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Impact of biochar on crop productivity and food security

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Abstract. Biochar, a carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions, has emerged as a promising soil amendment for sustainable agriculture. This review examines the impact of biochar on soil health and fertility, plant growth, and food security. Biochar improves soil physical properties by enhancing water retention, porosity, and soil structure, while also improving chemical characteristics such as nutrient availability, cation exchange capacity, and pH balance. Additionally, it promotes beneficial microbial activity, contributing to healthier and more productive soils. These improvements support enhanced plant growth through increased nutrient uptake, stronger root development, and greater tolerance to environmental stresses such as drought, salinity, and soil contamination. Consequently, biochar application has been associated with increased crop yields in various agricultural systems, particularly in degraded and nutrient-poor soils. Beyond its agronomic benefits, biochar contributes to food security by supporting sustainable agricultural productivity, restoring degraded soils, and improving resilience to climate change. Its capacity for long-term carbon sequestration also offers environmental benefits by mitigating greenhouse gas emissions. However, factors such as feedstock type, production conditions, soil characteristics, and application rates influence its effectiveness. Overall, biochar presents significant potential as a sustainable strategy for enhancing soil quality, agricultural productivity, and global food security.

Keywords: *Biochar, soil health, soil fertility, plant growth, crop productivity, and food security*

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1. Introduction

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass such as crop residues, wood waste, and animal manure under limited oxygen conditions. It has emerged as a sustainable soil amendment with significant potential to improve agricultural productivity and environmental sustainability (Pandian et al., 2024). Due to its porous structure and high surface area, biochar enhances soil physical properties by increasing water-holding capacity, improving soil aeration, reducing bulk density, and promoting better root penetration (Khan et al., 2024). These improvements are particularly beneficial in degraded, sandy, or drought-prone soils where water retention and soil structure are often poor.

Biochar also improves soil fertility by enhancing its chemical and biological properties (Ding et al., 2016). It increases the soil's cation exchange capacity, enabling better retention and availability of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. In acidic soils, biochar can raise pH levels and create more favorable conditions for nutrient uptake (Huang et al., 2023). Furthermore, its porous structure provides a suitable habitat for beneficial microorganisms, leading to increased microbial biomass, enhanced nutrient cycling, and improved soil ecosystem functioning (Rajput et al., 2026). These combined effects contribute to greater soil health and long-term agricultural sustainability.

The positive impacts of biochar on soil conditions often translate into improved plant growth and crop productivity (Chenchouni, 2026). Enhanced soil moisture retention, nutrient availability, and root development support higher germination rates, increased plant height, greater biomass accumulation, and improved yields in a wide range of crops, including maize, wheat, rice, soybean, vegetables, and fruit crops. Biochar also helps plants withstand environmental stresses such as drought, salinity, and heavy metal contamination by improving soil resilience and reducing the uptake of toxic substances (Chi et al., 2024). In some cases, it may also suppress soil-borne diseases through the stimulation of beneficial microbial communities.

Biochar plays an important role in promoting food security by increasing agricultural productivity, improving soil sustainability, and supporting climate change mitigation (Ayaz et al., 2021). Higher and more stable crop yields contribute to greater food availability and farmer incomes, particularly in regions facing soil degradation and nutrient depletion. Additionally, biochar sequesters carbon in a stable form, helping to reduce greenhouse gas emissions and mitigate climate change impacts on agriculture (Lehmann et al., 2021). Despite its many benefits, the effectiveness of biochar depends on factors such as feedstock source, production conditions, soil type, and application rate (Khan et al., 2024). Therefore, appropriate management practices are essential to maximize its contribution to sustainable agriculture and global food security.

2. Effects on soil health and fertility

2.1. Biochar and soil structure improvement

Biochar plays a major role in improving soil structure by increasing aggregation and stability (Sun & Lu, 2014). Its porous and lightweight nature helps bind soil particles together into more stable aggregates. This reduces the likelihood of soil erosion caused by wind and water. Improved aggregation also enhances root penetration, allowing plants to access deeper soil layers more easily (Wang et al., 2020). Over time, soils amended with biochar tend to become more friable and easier to cultivate.

