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Biochar: A Climate-Smart Solution for Sustainable Indian Agriculture and Environmental Stewardship

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INTRODUCTION

Indian agriculture is currently confronted with multiple interconnected challenges, including declining soil fertility, excessive dependence on chemical fertilizers, residue burning, groundwater depletion, climate variability, increasing greenhouse gas (GHG) emissions, and the continuous generation of agricultural wastes. With India's population expected to exceed 1.6 billion by 2050, ensuring sustainable food production while conserving natural resources has become a national priority. Simultaneously, India's commitment to achieving net-zero carbon emissions by 2070 and restoring degraded lands under national climate action plans necessitates the adoption of climate-smart agricultural technologies. Among the emerging sustainable technologies, biochar has attracted considerable attention because of its unique ability to simultaneously improve soil health, recycle agricultural residues, enhance crop productivity, and sequester atmospheric carbon. Unlike conventional methods of residue disposal, particularly open-field burning of rice straw that contributes significantly to air pollution in northern India, conversion of crop residues into biochar offers a value-added solution that transforms waste into a long-lasting soil amendment while reducing greenhouse gas emissions.

Biochar is a stable, carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions, primarily by pyrolysis (350–700°C) or hydrothermal carbonization (180–350°C). India generates more than 500 million tonnes of agricultural residues annually, including rice straw, wheat straw, sugarcane bagasse, cotton stalks, maize residues, coconut shells, groundnut husks, bamboo wastes, and other lignocellulosic biomass, providing enormous potential feedstock for sustainable biochar production (MNRE, 2024). Depending on the feedstock and production conditions, approximately 50–80% of the biomass carbon can be stabilized within biochar, making it one of the most promising negative-emission technologies available for agriculture.

Table 1: Major Agricultural Residues Suitable for Biochar Production in India

Agricultural residue	Major producing states
Rice straw	Punjab, Haryana, Uttar Pradesh, West Bengal
Wheat straw	Punjab, Haryana, Madhya Pradesh
Sugarcane bagasse	Uttar Pradesh, Maharashtra, Karnataka
Cotton stalk	Gujarat, Maharashtra, Telangana
Coconut shell	Kerala, Tamil Nadu
Groundnut shell	Gujarat, Andhra Pradesh
Maize stalk	Karnataka, Bihar
Bamboo	North-East India
Mustard stalk	Rajasthan
Soybean residue	Madhya Pradesh

Source: Adapted from Ministry of New and Renewable Energy (2024), ICAR (2023), Singh et al. (2022), and Lehmann and Joseph (2024).

Benefits of Biochar in Agriculture

Indian soils are predominantly characterized by low organic carbon content (<0.5%), widespread nutrient deficiencies, declining microbial activity, poor soil structure, and increasing degradation due to intensive cultivation. Biochar addresses several of these constraints simultaneously.

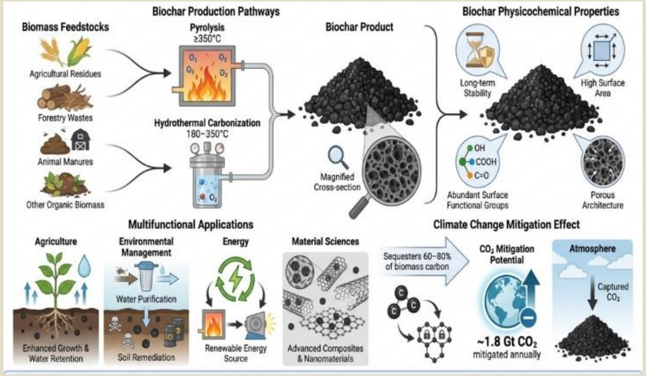

Figure 1: Overview of Biochar Production, Properties and Multifunctional Application

1. Sustainable Crop Residue Management

- Converts crop residues into a valuable soil amendment through pyrolysis.
- Reduces open-field burning and associated air pollution.
- Conserves nutrients present in agricultural residues.
- Lowers greenhouse gas and particulate emissions.
- Generates additional income through value-added products and carbon credits.
- Promotes a circular bioeconomy by recycling agricultural waste.

