VETERINARY TODAY
ISSN: 2583-8288
Technical Article
Published on: 09/03/2025

Biochar in Sustainable Agriculture: Properties, Benefits, and Practical Applications

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DOI:10.5281/Vettoday.14996167

1. Introduction

Biochar is a fine-grained, carbon-rich material that is lightweight and highly porous. It is produced through the pyrolysis of organic biomass, a process that involves heating biomass at temperatures ranging from 300 to 1,000°C under limited or no oxygen conditions. Various organic feedstocks, including agricultural residues, animal manure, and municipal waste, can be utilized for biochar production (Diatta *et al.*, 2020). This thermal transformation stabilizes carbon within biochar, preventing it from easily escaping into the atmosphere, thereby contributing to long-term carbon sequestration.

One of the defining physical characteristics of biochar is its black color and extensive surface area. The surface area of biochar significantly influences its ability to retain moisture, store nutrients, and interact with soil microbes and environmental contaminants. A larger surface area provides more active sites for adsorption reactions, facilitates microbial colonization, and enhances nutrient exchange processes (Wyn *et al.*, 2020). Typically, the surface area of biochar ranges from 8 to 132 m^2 per gram, while its total pore volume can vary between 0.016 and 0.083 cm^3 per gram (Leng *et al.*, 2021). These properties make biochar an effective soil amendment, improving soil aeration, water retention, and nutrient availability.

Biochar is composed of various essential elements, including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), sodium (Na), and silicon (Si). These elements are crucial for plant growth, with carbon being the predominant component, often exceeding 70%, followed by hydrogen and oxygen. The mineral elements in biochar are primarily found in its ash content. Due to its high cation exchange capacity (CEC), biochar enhances nutrient retention in soils, reducing nutrient leaching and improving plant uptake efficiency.

Beyond its role in soil improvement, biochar offers a range of environmental and agricultural benefits. It enhances soil structure, promotes microbial activity, and increases the availability of essential nutrients. By creating favorable conditions for beneficial soil microbes, biochar supports the decomposition of organic matter, indirectly increasing soil organic carbon levels. Soil organic carbon plays a key role in maintaining CEC, which is essential for nutrient exchange between soil and plant roots. A deficiency of carbon in the soil can negatively impact plant health, potentially leading to poor growth or plant death.

With its unique physicochemical properties, biochar plays a vital role in sustainable agriculture by improving soil fertility, enhancing crop productivity, and addressing environmental challenges. Additionally, its applications extend to carbon sequestration, pollution remediation, and water filtration, making it a valuable tool for ecological sustainability (Diatta et al., 2020).

2. Physiochemical Properties of Biochar

2.1. Physical Properties

2.1.1 Porosity and surface area

Biochar is a lightweight, fine-grained organic material with a highly porous structure that improves soil aeration and water retention. Its porosity enhances soil stability, forming pathways for air and water flow, which supports nutrient absorption and boosts crop productivity (Lu *et al.*, 2023). The surface area of biochar typically falls between 8 and 132 m^2 per gram, while its total pore volume ranges from 0.016 to 0.083 cm^3 per gram. (Leng *et al.*, 2021).

2.1.2 Water retention capacity

Biochar plays a crucial role in enhancing soil water-holding capacity (WHC) by increasing porosity and offering surfaces where water can adhere. Research indicates that biochar contributes to a 23% rise in capillary porosity and a 24% increase in total soil porosity (Zhang *et al.*, 2017). Its porous structure forms networks of water-retaining channels, which help minimize surface runoff and reduce soil erosion. This ability to retain moisture makes biochar particularly beneficial in regions prone to drought, as it supports soil hydration and improves water availability for plant growth. (Razzaghi *et al.*, 2020).

2.1.3 Bulk density and soil texture improvement

Due to its low bulk density, biochar helps alleviate soil compaction, improving overall soil structure, especially in dense clay soils. By loosening compacted soil, it allows for better root growth and penetration, enabling plants to access nutrients and water more efficiently. Additionally, biochar enhances soil friability, making it softer and easier to work with, which benefits agricultural practices by simplifying tillage and promoting healthier plant development.

2.1.4 Thermal stability

Biochar's unique aromatic carbon structure grants it high thermal stability, making it resistant to quick decomposition. This stability allows biochar to remain in the soil for extended periods, continuously enhancing soil quality and fertility. Additionally, its long-lasting presence contributes to carbon sequestration by storing carbon in the soil instead of releasing it into the atmosphere. As a result, biochar not only improves agricultural productivity but also plays a role in mitigating climate change (Gross *et al.*, 2021).