2.2. Enhancement of soil porosity and aeration

One of the key physical benefits of biochar is its ability to increase soil porosity. The internal pore network of biochar creates additional air spaces within the soil matrix (Yu et al., 2016). This improves oxygen availability in the root zone, which is essential for root respiration and growth. Better aeration also supports beneficial microbial processes that require oxygen (Lei et al., 2022). As a result, soils become more biologically active and functionally efficient.

2.3. Improvement of water retention capacity

Biochar significantly enhances the water-holding capacity of soils, especially in sandy or degraded soils (Acharya et al., 2024). Its porous structure acts like a sponge, absorbing and retaining water for longer periods. This helps reduce water stress during dry periods and improves drought resilience in plants (Seleiman et al., 2021). At the same time, it prevents excessive water loss through rapid drainage (Li et al., 2021). Consequently, biochar contributes to more stable soil moisture conditions.

2.4. Reduction of soil bulk density

The addition of biochar can reduce soil bulk density, making soils less compacted (Blanco-Canqui, 2017). Lower bulk density improves root growth by reducing mechanical resistance in the soil. It also enhances the movement of air and water through the soil profile (Xue et al., 2022). This creates a more favorable environment for both plants and soil organisms (Kabir et al., 2023). Over time, reduced compaction leads to healthier and more productive soils.

2.5. Nutrient retention and cation exchange capacity

Biochar improves soil chemical fertility by increasing cation exchange capacity (Kapoor et al., 2022). This allows soils to retain essential nutrients such as potassium, calcium, magnesium, and ammonium. Instead of being lost through leaching, these nutrients remain available for plant uptake. The high surface area of biochar provides numerous binding sites for nutrient ions (Ding et al., 2016). This leads to more efficient nutrient use in agricultural systems.

2.6. Soil pH regulation and acidity reduction

Many types of biochar are alkaline, which enables them to neutralize acidic soils (Joseph et al., 2021). This pH adjustment improves nutrient availability, as extreme acidity can limit nutrient uptake by plants. By raising soil pH to a more neutral range, biochar enhances overall soil fertility (Ding et al., 2016). It also reduces the toxicity of certain elements like aluminum in acidic conditions. As a result, plants can grow more effectively in previously unfavorable soils.

2.7. Reduction of nutrient leaching

Biochar helps reduce nutrient losses by retaining nutrients within the root zone (Prendergast-Miller et al., 2014). In highly permeable soils, nutrients are often washed away by rainfall or irrigation. Biochar's adsorption properties help trap these nutrients and release them gradually over time (Ding et al., 2016; Elkhlifi et al., 2023). This improves fertilizer efficiency and reduces the need for frequent applications. Ultimately, it supports more sustainable nutrient management practices.

2.8. Support for soil microbial communities

Biochar creates a favorable habitat for soil microorganisms due to its porous structure (Palansooriya et al., 2019). Microbes can colonize its surfaces and find protection from environmental stress. This leads to increased microbial diversity and abundance in the soil. Enhanced microbial activity improves decomposition and nutrient cycling processes (Tang, 2025). Overall, biochar strengthens the biological foundation of soil health.

2.9. Promotion of symbiotic relationships

Biochar can enhance beneficial plant–microbe interactions, particularly mycorrhizal associations (Mickan et al., 2016). These symbiotic fungi help plants absorb nutrients and water more efficiently. The presence of biochar improves conditions for these fungi to thrive and expand (Idbella et al., 2024). This results in better plant nutrient uptake and improved stress tolerance. Such relationships contribute to healthier and more resilient crops.

2.10. Long-term carbon storage and soil sustainability

Biochar contributes to long-term soil sustainability through stable carbon sequestration (Yang et al., 2025). Unlike fresh organic matter, biochar decomposes very slowly in soil. This allows carbon to remain stored in the soil for decades or even centuries. In addition to carbon storage, it continuously supports soil fertility and structure (Ding et al., 2016). Therefore, biochar is considered a sustainable amendment that benefits both agriculture and the environment over the long term.

