



POPULAR SCIENCE ARTICLE

How Biochar Contributes to Sustainable Agriculture: Impacts on Soil Health, Crop Productivity, Resource-Use Efficiency and Carbon Sequestration

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ABSTRACT

Sustainable agriculture requires production systems that maintain crop productivity while conserving soil, water, nutrients, and other natural resources. Biochar has emerged as a promising carbon-rich soil amendment with potential applications in sustainable and climate-resilient agriculture. It is generally produced through the thermochemical conversion of biomass under oxygen-limited conditions and possesses distinctive physicochemical properties, including a porous structure, relatively stable carbon, variable surface functional groups, and, in many cases, considerable nutrient-retention capacity. The agricultural effects of biochar depend strongly on the type of feedstock, production conditions, application rate, soil properties, crop species, and environmental conditions. Evidence from scientific studies indicates that appropriately selected biochar can improve soil physical properties, increase nutrient retention, enhance water-holding capacity, influence soil microbial activity, and support crop growth, particularly in degraded, acidic, coarse-textured, or nutrient-poor soils. Biochar can also contribute to long-term carbon storage because a proportion of its carbon is relatively resistant to microbial decomposition. Furthermore, conversion of agricultural residues into biochar provides an opportunity for waste valorization and nutrient recycling within a circular bioeconomy. However, biochar is not universally beneficial, and inappropriate feedstocks, production conditions, or application rates may cause undesirable effects such as excessive alkalinity, salinity, nutrient imbalance, or contaminant introduction. Therefore, biochar should be regarded as a site-specific soil management tool rather than a universal substitute for fertilizers. This article discusses biochar production, properties, interactions with soil, effects on nutrient and water management, crop productivity, soil microorganisms, carbon sequestration, environmental sustainability, limitations, and future research priorities.

Keywords: Biochar; sustainable agriculture; soil health; nutrient-use efficiency; carbon sequestration; climate-smart agriculture

1. INTRODUCTION

Agriculture faces growing challenges from soil degradation, declining organic carbon, nutrient losses, water scarcity, agricultural waste, and climate change, threatening long-term crop productivity and environmental sustainability. Biochar, a carbon-rich material produced through thermochemical conversion of biomass under limited oxygen, has emerged as a promising soil amendment (Blanco-Canqui, 2021). Its porous structure and relatively stable carbon can improve soil properties, nutrient and water retention, microbial activity, and crop

performance while supporting carbon sequestration and agricultural waste recycling (Brtnicky *et al.*, 2021). Biochar can complement Integrated Nutrient Management (INM) by improving nutrient retention and fertilizer-use efficiency when combined with mineral fertilizers, organic amendments, and beneficial microorganisms. Its integration into INM may help reduce nutrient losses, improve soil health, and support more resource-efficient and sustainable crop production (Kaushik *et al.*, 2025).

However, a major research gap remains

between the reported potential of biochar and its reliable field-scale application. Biochar responses vary considerably with feedstock, production conditions, soil type, crop, climate, and application rate, making generalized recommendations difficult. Moreover, evidence from long-term and multi-location field studies remains limited, particularly regarding optimum application rates, biochar–soil–microbe interactions, carbon persistence, environmental risks, economic feasibility, and overall life-cycle sustainability.

Therefore, this article reviews the role of biochar in sustainable agriculture, focusing on production and properties, soil health, nutrient and water-use efficiency, crop productivity, microbial interactions, carbon sequestration, greenhouse-gas mitigation, and waste valorization. It also evaluates key limitations and future research priorities for developing safe, economically viable, and site-specific biochar management strategies for sustainable and climate-resilient agriculture.

2. BIOCHAR: DEFINITION, FEEDSTOCKS, AND CHARACTERISTICS

“Biochar is a carbon-rich solid produced by the thermochemical conversion of biomass under conditions of limited oxygen and intended for applications that can provide environmental or agricultural benefits”. It can be produced from a wide range of biomass materials, including crop residues, wood and forestry wastes, fruit and vegetable wastes, animal manure, and other suitable organic materials (Joseph *et al.*, 2021).

