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Biochar: a sustainable solution for soil health restoration, crop productivity, and carbon sequestration

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Abstract

Declining soil fertility, depletion of soil organic carbon (SOC), deterioration of soil structure, and indiscriminate burning of crop residues have emerged as major challenges to sustainable agriculture. In India, the average soil organic carbon content ranges between 0.3% and 0.6%, which is considerably lower than the desirable level for maintaining healthy and productive soils. Continuous intensive cultivation, excessive dependence on chemical fertilizers, frequent tillage, limited recycling of crop residues, and climate variability have accelerated the loss of soil carbon and reduced soil biological activity. Biochar, a stable carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, has gained global recognition as an effective soil amendment capable of addressing these challenges simultaneously. Biochar improves soil physical, chemical, and biological properties, enhances water-holding capacity, increases nutrient-use efficiency, promotes beneficial microbial activity, and sequesters carbon in soils for extended periods. In addition to improving agricultural productivity, biochar contributes to climate change mitigation by reducing greenhouse gas emissions associated with crop residue burning and by storing carbon in a stable form.

Keywords: Soil fertility, sustainable agriculture, fertilizers, tillage, biochar, greenhouse

1. Introduction

Healthy soil is the foundation of sustainable agricultural production. Soil provides physical support to plants, stores and supplies water and nutrients, sustains millions of microorganisms, and regulates numerous ecological processes essential for crop growth. Among the various indicators of soil quality, Soil Organic Carbon (SOC) is considered one of the most important because it governs soil fertility, aggregation, water retention, nutrient cycling, and microbial activity.

Unfortunately, Indian agriculture has witnessed a gradual decline in soil organic carbon over the past several decades. A nationwide assessment conducted during 2017–2023 reported that the average SOC content of Indian soils is only about 0.3–0.6%, indicating widespread depletion of soil carbon reserves. The report also highlighted that carbon loss from agricultural soils is occurring faster than its natural replenishment, raising serious concerns regarding long-term soil productivity and food security.

Several interacting factors contribute to this decline:

- Intensive cultivation and repeated tillage
- Limited return of crop residues to the soil
- Excessive dependence on chemical fertilizers
- Declining biological activity in soils
- Deforestation and land-use changes
- Rising temperatures and changing rainfall patterns
- Widespread burning of agricultural residues after harvest

The depletion of soil organic carbon adversely affects soil structure, increases bulk density, reduces porosity, lowers water infiltration and storage capacity, diminishes nutrient retention, suppresses microbial populations, and ultimately results in declining crop productivity. As climate variability intensifies, degraded soils become increasingly vulnerable to drought, erosion, and nutrient losses.

Restoring soil carbon has therefore become one of the primary objectives of sustainable and climate-resilient agriculture. Among the

available approaches, biochar has emerged as one of the most promising technologies because it simultaneously addresses soil degradation, crop residue management, carbon sequestration, and environmental protection.

2. Crop Residue Burning: A Growing Agricultural and Environmental Challenge

Every year, millions of tonnes of agricultural residues are generated following the harvest of cereals, pulses, oilseeds, cotton, and other crops. While these residues represent a valuable source of organic carbon and plant nutrients, they are often regarded as waste and are burned in the field to facilitate rapid land preparation for the next crop.

Crop residue burning causes significant losses of valuable nutrients contained within the biomass. Essential plant nutrients such as nitrogen, phosphorus, sulphur, and organic carbon are lost during combustion instead of being recycled into the soil. Furthermore, residue burning destroys beneficial soil microorganisms that play a vital role in nutrient mineralization and maintaining soil health.

The environmental consequences are equally severe. Burning agricultural residues releases carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), fine particulate matter, and other pollutants into the atmosphere. These emissions contribute to air pollution, deterioration of human health, and increased greenhouse gas concentrations that accelerate global climate change.

Instead of burning residues, converting them into biochar offers a sustainable alternative that conserves nutrients, enriches soil organic matter, and locks carbon into the soil for decades or even centuries.

3. What is Biochar?

Biochar is a stable, carbon-rich material produced by heating biomass under oxygen-limited or oxygen-free conditions through a process known as **pyrolysis**. Agricultural residues, forest biomass, wood waste, crop stalks, husks, shells, and other organic materials can all serve as feedstocks for biochar production. During pyrolysis, most volatile compounds are removed while a stable carbon matrix remains, producing a porous material with exceptional physical and chemical properties.

The document indicates that biochar is typically produced at temperatures ranging from **300°C to 600°C**, depending on the feedstock and production method. The resulting product possesses:

- High carbon content
- Large surface area
- Highly porous structure
- Mixed organic and inorganic composition
- Oxygen-containing functional groups on the surface

These characteristics make biochar an excellent soil amendment capable of retaining water and nutrients while providing a favourable habitat for beneficial soil microorganisms.

