondon et al., 2007). Pandian et al., experimented that concerning fungal populations, the highest bacterial count ($42\times10^{\wedge-6}$ CFU) was found in red gram stalk biochar, followed by higher colony numbers ($33\times10^{\wedge-3}$ CFU) in coconut coir pith, and actinomycetes ($30\times10^{\wedge-4}$ CFU) in cotton stalk biochar (Pandian et al., 2016).

4.2 Soil Enzyme Activities

Alterations in the soil microbial community and enzyme activity profoundly influence the biogeochemical processes occurring within the soil (Awad et al., 2012; Lehmann et al., 2011).

Soil enzymes mainly come from animal cell secretions, plant roots, and soil microorganisms. Their activity indicates the extent and direction of various biochemical processes in the soil. The outcome of biochar applications on the microecology of agricultural soils is demonstrated by alterations in soil metabolic characteristics driven by enzyme activity. Researchers discovered a positive correlation between glucomannan enzyme activity and the soil's physical and chemical properties, with a notable emphasis on total organic carbon content (Turner et al., 2002). The study in 2016 demonstrated that biochar boosted the activity of soil enzymes, increasing dehydrogenase activity by 27% compared to the control group, and urease activity rose from 7.4% to 39% (Pandey et al., 2016). According to researchers, the enhancement of biochar modifies the adsorption-inhibiting enzyme reactions in the soil, resulting in variable transformation in the activities of glucoamylase, lipase, leucine aminopeptidase, and acetylglucosamine enzymes (Bailey et al., 2011) .

The supplement of biochar significantly impacts soil carbon, thereby increasing enzyme activity (Lal, 2013). Awad et al., concluded that biochar-enriched soil enhances enzyme activity associated with nitrogen and phosphorus transformation and application, leading to the suppression of soil carbon mineralization (Awad et al., 2012). (Chen et al., 2013) found that biochar inclusion improved soil pH, Causing a rise in alkaline phosphatase activity. The enzyme alkaline phosphatase plays a role in phosphorus mineralization and its subsequent utilization in soil, and that increased biochar ultimately enhances soil alkaline phosphatase activity while decreasing d-glucosidase activities (Jin, 2010). Researchers observed that biochar application boosts alkaline phosphatase activity, thereby increasing phosphorus availability (Xiao et al., 2016).

By applying biochar with a rate of 5.0 t/ha, along with 75% RDF and 4 t/ha of FYM, enhanced the carbon content of soil microbial biomass, dehydrogenase enzyme activity, and soil organic carbon-reducing exchangeable aluminum and acidity (Rafi et al., 2015). It was discovered that adding wheat straw biochar elevated urease activities due to higher uptake of p-nitrophenol from biochar decomposition, which may have enhanced phosphorus availability through increased alkaline phosphatase activity following biochar application (Zhu et al., 2017).

To sum it up, the permeable nature of biochar offers a habitat for soil organisms and microorganisms, enhances their diversity and activity, and encourages soil aggregate formation (Knicker et al., 2007; Kolb et al., 2009; Kim et al., 2007; Ameloot et al., 2013; Demisie et al., 2014). The enhancement of bacterial activity, particularly nitrogen-fixing bacteria, benefits soil chemical processes. The addition of biochar also boosts soil enzyme activity and abundance. However, most recent research has focused on biochar's impact on crop yields. Future research should investigate how biochar enhances the growth and reproduction of soil bacteria, fungi, and overall biomass.

5. Conclusion and Future Research Directions

5.1 Conclusion

For the growing demands of agricultural production, declining soil fertility is problematic. The excessive use of synthetic fertilizers and monocropping has harmed soil health and quality. Biochar application can improve soil properties, but its effectiveness is based on the category of biochar, soil type, and application rate.

Biochar is a high-carbon product made under high temperatures and low oxygen conditions. It features an extensive surface area, elevated cation exchange capacity, and significant porosity, along with numerous functional groups. Made from various raw materials, biochar is environmentally friendly and can be used in soil and water applications. Modified biochar is also applied for various purposes.

Incorporating biochar into soil decreases bulk density, enhances porosity and adsorption capacity, improves hydraulic characteristics, darkens soil color, and raises soil temperature. It influences soil enzyme activity, which facilitates soil organism and microorganism growth and improves soil chemical processes, enhancing soil nutrients and plant growth. This, in turn, increases agricultural production and reduces greenhouse gas emissions.

Biochar not only improves soil fertility but also reduces offsite pollution by increasing nutrient retention and decreasing nutrient leaching. Recent research on biochar use in soils has augmented and is expected to be sustained due to its many benefits discussed in this review.

5.2 Future Research Directions

Based on the physical, chemical, and biological effects of biochar addition to soil reviewed, we recommend further research in the following areas:

(i) Establish standardized guidelines and criteria for biochar production. The physicochemical properties of biochar are significantly affected by pyrolysis times, temperatures, and feedstock materials. Given the current high cost of some biochar preparations, it is essential to implement universal preparation standards. The combined use of biochar to optimize its utilization is a crucial direction for future biochar development, providing a scientific basis for widespread application.

(ii) Conduct long-term monitoring of biochar application impacts. Most observed soil effects from biochar application are based on laboratory studies, short-term, small-scale field experiments, or greenhouse experiments. As biochar degrades slowly in soil, its physical and chemical properties, along with eco-environmental benefits, vary over time. Comprehensive, large-scale, long-term field trials are needed to understand the long-term mechanisms of biochar addition and assess its potential negative environmental impacts, enabling the development of better solutions for large-scale applications.

(iii) Promote the use of microbially modified biochar. Biochar is known to enhance soil microbial activity. However, research on microbial alteration and further modification techniques, such as acid-base modifications, is limited. Inoculating biochar with specific microorganisms before soil application can create a beneficial living environment for microbes, improving soil conditions for plants with specific needs.

(iv) Enhance research on the pore structure, soil density, and hydraulic characteristics of biochar. Moisture is vital for plant and animal growth. Future research should investigate the mechanisms by which biochar affects soil hydraulic properties, aiming to alleviate soil water shortages in arid regions and increase crop yield. Determining the optimal biochar application rate for soil moisture improvement is also essential.

(v) Expand studies on the effects of biochar addition on soil ecosystems. Soil ecosystems comprise soil fauna, plants, and microorganisms. Integrating these elements with the benefits of biochar addition is promising. While research on soil plants has advanced, studies on soil fauna and microorganisms have lagged, especially at the microscale level. A comprehensive investigation of soil ecosystems is necessary to facilitate the widespread use of biochar in soil.

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