The properties of biochar differ substantially from those of the original biomass. During thermochemical conversion, biomass undergoes dehydration, devolatilization, decomposition, and carbonization. These processes produce a material containing relatively stable carbon structures along with mineral components inherited from the original feedstock. Biochar should not simply be considered identical to ordinary charcoal or biomass ash. Although charcoal and biochar may be produced through related thermochemical processes, the term biochar generally emphasizes purposeful production and use for soil, environmental, or carbon-management applications. Biomass ash, in contrast, consists mainly of the inorganic mineral residue remaining after more complete combustion and contains relatively little organic carbon.

Important characteristics of biochar include:

- carbon content and carbon stability;
- pH and electrical conductivity;
- porosity and pore-size distribution;

- specific surface area;
- surface functional groups;
- cation exchange capacity;
- ash and mineral content;
- nutrient composition; and
- water-retention characteristics.

These properties determine how a particular biochar interacts with soil and plants.

3. PRODUCTION OF BIOCHAR

Biochar can be produced through several thermochemical processes. Pyrolysis is the most widely discussed method and involves heating biomass under limited or very low oxygen conditions. Depending on the feedstock and production system, temperatures commonly used for biochar production may broadly range from approximately 300 to 700°C.

The general conversion pathway can be represented as:

Biomass → Thermochemical conversion → Biochar + Condensable liquids/bio-oil + Gaseous products

3.1 Slow Pyrolysis: Slow pyrolysis generally involves relatively slow heating and longer residence times. It commonly favours the production of solid carbonaceous material and is therefore widely used for biochar production.

3.2 Fast Pyrolysis: Fast pyrolysis uses rapid heating and short vapour residence times and is generally designed to maximize liquid products such as bio-oil. Biochar is also produced as a solid coproduct.

3.3 Gasification: Gasification converts biomass at relatively high temperatures with a controlled supply of oxygen, air, steam, or other gasifying agents. The primary product is combustible synthesis gas or syngas, although a carbonaceous solid fraction may also be generated.

3.4 Hydrothermal Carbonization:

Hydrothermal carbonization is particularly suitable for wet biomass because extensive pre-drying is not always necessary. Biomass is treated in water at elevated temperature and pressure to produce a carbon-rich material called hydrochar. Hydrochar differs from conventional pyrolysis-derived biochar in several physicochemical characteristics and should therefore be evaluated separately for agricultural applications.

After production, biochar may be cooled, crushed, sieved, characterized, and, where appropriate, conditioned or combined with nutrient-rich materials before soil application. Proper characterization is essential because

biochars produced from different feedstocks and processing conditions can behave very differently in soil.

4. CHEMICAL AND PHYSICOCHEMICAL PROPERTIES OF DIFFERENT BIOCHARS

Biochar composition is strongly influenced by the original feedstock and thermochemical conditions. Wood-derived biochars generally contain a relatively high proportion of carbon and often have lower ash and nutrient concentrations than manure-derived biochars. Crop-residue biochars can contain considerable amounts of mineral nutrients, particularly potassium, calcium, magnesium, phosphorus, and silicon, depending on the plant material used.

Manure-derived biochars generally have higher ash and mineral nutrient contents, particularly phosphorus, potassium, calcium, and magnesium. However, their electrical conductivity and salt content may also be comparatively high, which should be considered before application. Increasing pyrolysis temperature generally increases the degree of carbonization and aromaticity while reducing some volatile components. It may also alter pH, porosity, surface area, nutrient availability, and surface functional groups. Consequently, no single type of biochar is suitable for every soil or crop.

5. EFFECTS OF BIOCHAR ON SOIL HEALTH

Soil health reflects the capacity of soil to function as a living ecosystem while sustaining plants, animals, and environmental quality. Biochar may influence the physical, chemical, and biological components of soil health (Murtaza *et al.*, 2021).

