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Original Article

Applications of Biochar in Soil Improvement: A Review

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Abstract

Biochar is a carbon-rich material produced from agricultural and organic biomass through pyrolysis. In recent years, bio char has gained significant attention as a sustainable soil amendment that enhances soil fertility, improves crop productivity, and contributes to long-term carbon sequestration. This review focuses on the chemical characteristics, production methods, and multiple applications of biochar in soil improvement. Key benefits such as enhanced nutrient retention, improved water-holding capacity, increased soil microbial activity, pH regulation, and reduction of heavy metal mobility are discussed. The paper also highlights the relevance of biochar in rural agricultural systems, particularly in regions with low soil fertility. As biochar production uses locally available wastes such as crop residues, cow dung, leaves, and agro-wastes, it offers an environmentally friendly and economically viable approach to sustainable soil management. The review concludes that biochar is a promising, low-cost, and eco-friendly material that can significantly strengthen soil health and rural farming practices.

Keywords-*Biochar, Soil Fertility, Carbon Sequestration, Agriculture, Green Chemistry, Sustainable Soil Management.*

Introduction

Soil degradation is one of the major challenges affecting agricultural productivity in many rural regions of India. Continuous cultivation, excessive use of chemical fertilizers, and poor organic matter management have reduced soil quality, resulting in low fertility and declining crop yields. In recent years, biochar has emerged as an effective, eco-friendly solution for restoring soil health. Biochar is a carbon-rich, highly stable material produced by pyrolysis of agricultural biomass under limited oxygen. It has a unique porous structure and high surface area, which makes it exceptionally useful for improving soil properties.

The concept of using charcoal as a soil amendment has existed for centuries, particularly in the Amazon Basin's "Terra Preta" soils. Modern research in green chemistry and sustainable agriculture has further proven that biochar can significantly enhance soil fertility, water retention, nutrient availability, and microbial activity. For rural farming communities, biochar offers an affordable and easily accessible option as it can be prepared using locally available biomass such as crop residues, cow dung, dry leaves, coconut shells, sugarcane waste, and forestry residues. This review focuses on the scientific principles, chemical properties, and key applications of biochar in soil improvement. The study particularly highlights its relevance to rural agricultural systems where soil fertility management plays a crucial role in sustaining crop production.

Biochar: Definition and Chemical Background

Biochar is a solid, carbon-rich, porous material obtained from the thermal decomposition of organic biomass under limited oxygen conditions a process known as pyrolysis. Chemically, biochar consists of:

- 60–80% carbon (mostly aromatic carbon)
- Hydrogen, nitrogen, oxygen in smaller proportions
- Minerals such as potassium, calcium, magnesium, phosphorus
- Functional groups including phenolic, carboxyl, and hydroxyl groups
- These chemical features give biochar high cation exchange capacity (CEC), stability, and the ability to interact with soil nutrients.

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- Biochar is distinct from activated carbon because it is produced at lower temperatures and retains more minerals and organic components beneficial for soil improvement.

Production of Biochar

Biochar can be produced using simple, low-cost setups suitable for rural regions. It is generated through:

a) Slow Pyrolysis (Most common)

- Temperature: 300–500°C
- Heating rate: slow
- Produces high-quality biochar
- Suitable for agricultural residues

b) Fast Pyrolysis

- Temperature: 500–700°C
- Produces more liquid bio-oil and less solid biochar
- Used in industrial systems

c) Gasification

- Higher temperatures (700°C+)
- Produces syngas & low solid yield
- **Common Raw Materials for Rural Areas**
- Sugarcane bagasse
- Rice husk
- Coconut shells
- Cotton waste
- Cow dung cakes
- Dry leaves & branches
- Groundnut shell
- Crop residues

Biochar preparation does not require high technology, which makes it ideal for rural applications and sustainable agriculture initiatives.