2. Improves Soil Fertility

- Increases soil organic carbon (SOC).
- Enhances cation exchange capacity (CEC) and nutrient retention.
- Reduces nutrient leaching and improves fertilizer-use efficiency.
- Improves soil structure, aggregation, and aeration.
- Decreases bulk density and facilitates root growth.
- Stimulates beneficial microbial activity and nutrient cycling.
- Particularly beneficial for degraded and low-carbon Indian soils.

3. Enhances Water-Use Efficiency

- Increases soil water-holding capacity (10–30%).
- Improves infiltration and reduces surface runoff.
- Enhances plant-available water during dry periods.
- Increases drought tolerance and crop resilience.
- Reduces irrigation requirements, especially in rainfed agriculture.

4. Climate Change Mitigation

- Sequesters stable carbon in soil for hundreds to thousands of years.
- Reduces methane emissions from flooded rice fields.
- Lowers nitrous oxide emissions by improving nutrient-use efficiency.
- Minimizes emissions from crop residue burning.
- Supports climate-smart and low-carbon agricultural systems.

5. Wastewater Treatment and Environmental Remediation

- Adsorbs heavy metals, pesticides, dyes, antibiotics, and pharmaceutical residues.
- Removes excess nitrogen and phosphorus from wastewater.
- Enhances microbial degradation of pollutants.
- Improves remediation of contaminated soils and groundwater.
- Provides a sustainable, low-cost solution for environmental protection.

Indian Cropping Systems Where Biochar Can Be Successfully Used

Biochar is not equally effective across all crops. Its benefits depend upon soil type, irrigation, climate, crop species, and application rate. Research conducted across India suggests the following recommendations.

Table 2: Potential Applications of Biochar in Major Indian Cropping Systems

Cropping system	Recommended biochar application	Major benefits
Rice	5–10 t ha^{-1}	reduction in methane, higher grain yield
Wheat	5–10 t ha^{-1}	Better soil moisture and grain quality
Rice–Wheat System	5–10 t ha^{-1} every 2–3 years	Improves soil organic carbon
Maize	10–20 t ha^{-1}	Enhanced root growth and drought tolerance
Sugarcane	10–20 t ha^{-1}	Increased cane yield
Cotton	5–15 t ha^{-1}	Better moisture and fibre quality
Pulses (Chickpea, Pigeonpea, Lentil)	2–5 t ha^{-1}	Enhanced nodulation and N fixation
Oilseeds (Mustard,	5–10 t ha^{-1}	Improved nutrient-use

Groundnut, Soybean)		efficiency and water availability
Vegetable crops	5–20 t ha^{-1}	Higher fruit yield
Fruit orchards (Mango, Citrus, Guava, Pomegranate)	5–15 kg per tree annually	Healthy root growth, microbial activity and better moisture retention
Tea and Coffee plantations	5–10 t ha^{-1}	Improved soil acidity management and organic carbon

Current Status of Biochar Adoption in India

Although research on biochar has expanded rapidly, field-scale adoption remains limited. The principal barriers include:

- High initial investment in pyrolysis technologies.
- Lack of awareness among farmers and extension agencies.
- Limited availability of quality-certified biochar.
- Absence of dedicated national biochar policies.
- Inadequate carbon-credit mechanisms for smallholder farmers.
- Limited long-term field validation under diverse agro-climatic conditions.

Nevertheless, India's growing emphasis on Natural Farming, Climate-Smart Agriculture, Soil Health Management, PM-PRANAM, National Mission on Sustainable Agriculture, and Carbon Farming presents significant opportunities for integrating biochar into mainstream agricultural practices.

Future Outlook

The future of biochar in India lies in integrating crop residue management with decentralized biochar production, precision nutrient management, and carbon credit markets. Biochar can become a cornerstone of sustainable farming by improving soil health, reducing dependence on chemical fertilizers, increasing resilience to climate change, and generating additional income through carbon sequestration. Continued research, farmer awareness, policy support, and development of affordable biochar production technologies will be essential for realizing its full potential across diverse Indian agroecosystems.

CONCLUSION

Biochar simultaneously improves soil health, enhances crop productivity, conserves water, mitigates climate change, recycles agricultural residues, and supports environmental remediation, making it a promising technology for sustainable agriculture in India.