Feedstock	General characteristics	Potential agricultural significance
Wood/forestry residues	Relatively high stable carbon; often lower ash	Carbon storage, porosity and soil physical improvement
Crop residues	Variable carbon and mineral content	Nutrient recycling and soil amendment
Rice husk	Often rich in silica and mineral ash	Potential Si contribution and modification of soil properties
Animal manure	Generally nutrient- and ash-rich	Nutrient supply and soil fertility management
Horticultural residues	Variable carbon and nutrients	Waste valorization and nutrient recycling

5.1 Effects on Soil Physical Properties:

Biochar is generally porous and has a comparatively low bulk density. Its incorporation into certain soils can modify soil porosity, aggregation, aeration, bulk density, and water-holding characteristics. These effects can be particularly important in degraded or coarse-textured soils. Biochar pores can retain water and provide microsites within the soil matrix. However, the magnitude of these effects depends on biochar particle size, porosity, application rate, soil texture, and ageing processes (Premalatha *et al.*, 2023).

5.2 Effects on Soil Chemical Properties:

Biochar can influence soil pH, cation exchange capacity, nutrient retention, soil organic carbon, and nutrient availability. Alkaline biochars may be particularly useful in some acidic soils because they can contribute to increasing soil pH and reducing acidity. Surface functional groups and mineral components may interact with nutrient ions and influence their retention or mobility. Consequently, biochar may reduce losses of certain nutrients under appropriate conditions (Schmidt *et al.*, 2021).

5.3 Effects on Soil Biological Properties:

The porous structure of biochar can provide physical microsites for soil microorganisms. Changes in soil moisture, pH, aeration, nutrient availability, and organic substrates following biochar application can also alter microbial activity and community composition. However, biological responses vary considerably with soil conditions and biochar characteristics. Therefore, increased microbial activity should not be considered an automatic consequence of all biochar applications (Wang *et al.*, 2021).

6. BIOCHAR AND NUTRIENT-USE EFFICIENCY

Efficient nutrient management is essential for sustainable agricultural production. Losses of nitrogen, phosphorus, potassium, and other nutrients through leaching, volatilization, erosion, or fixation can reduce fertilizer-use efficiency and increase environmental impacts. Biochar may influence nutrient dynamics through adsorption, ion exchange, changes in soil pH, altered microbial activity, and interactions with soil organic matter. Its surface properties can help retain some nutrient ions and potentially reduce their movement beyond the root zone. Biochar can also be combined with compost, manure, mineral fertilizers, or microbial inputs to develop integrated nutrient-management strategies. Such combinations may improve nutrient synchronization between soil nutrient availability and crop demand.

Nevertheless, biochar should not be considered a complete fertilizer or a universal replacement for mineral fertilizers. Many biochars contain limited amounts of plant-available nitrogen and other essential nutrients. Therefore, biochar application should be integrated with soil testing, crop nutrient requirements, and appropriate fertilizer-management practices.

7. BIOCHAR AND SOIL WATER MANAGEMENT

Water scarcity and irregular rainfall are major constraints to agricultural productivity. Biochar has attracted attention for its potential role in improving soil water relations. The porous structure of some biochars can increase water retention and modify pore-size distribution, potentially increasing the amount of water available to plants. These effects may be particularly relevant in sandy or coarse-textured soils where water drains rapidly. Improved soil moisture conditions may support root growth, nutrient uptake, microbial processes, and plant tolerance to temporary water stress. Consequently, biochar may contribute to improved water-use efficiency in certain soil-crop systems.

However, effects on soil water depend on feedstock, production temperature, pore characteristics, application rate, soil texture, and climatic conditions. Biochar therefore cannot be assumed to improve water availability equally in every soil.

8. EFFECTS OF BIOCHAR ON PLANT GROWTH AND CROP PRODUCTIVITY

Biochar can influence plant growth indirectly by modifying the soil environment. Improvements in nutrient retention, soil structure, moisture availability, pH, and microbial activity can create favourable conditions for root development and nutrient uptake. Positive crop responses are frequently associated with degraded, acidic, nutrient-poor, or coarse-textured soils where biochar corrects an existing soil limitation. Biochar may influence seedling establishment, vegetative growth, root development, nutrient-use efficiency, yield, and, in some cases, crop-quality characteristics (Zhao *et al.*, 2021).