3. Chemical Properties

3.1 pH and Electrical Conductivity (EC)

With a typically alkaline pH ranging from 7 to 10, biochar is effective in neutralizing acidic soils, helping to create a more balanced growing environment. It also plays a crucial role in stabilizing soil pH, preventing drastic fluctuations that could impact plant health. By maintaining a steady pH level, biochar enhances the availability of essential nutrients, promoting better nutrient uptake by plants (Chintala *et al.*, 2014). However, applying excessive amounts of biochar to already alkaline soils may lead to adverse effects, potentially disrupting soil chemistry and plant growth (Chathurika *et al.*, 2016).

3.2 Cation Exchange Capacity (CEC) and Nutrient Retention

Biochar possesses a high cation exchange capacity (CEC), allowing it to effectively capture and exchange vital nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). This characteristic helps retain essential cations within the soil, preventing them from being washed away through leaching. As a result, biochar contributes to long-term soil fertility by ensuring a steady supply of nutrients for plant uptake. Over time, this nutrient retention ability supports healthier plant growth and enhances soil productivity, making biochar a valuable soil amendment (Karimi *et al.*, 2020; Adhikari *et al.*, 2022).

3.3 Carbon Content and Stability

Biochar is mainly composed of recalcitrant carbon, which is highly resistant to microbial breakdown. This resistance allows biochar to persist in the soil for extended periods without rapidly decomposing. As a result, it serves as an effective tool for long-term carbon sequestration by storing carbon in the soil rather than allowing it to return to the atmosphere as carbon dioxide. By reducing greenhouse gas emissions, biochar plays a role in mitigating climate change while simultaneously improving soil health (Lehmann *et al.*, 2006).

3.4 Adsorption and Contaminant Removal

Biochar exhibits strong adsorption capabilities, allowing it to bind heavy metals, pollutants, and surplus nutrients within the soil. By immobilizing these potentially harmful substances, biochar reduces their bioavailability, preventing them from being absorbed by plants. This process not only enhances soil quality but also minimizes the risk of toxic accumulation in crops, promoting safer agricultural practices. As a result, biochar serves as an effective soil amendment for remediating contaminated soils and maintaining a healthier growing environment (Kookana *et al.*, 2011).

4. Applications of Biochar in Agriculture

4.1. Soil Fertility Enhancement

By improving nutrient retention and reducing leaching, biochar enhances soil organic matter content and fosters beneficial microbial activity. This leads to better plant growth and yield (Jeffery *et al.*, 2011).

4.2. Water Retention and Management

Biochar increases soil moisture retention, reducing drought stress and irrigation frequency. This makes it particularly useful in arid and semi-arid regions.

4.3. Soil Microbial Activity Improvement

The porous nature of biochar creates a habitat for beneficial soil microorganisms. This fosters microbial diversity and improves nutrient cycling, leading to healthier soil ecosystems (Steiner *et al.*, 2008).

4.4. Carbon Sequestration and Climate Change Mitigation

Biochar's ability to store carbon for extended periods helps reduce atmospheric CO_2 levels. Additionally, it minimizes greenhouse gas emissions such as methane and nitrous oxide from agricultural fields (Woolf *et al.*, 2010).

4.5. Heavy Metal and Pollutant Remediation

Biochar can immobilize heavy metals and other toxic compounds in contaminated soils, preventing their uptake by plants and improving soil safety for agricultural use (El-Naggar *et al.*, 2018).

4.6. Composting and Waste Management

Adding biochar to compost enhances microbial decomposition, reduces odor emissions, and improves the quality of organic fertilizers, contributing to more sustainable farming practices.

4.7. Livestock Applications

Biochar can be used in animal husbandry to improve feed efficiency, reduce enteric methane emissions, and enhance manure quality for composting and fertilization.

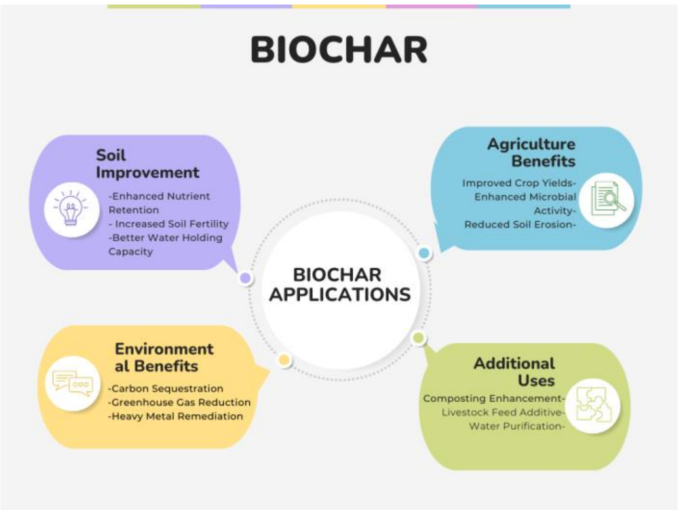

Fig. 1: Applications of biochar in Agriculture

5. Preparation of Biochar

5.1 Raw Materials for Biochar Production

Sr. No.	Residues	Examples
1.	Agricultural	rice husks, wheat straw, and corn stalks.
1.	Forestry by-products	sawdust, wood chips, and tree bark
2.	Organic waste	manure, food scraps, and sewage sludge.