4. Historical Background: Terra Preta

Although biochar has recently gained worldwide scientific attention, its concept is not new. Historical evidence from the Amazon Basin demonstrates that indigenous communities created extraordinarily fertile soils known as **Terra Preta**, meaning "black earth."

These soils contain large quantities of stable charcoal incorporated into the soil thousands of years ago. Remarkably, Terra Preta soils continue to remain highly fertile even today because the biochar present in them retains carbon for extremely long periods while improving nutrient availability and soil structure. Modern biochar technology has evolved from understanding these ancient soil management practices and adapting them for contemporary agriculture.

5. Feedstocks for Biochar Production

One of the greatest advantages of biochar technology is its flexibility in utilizing a wide range of biomass resources. Almost any organic material containing carbon can be converted into biochar through the pyrolysis process. The quality and characteristics of the resulting biochar depend on the type of feedstock, its moisture content, and the production temperature.

Agricultural residues are among the most abundant and economical feedstocks for biochar production. Instead of being burned or discarded, these residues can be converted into valuable soil amendments that improve soil fertility while reducing environmental pollution.

Agricultural Residues

Common agricultural residues suitable for biochar production include: Cotton stalks, Pigeon pea stalks, Maize stalks, Corn cobs, Wheat straw, Rice straw, Pearl millet stalks, Soybean stalks, Mustard stalks, Other crop residues generated after harvest

Forest Residues

Forestry operations also generate significant quantities of biomass that can be utilized for

biochar production, such as: Sawdust, Wood chips, small branches, Wood processing residues

Agro-Industrial Residues

Several agro-processing industries produce organic wastes that are suitable feedstocks for biochar production, including: Coconut shells, Coffee husks, Jatropha husks, Cocoa pod husks, Paper mill waste, Sugar beet processing residues. The source document emphasizes that nearly any carbon-rich organic material can be transformed into biochar through pyrolysis, making this technology adaptable across diverse agricultural systems.

6. Biochar Production Technology

Biochar is produced through a thermochemical process known as pyrolysis, in which biomass is heated under oxygen-limited or nearly oxygen-free conditions. Unlike open burning, where biomass is completely oxidized into ash and gases, pyrolysis converts much of the biomass carbon into a stable solid form known as biochar. According to the source document, biochar production generally occurs at temperatures ranging from 300°C to 600°C, depending on the feedstock and production system. During heating, moisture evaporates first, followed by the decomposition of cellulose, hemicellulose, and lignin. Volatile gases are released while the remaining carbon-rich fraction gradually develops into porous biochar.

The process generally involves the following steps:

i. Collection of biomasses.
ii. Drying to reduce moisture content.
iii. Size reduction where necessary.
iv. Loading the biomass into the selected pyrolysis unit.
v. Controlled carbonization under limited oxygen.
vi. Cooling after carbonization.
vii. Collection and storage of biochar for field application.

Proper control of oxygen during carbonization is essential. Excess oxygen may lead to complete combustion of the biomass, reducing biochar yield and increasing carbon losses.

7. Methods of Biochar Production: The source document describes several approaches for producing biochar, each differing in construction cost, production capacity, and operational efficiency.

7.1 **Pit Method**: The pit method is one of the simplest and most economical techniques. A pit of suitable dimensions is excavated in the ground, filled with dry biomass, and ignited. By limiting oxygen during burning, biomass undergoes carbonization instead of complete combustion. After carbonization, the material is cooled and collected as biochar.

Advantages

- Low initial investment
- Suitable for small-scale farmers
- Easy construction
- Utilizes locally available materials
- Limitations
- Difficult temperature control
- Lower production efficiency
- Greater variability in biochar quality

7.**2 Kon-Tiki Method**

The Kon-Tiki kiln consists of a cone-shaped structure designed to improve airflow and carbonization efficiency. Biomass is gradually added layer by layer, allowing controlled pyrolysis with relatively lower smoke emissions.

Advantages

- Better combustion control
- Reduced smoke emission
- Higher biochar quality
- Improved conversion efficiency

7.3 **Drum Kiln Method**

The source document presents the CRIDA Drum Kiln as an improved technology for producing biochar from agricultural residues. This system uses a 250-litre iron drum with approximate dimensions of 60 cm diameter × 90 cm height. It operates with dried agricultural residues and generally carbonizes biomass at an estimated temperature of 400–500°C. Compared with traditional open burning, drum kilns provide better control over the carbonization process, resulting in more uniform and higher-quality biochar.

8. Characteristics of High-Quality Biochar

The effectiveness of biochar depends largely on the quality of the final product. According to the source document, good-quality biochar possesses the following characteristics:

- Black in colour.
- Lightweight and porous.
- Brittle and easily crushed by hand.
- Free from smoke or burnt odour.
- Slowly sinks when placed in water.

common production errors that reduce biochar quality:

- Excess oxygen causing complete burning.
- Incomplete carbonization.
- Use of wet biomass.
- Rapid cooling by suddenly adding water.