Nevertheless, crop responses to biochar are variable. Neutral or negative responses can occur when inappropriate biochars or excessive application rates are used. Crop species, soil fertility, environmental conditions, feedstock, pyrolysis conditions, and interactions with fertilizers all influence the final response.

Therefore, biochar should be applied according to crop and soil requirements rather than at a universal application rate.

9. BIOCHAR-SOIL-MICROBE INTERACTIONS

Soil microorganisms are essential for decomposition, nutrient cycling, soil aggregation, and plant nutrient availability. Biochar can influence microbial communities both directly and indirectly. Its pore structure may provide protected microsites for microorganisms, while its effects on soil moisture, pH, aeration, and nutrient availability can alter microbial habitat conditions. Biochar may also interact with microbial metabolites, dissolved organic matter, and soil enzymes (Zhang *et al.*, 2022).

A simplified relationship can be represented as:

Biochar application → changes in soil habitat and resource availability → microbial responses → changes in nutrient cycling and soil functioning → potential effects on plant growth

The direction and magnitude of these interactions depend on the biochar-soil-crop combination. Further long-term research is required to understand how biochar affects specific beneficial and harmful microorganisms under field conditions.

10. BIOCHAR, CARBON SEQUESTRATION, AND CLIMATE-SMART AGRICULTURE

One of the major environmental interests in biochar is its potential contribution to carbon sequestration. During biomass growth, plants remove carbon dioxide from the atmosphere through photosynthesis. If biomass decomposes or is burned, much of this carbon can return to the atmosphere relatively rapidly. Thermochemical conversion can transform part of the biomass carbon into relatively stable carbon structures. When appropriately produced biochar is incorporated into soil, a portion of this carbon may remain in the soil for substantially longer periods than uncharred biomass.

The conceptual pathway is (Lehmann *et al.*, 2021):

Atmospheric CO₂ → Plant biomass → Biomass residues → Biochar production → Stable carbon in soil

Biochar can also influence greenhouse-gas emissions such as nitrous oxide, methane, and carbon dioxide by modifying soil aeration, nutrient availability, moisture, pH, and microbial processes. However, the magnitude and direction of greenhouse-gas responses depend on soil and management conditions. Thus, biochar can potentially contribute to climate-smart agriculture through the combined functions of carbon management, soil

improvement, resource-use efficiency, and increased resilience to environmental stress.

11. BIOCHAR IN AGRICULTURAL WASTE MANAGEMENT AND THE CIRCULAR BIOECONOMY

Large quantities of crop residues, pruning wastes, forestry residues, animal manures, and horticultural wastes are generated annually. Improper disposal or open burning of these materials can contribute to air pollution, greenhouse-gas emissions, and nutrient losses. Converting suitable agricultural residues into biochar provides an opportunity to transform waste biomass into a value-added product. The resulting biochar can potentially return carbon and certain nutrients to agricultural soils. Biochar influences soil-plant systems through several key mechanisms, including surface adsorption and ion exchange, nutrient retention, pH modification, improved soil porosity and water retention, microbial habitat formation, immobilization of potentially toxic metals, and stabilization of organic carbon (Kaushik *et al.*, 2026). Together, these mechanisms can improve soil health, resource-use efficiency, crop performance, and long-term carbon sequestration.

This circular pathway can be represented as:

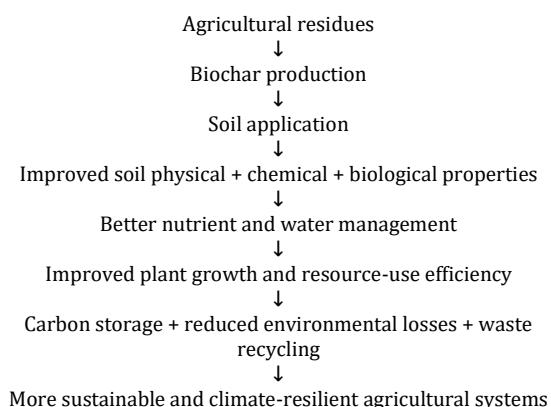
Agricultural production → Biomass residues → Biochar production → Soil application → Improved resource cycling → Crop production

This approach supports the principles of a circular bioeconomy by recovering value from biological wastes, reducing waste disposal, recycling nutrients, and potentially storing carbon within agricultural soils.