3. Impact on plant growth and crop productivity

3.1. Biochar and seed germination

Biochar can significantly improve seed germination by enhancing soil physical properties (Hafeez et al., 2017). Its porous structure helps retain moisture around seeds, ensuring a stable water supply during early growth stages. This consistent moisture availability supports faster and more uniform germination. In addition, biochar improves soil aeration, which allows better oxygen access to developing seeds (Joseph et al., 2021). These combined conditions create a more favorable environment for successful seed emergence and early establishment.

3.2. Early root development in biochar-amended soils

Root development is often enhanced in soils amended with biochar due to improved soil structure (Chang et al., 2021). The reduced soil compaction allows roots to penetrate more easily and grow deeper. Biochar also increases water-holding capacity, which supports continuous root hydration (Bruun et al., 2014). Additionally, it enhances nutrient availability in the root zone, promoting stronger root growth. As a result, plants develop more extensive root systems that improve overall stability and nutrient uptake.

3.3. Improved soil moisture retention

One of the key benefits of biochar is its ability to retain soil moisture (Acharya et al., 2024). Its porous nature allows it to absorb and hold water, releasing it slowly over time. This is especially beneficial during dry periods when water availability is limited. Improved moisture retention helps maintain plant physiological processes such as photosynthesis and nutrient transport (Xing et al., 2022). Consequently, crops grown in biochar-amended soils are better able to withstand short-term drought stress.

3.4. Enhanced nutrient availability

Biochar improves nutrient availability by increasing the soil's cation exchange capacity (Ding et al., 2016). This allows essential nutrients such as potassium, calcium, and magnesium to be held in the root zone for longer periods (Liu et al., 2018). It reduces nutrient leaching, especially in sandy soils where losses are typically high. As a result, plants can access nutrients more efficiently throughout their growth cycle. This improved nutrient retention contributes to healthier and more vigorous plant development.

3.5. Increased crop yield potential

Many studies have shown that biochar application can lead to increased crop yields (Hussain et al., 2017; Khan et al., 2024). Crops such as maize, rice, wheat, and soybean often respond positively to biochar-amended soils (Schmidt et al., 2021; Khan et al., 2024). Yield improvements are mainly attributed to better nutrient use efficiency and improved soil structure. Biochar also supports more stable moisture conditions, reducing yield fluctuations under stress (Naeem et al., 2024). Overall, these factors contribute to higher and more reliable agricultural productivity.

3.6. Soil microbial activity enhancement

Biochar provides a habitat for beneficial soil microorganisms due to its porous structure (Khan et al., 2024). These microbes play an important role in nutrient cycling and organic matter decomposition. Increased microbial activity enhances soil fertility and supports plant growth. Biochar can also promote beneficial microbial diversity, improving soil ecosystem balance (Zhang et al., 2019). This biological improvement contributes indirectly to better plant health and productivity.

3.7. Drought stress tolerance in plants

Plants grown in biochar-amended soils often show improved tolerance to drought stress (Naeem et al., 2024; Zhang et al., 2024). This is mainly due to increased water retention in the soil, which helps sustain plant functions during dry conditions. Biochar also improves root access to deeper moisture reserves (Gaurav et al., 225). As a result, plants maintain photosynthesis and growth for longer periods under water scarcity. This leads to better survival rates and more stable yields in drought-prone environments.

3.8. Salinity stress mitigation

Biochar can help reduce the negative effects of soil salinity on plant growth (Huang et al., 2023). It improves ion balance in the soil by reducing the availability of harmful sodium ions. This helps prevent excessive sodium uptake by plants, which can damage cellular functions. Biochar also enhances water retention, which dilutes salt concentration in the root zone (Zhang et al., 2023). Together, these effects support healthier plant growth in saline soils.

3.9. Heavy metal immobilization

Another important benefit of biochar is its ability to immobilize heavy metals in soil (Wang et al., 2022). It binds with toxic elements such as lead, cadmium, and arsenic, reducing their mobility. This limits the uptake of harmful substances by plants. As a result, crops grown in contaminated soils become safer for consumption. This property makes biochar especially valuable for soil remediation and sustainable agriculture (Ayaz et al., 2021).

3.10. Improved plant biomass and crop quality

Biochar-amended soils often produce plants with greater biomass due to improved nutrient and water availability (Khan et al., 2024). Enhanced photosynthesis supports faster and healthier plant growth. In many cases, crop quality also improves, including nutritional content in edible parts (Korai et al., 2025). Better soil conditions allow plants to allocate more energy to growth and yield formation. Overall, biochar contributes not only to higher productivity but also to improved crop quality.