Chemical Properties of Biochar

Biochar's unique chemical properties make it an excellent soil amendment:

a) High Carbon Content

Provides long-term stability and enhances soil organic carbon pool.

b) pH Regulation

Most biochars are alkaline and help neutralize acidic soils.

c) Cation Exchange Capacity (CEC)

Biochar improves nutrient retention by adsorbing K^+, Mg^{2+}, Ca^{2+}, NH_4^+ ions.

d) High Surface Area and Porosity

Allows water retention and provides habitat for beneficial microbes.

e) Functional Groups

Carboxyl and phenolic groups improve soil–nutrient interactions.

f) Heavy Metal Binding Capacity

Biochar immobilizes heavy metals, reducing their toxicity to plants.

Applications of Biochar in Soil Improvement

Biochar has numerous applications that directly enhance soil quality and support sustainable agriculture. Its unique physicochemical properties make it suitable for improving physical, chemical, and biological characteristics of soil.

a) Improvement of Soil Fertility

Biochar increases soil organic carbon, boosts nutrient-holding capacity, and reduces nutrient leaching. It enhances the availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). This results in better plant growth and increased crop yields.

b) Enhancement of Soil Structure

The porous structure of biochar improves soil aeration, reduces compaction, and enhances root penetration. Sandy soils benefit through increased water retention, while clayey soils experience reduced hardness and better drainage.

c) Water-Holding Capacity

Biochar is highly porous and acts like a sponge. When mixed with soil, it stores water during rainfall and releases it slowly, making it especially valuable in drought-prone rural regions.

d) pH Correction in Acidic Soils

Most biochars are alkaline. When applied to acidic soils, they raise pH levels, improve nutrient availability, and reduce toxicities such as aluminium toxicity.

e) Enhanced Soil Microbial Activity

Biochar provides shelter and habitat for beneficial microorganisms. Microbial populations responsible for nutrient cycling (N-fixing bacteria, mycorrhizal fungi) increase significantly.

f) Reduction of Heavy Metal Mobility

Biochar immobilizes heavy metals (Pb, Cd, Ni, Cr) by adsorption, preventing them from entering plant tissues. This makes it beneficial for soil remediation.

g) Carbon Sequestration

Biochar is highly stable and remains in soil for hundreds of years. Adding biochar traps atmospheric carbon and reduces greenhouse gas emissions — an important aspect of climate-smart agriculture.

Role of Biochar in Rural Agriculture

Biochar is particularly beneficial for farmers in rural regions like Sangli, Jath, and drought-prone zones of Maharashtra.

a) Low-Cost Soil Amendment

Biochar can be prepared from freely available waste materials such as crop residues, cow dung, sugarcane trash, and leaves. Thus, even small farmers can afford it.

b) Increased Crop Yield

Studies show that biochar-amended soils increase the yields of crops like jowar, bajra, wheat, vegetables, and fruits due to improved nutrient and water availability.

c) Water Efficiency

Areas with low rainfall benefit greatly as biochar helps soil retain more moisture.

d) Waste Management

Farm waste is converted into useful material instead of burning it, reducing air pollution.

e) Suitable for Organic Farming

Biochar is chemical-free and supports long-term organic soil health.

Advantages of Biochar

- Eco-friendly
- Enhances soil fertility
- Long-term stability
- Improves crop productivity
- Works in all soil types
- Local raw materials available
- Reduces requirement of chemical fertilizers
- Improves soil microbial life

- Controls greenhouse gas emissions

Limitations of Biochar:

While biochar has many benefits, certain limitations must be considered:

- Quality varies depending on feedstock and pyrolysis temperature
- Over-application may alter soil pH excessively
- Benefits differ from soil to soil
- Requires proper mixing into the topsoil
- Initial preparation may require time and training

Conclusion

Biochar is an effective, low-cost, and sustainable soil amendment that significantly improves soil health and agricultural productivity. Its ability to enhance soil structure, water retention, nutrient availability, and microbial activity makes it highly suitable for rural farming communities. As a carbon-rich and environmentally friendly material, biochar also contributes to climate mitigation through carbon sequestration. This review highlights the potential of biochar as a practical solution for soil improvement, especially in regions with low fertility and erratic rainfall. Considering its advantages and easy availability, biochar can play a major role in sustainable agriculture and environmental conservation.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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