12. ROLE OF BIOCHAR IN SUSTAINABLE AGRICULTURE

The contribution of biochar to sustainable agriculture results from interactions among several mechanisms rather than from a single property.

A conceptual framework is:



Biochar therefore has potential relevance to multiple dimensions of agricultural sustainability, including soil conservation, resource-use efficiency, waste management, climate-change mitigation, and crop resilience.

Its role should, however, be considered as part of integrated soil and crop management rather than as a stand-alone solution.

13. ADVANTAGES OF BIOCHAR

- 1. Improves soil health and fertility:** Biochar improves soil structure, porosity, aeration, CEC, nutrient retention, and soil organic carbon, and may help correct acidity in acidic soils.
- 2. Enhances nutrient and water-use efficiency:** It can reduce nutrient leaching, improve fertilizer-use efficiency, increase soil water-holding capacity, and enhance drought resilience, particularly in coarse-textured soils.
- 3. Supports soil biology and crop productivity:** Its porous structure provides favourable microsites for soil microorganisms, while improved soil conditions can support root growth, nutrient uptake, and crop productivity.
- 4. Promotes carbon sequestration and climate benefits:** Its relatively stable carbon can remain in soil for extended periods and may contribute to carbon sequestration and mitigation of greenhouse-gas emissions such as N₂O and CH₄ under suitable conditions.
- 5. Promotes waste recycling and circular bioeconomy:** Biochar converts crop residues, pruning waste, manure, and other suitable biomass into value-added soil amendments, reducing waste disposal and supporting resource recycling.
- 6. Supports environmental and agricultural sustainability:** Biochar can contribute to degraded-soil restoration, contaminant management, resource conservation, climate-smart agriculture, and the long-term sustainability of agricultural production systems.

14. FUTURE RESEARCH PRIORITIES

- 1. Feedstock and production optimization:** Identify suitable biomass feedstocks and optimize pyrolysis temperature, heating rate, and residence time to produce high-quality biochar with desirable agricultural properties.
- 2. Site-specific application strategies:** Develop optimum crop- and soil-specific application rates for different crops, soil

types, climatic conditions, and agricultural production systems.

3. **Integration with fertilizers and biological inputs:** Investigate interactions of biochar with mineral fertilizers, compost, FYM, vermicompost, beneficial microorganisms, and rhizosphere processes to improve nutrient-use efficiency and crop productivity.
4. **Soil, water, and microbial responses:** Evaluate long-term effects on soil properties, water-use efficiency, drought tolerance, root development, microbial diversity, and soil enzyme activities.
5. **Carbon sequestration and environmental safety:** Assess long-term biochar carbon stability, greenhouse-gas emissions (CO_2 , N_2O , and CH_4), contaminant behaviour, and potential environmental risks.
6. **Long-term field validation and sustainability assessment:** Conduct multi-year and multi-location field trials, supported by economic analysis, life-cycle assessment (LCA), and carbon-footprint assessment to determine practical and environmental sustainability.
7. **Standardization and farmer-friendly technologies:** Develop biochar quality standards and low-cost, energy-efficient, and scalable production technologies, supported by interdisciplinary research integrating soil science, agronomy, horticulture, microbiology, engineering, environmental science, economics, and carbon accounting.

15. CONCLUSION

Biochar is a promising soil amendment that can contribute to sustainable agriculture by improving soil health, nutrient retention, water-use efficiency, microbial activity, and crop productivity. Its stable carbon content also supports long-term carbon sequestration, while the conversion of agricultural residues into biochar promotes waste recycling and the circular bioeconomy. However, its effectiveness depends on feedstock type, production conditions, soil properties, crop species, and application rate. Therefore, the scientifically optimized and site-specific use of biochar can serve as a powerful strategy for building productive, resource-efficient, climate-resilient, and environmentally sustainable agricultural systems for the future.

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