4. Contribution to food security

4.1. Biochar as a tool for strengthening food security

Biochar is a carbon-rich material produced from organic biomass through pyrolysis under limited oxygen conditions (Liu et al., 2015). It has gained attention for its ability to improve soil health and agricultural productivity. Food security depends on the consistent availability of sufficient and nutritious food for growing populations. Soil quality is one of the most important factors influencing food production systems. Biochar supports food security by enhancing soil properties that directly affect crop growth (Khan et al., 2024). Its long-lasting nature in soil makes it a sustainable agricultural input.

4.2. Enhancement of soil fertility

Biochar improves soil fertility by increasing the soil's ability to retain and supply essential nutrients (Ding et al., 2016). Nutrients such as nitrogen, phosphorus, and potassium are held more effectively in biochar-amended soils (Hossain et al., 2020). This reduces nutrient loss caused by leaching, especially in low-quality or sandy soils. As a result, plants have better access to nutrients throughout their growth cycle. Farmers can achieve more consistent soil productivity over time. This contributes to improved agricultural outcomes and long-term soil health.

4.3. Improved crop productivity and yield stability

One of the most important benefits of biochar is its positive impact on crop yields (Hossain et al., 2020). By improving nutrient availability and soil conditions, biochar supports stronger plant development. Crops grown in biochar-treated soils often show improved root systems and overall vitality (Liu et al., 2025). This leads to more stable and predictable harvests across seasons. In degraded soils, yield improvements can be especially noticeable. Over time, this strengthens food production systems and reduces the risk of crop failure.

4.4. Soil structure and physical improvement

Biochar enhances soil structure by increasing porosity and improving aggregation (Blanco-Canqui, 2017). These changes allow better movement of air and water within the soil. Improved aeration supports healthy root growth and beneficial microbial activity. It also reduces soil compaction, which can restrict plant development (Liu et al., 2017). Better soil structure helps water infiltrate more effectively instead of running off the surface. This creates a more supportive environment for sustained crop growth.

4.5. Restoration of degraded agricultural lands

Many agricultural areas suffer from long-term soil degradation due to intensive farming and environmental pressures. Biochar can help restore these soils by improving organic matter content and microbial activity (Azeem et al., 2023; Zhang et al., 2023). It supports nutrient cycling processes that are essential for soil regeneration. Over time, degraded soils can regain productivity and support crop cultivation again (Ayub et al., 2019). This is particularly important in regions facing land scarcity and food shortages. The restoration of soil health directly contributes to expanding food production capacity.

4.6. Reduction in dependence on synthetic fertilisers

Biochar supports more sustainable farming by reducing reliance on chemical fertilizers (Pandian et al., 2024). Its ability to retain nutrients means that fewer fertilisers are required to maintain crop growth. This lowers input costs for farmers and reduces environmental pollution. Excess fertiliser runoff, which can damage waterways, is also reduced. Biochar therefore encourages more efficient nutrient use in agriculture (Ayaz et al., 2021). This contributes to both economic and environmental sustainability.

4.7. Prevention of soil degradation and erosion

Soil degradation, including erosion and nutrient loss, poses a major threat to global food security. Biochar helps stabilise soil particles and improve resistance to erosion (Sharma, 2024). It reduces nutrient leaching by holding nutrients within the soil profile (Gao & DeLuca, 2016). Improved soil structure also limits the impact of heavy rainfall and wind erosion. These protective effects help maintain long-term soil productivity. As a result, farmland remains more productive and resilient over time.

4.8. Climate change adaptation and resilience

Biochar helps farmers adapt to climate change by improving soil water retention (Pandian et al., 2024). Soils treated with biochar can hold more moisture, which is crucial during drought conditions. This allows crops to survive longer periods without rainfall. It also helps stabilise soil moisture during irregular weather patterns. In addition, biochar enhances overall crop resilience to environmental stress (Chi et al., 2024). These benefits make agricultural systems more stable under climate variability.