5.2 Methods of Biochar Preparation

5.2.1. Traditional Kilns

Traditional methods, including earth pits and brick kilns, have been used for centuries. While cost-effective, they are often inefficient and produce emissions that contribute to air pollution.

5.2.2. Modern Pyrolysis Techniques

Modern pyrolysis techniques allow for greater control over process parameters, leading to higher-quality biochar. Key methods include:

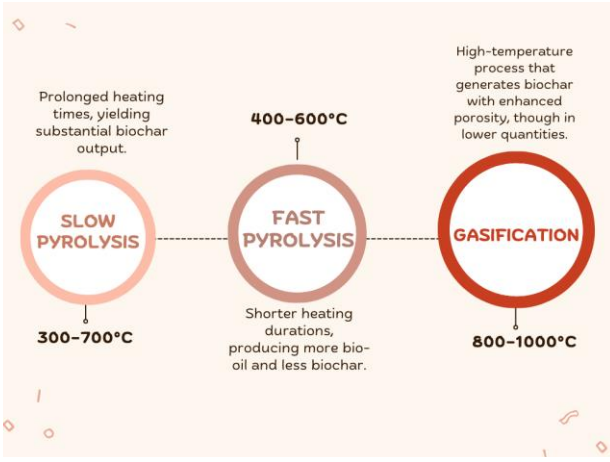

Fig 2: Modern Pyrolysis Techniques

6. Factors Influencing Biochar Quality

Several factors affect biochar's properties:

A. Temperature: Higher temperatures lead to increased carbon content but lower overall yield.
B. Residence Time: Extended heating improves stability and adsorption capacity.
C. Feedstock Composition: Different biomass sources result in varying nutrient levels and porosity.

7. Future Innovations in Biochar: Emerging Applications

The potential of biochar extends beyond traditional uses, with several cutting-edge applications that remain largely unexplored. These advancements could significantly transform various industries:

7.1 Space farming and extra-terrestrial soil enhancement

Biochar could play a crucial role in supporting plant growth in extraterrestrial environments, such as Mars and lunar colonies. Its ability to retain moisture and promote beneficial microbial activity could enhance soil fertility for space-based agriculture.

7.2 Biochar in targeted medicine and drug delivery

Engineered biochar nanoparticles may be utilized for precise drug delivery systems, ensuring controlled and sustained release of medications. Additionally, its potential use in detoxification therapies for removing heavy metals and toxins from the human body could be an area of future research.

7.3 Quantum Dot Technology and advanced se miconductors

Carbon-derived quantum dots from biochar could revolutionize the field of nanotechnology and semiconductor design. These materials may lead to breakthroughs in electronics, solar energy technology, and optical sensors.

7.4 Biochar Enhanced Supercapacitors and energy storage

Modified biochar could be an innovative material for use in next-generation supercapacitors and battery technologies. Its application in sustainable energy storage solutions could support the transition to eco-friendly power systems.

7.5 Antimicrobial coatings and sustainable pac kaging

By infusing biochar with antimicrobial properties, it could be used to develop sustainable food packaging solutions that extend product shelf life and reduce spoilage. Additionally, it may have applications in medical dressings and coatings to prevent infections.

7.6 AI-Driven biochar optimization

Artificial intelligence (AI) could be leveraged to design biochar formulations tailored to specific purposes, such as soil enhancement or industrial processes. Machine learning algorithms could analyze extensive datasets to optimize biochar production techniques.

7.7 Biochar for Climate-Resilient Urban Infrast ructure

Urban environments could benefit from biochar integration into roads, pavements, and green spaces to improve flood management, carbon sequestration, and heat mitigation. Biochar-infused materials, such as asphalt and insulation, could contribute to climate-adaptive city planning.

7.8 Hydrogen production from biochar

Optimizing pyrolysis and gasification techniques could enhance biochar's role in hydrogen generation, aiding the growth of the clean hydrogen economy. Additionally, catalytic biochar materials may be explored for efficient hydrogen storage.

7.9 Air purification and carbon capture with bi ochar

The porous nature of biochar could be further engineered to enhance its ability to trap airborne pollutants and improve indoor air quality. Its integration into carbon capture systems could also assist in reducing industrial emissions.

7.10 Biochar in synthetic biology and environ mental remediation

Genetically engineered microorganisms could be incorporated into biochar to enhance its capacity for breaking down pollutants like plastics and persistent chemicals. This could lead to a new category of biochar infused with living organisms designed for targeted environmental cleanup.

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