4.9. Contribution to carbon sequestration and climate mitigation

Biochar plays an important role in climate change mitigation through long-term carbon storage (Lehmann et al., 2021). The carbon in biochar is stable and can remain in soils for hundreds of years (Joseph et al., 2021). This reduces the amount of carbon dioxide released into the atmosphere. At the same time, improved soil health can increase agricultural productivity. This dual benefit supports both environmental protection and food production. Therefore, biochar contributes to more sustainable and climate-friendly farming systems.

4.10. Waste recycling and circular economy benefits

Biochar production supports sustainable waste management by converting agricultural and forestry residues into valuable products (Kataya et al., 2023). Materials that would otherwise be burned or left to decompose can be reused beneficially. This reduces environmental pollution and greenhouse gas emissions from waste disposal (Feng et al., 2020). It also promotes circular economy principles by turning waste into a productive agricultural resource. Farmers benefit from an additional soil amendment while reducing waste disposal issues. Overall, this strengthens both environmental sustainability and food security systems.

5. Limitations and challenges of biochar

5.1. Variable effectiveness

Biochar does not produce consistent results across all environments, which is one of its main limitations (Sohi et al., 2009). Its effectiveness depends on several interacting factors such as feedstock type, pyrolysis temperature, soil properties, climate conditions, and crop species. Because these factors vary widely between regions and farming systems, the outcomes of biochar application can differ significantly (Khan et al., 2024). In some cases, strong improvements in soil quality and crop yield are observed, while in others the effects are minimal or uncertain. This variability makes it difficult to predict performance without site-specific testing. As a result, farmers and researchers must carefully evaluate local conditions before application.

5.2. Production costs

The cost of producing biochar at a large scale remains a significant barrier to widespread use (Shackley et al., 2011). Expenses are associated with collecting raw biomass, preparing feedstock, and operating pyrolysis equipment. Additional costs arise from energy consumption during production and the transportation of biochar to agricultural sites (Mohammadi et al., 2020). These financial requirements can make biochar less competitive compared to conventional soil amendments. In low-resource or developing agricultural systems, these costs may be particularly restrictive. Therefore, economic feasibility is a key challenge for broader adoption.

5.3. Soil and nutrient interactions

Biochar can sometimes interact with soil nutrients in ways that temporarily reduce their availability to plants (DeLuca et al., 2024). Freshly applied biochar may adsorb nutrients such as nitrogen, phosphorus, and potassium, leading to short-term nutrient immobilization (Major et al., 2012). This can limit nutrient uptake by crops during early growth stages if no additional fertilisation is provided. However, this effect is usually temporary as the biochar surface stabilises over time. In some cases, nutrient retention may even improve long-term soil fertility once equilibrium is reached. Proper management practices are therefore required to avoid early-stage growth limitations.

5.4. Lack of standards and guidelines

There is currently no universal standard for biochar application rates or production methods (Young et al., 2019). This is because optimal conditions vary depending on soil type, climate, and agricultural goals. As a result, recommendations differ widely between studies and regions. The absence of consistent guidelines makes it difficult for farmers to apply biochar with confidence. In addition, variability in production processes leads to differences in biochar quality and performance (Ronsse et al., 2013). Establishing standardised frameworks would help improve reliability and adoption.

5.5. Limited long-term research

Although short-term studies show promising results, long-term research on biochar is still limited (Yang et al., 2025). The extended effects of biochar on soil health, microbial activity, and ecosystem stability are not yet fully understood (Wang et al., 2016). This lack of long-term data creates uncertainty about its sustained benefits and potential risks. In particular, more field trials over multiple growing seasons are needed. Without long-term evidence, it is difficult to fully assess its environmental and agricultural impacts. Continued research is essential to strengthen confidence in its widespread use.

6. Conclusions

Biochar is a promising soil amendment with substantial potential to improve soil health, fertility, and crop productivity. Its ability to enhance water retention, nutrient availability, microbial activity, and carbon sequestration makes it a valuable tool for sustainable agriculture. By supporting higher and more resilient crop yields, biochar can contribute significantly to food security, particularly in regions facing soil degradation and climate-related challenges. However, successful implementation requires careful consideration of biochar type, application rate, soil conditions, and local agricultural practices to maximize benefits and minimize limitations.

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