Careful control of feedstock moisture, oxygen

availability, and carbonization conditions is therefore essential for producing high-quality biochar suitable for agricultural applications.

10. Mechanisms of Biochar Action in Soil

Biochar influences soil through several interconnected physical, chemical, and biological mechanisms. Rather than functioning as a conventional fertilizer, biochar modifies the soil environment, creating favourable conditions for improved nutrient cycling, root development, and microbial activity.

The primary mechanisms include:

10.1 Improvement of Soil Structure

The porous carbon matrix of biochar promotes aggregation of soil particles, resulting in improved soil structure. Better aggregation increases pore continuity, enhances aeration, facilitates root penetration, and improves water movement within the soil profile.

In compacted soils, biochar helps reduce bulk density while increasing total porosity, thereby creating a more favourable rooting environment.

10.2 Nutrient Retention

Many agricultural soils experience nutrient losses through leaching, particularly under high rainfall or excessive irrigation. Biochar acts as a nutrient reservoir by adsorbing dissolved nutrients onto its extensive surface area and gradually releasing them to plants.

The source document notes that biochar improves nutrient-use efficiency and enhances the effectiveness of organic fertilizers and composts by reducing nutrient losses.

10.3 Enhancement of Microbial Habitat

The internal pore network of biochar provides protected microhabitats for bacteria, fungi, and other beneficial soil organisms. These microorganisms contribute to decomposition, nutrient mineralization, nitrogen cycling, and suppression of certain soil-borne pathogens.

Research summarized in the source document indicates that biochar promotes soil biological activity and supports beneficial microbial populations, thereby improving overall soil health.

11. Effects of Biochar on Soil Physical Properties

The physical condition of soil directly influences water availability, aeration, root growth, and crop productivity. Biochar substantially improves several important physical properties of soil.

11.1 Bulk Density

Bulk density refers to the mass of dry soil per unit volume. High bulk density indicates soil compaction, which restricts root penetration and reduces water infiltration.

The incorporation of biochar lowers bulk density because biochar particles are lightweight and porous. As a result, soils become less compact and easier for plant roots to explore.

11.2 Soil Porosity

Biochar increases both macro- and microporosity within the soil. Improved porosity enhances gaseous exchange, facilitates root respiration, and promotes efficient movement of water through the soil profile. Greater pore connectivity also supports increased microbial colonization and biological activity.

11.3 Water-Holding Capacity

One of the most widely recognized benefits of biochar is its ability to improve soil water retention. The porous structure acts like a sponge, absorbing water during rainfall or irrigation and gradually releasing it to plants during dry periods. improved water-holding capacity is particularly beneficial under rainfed conditions, where moisture conservation is essential for maintaining crop growth. Studies cited in the document report reductions in irrigation requirements following biochar application.

11.4 Soil Drainage

Although biochar retains water, it also improves drainage by increasing soil aggregation and maintaining continuous pore spaces. Consequently, soils become less susceptible to waterlogging while still retaining adequate moisture for plant growth.

12. Effects of Biochar on Soil Chemical Properties

Biochar significantly influences the chemical environment of soil by improving nutrient availability, enhancing nutrient retention, and increasing the efficiency of applied fertilizers.

12.1 Increased Soil Organic Carbon

Because biochar is composed primarily of stable carbon, its incorporation directly increases soil organic carbon content. Unlike fresh organic matter, which decomposes rapidly, biochar remains stable in soil for decades or even centuries, contributing to long-term carbon storage.

12.2 Improved Nutrient Retention

The extensive internal surface area and high adsorption capacity of biochar enable it to retain

essential nutrients within the root zone. This reduces nutrient losses caused by leaching and volatilization, thereby increasing fertilizer-use efficiency.

The source document states that biochar enhances the effectiveness of organic fertilizers and improves nutrient availability for crops.

12.3 Reduced Dependence on External Inputs

By improving nutrient retention and soil fertility, biochar can reduce dependence on chemical fertilizers and other soil amendments.

13. Effects of Biochar on Soil Biological Properties

Healthy agricultural soils contain billions of microorganisms that regulate nutrient cycling, organic matter decomposition, and soil fertility. The decline in soil organic carbon often results in reduced microbial diversity and activity.

Biochar provides favourable habitats for these microorganisms because of its porous internal structure and large surface area. Beneficial bacteria and fungi colonize biochar pores, where they are protected from environmental stress while remaining actively involved in nutrient transformation processes.

The source document reports that biochar enhances microbial growth, increases biological activity, and improves the overall functioning of soil ecosystems. It also notes that soils rich in carbon exhibit better resilience during dry periods and require lower chemical inputs to sustain productivity.

Biochar and Carbon Sequestration

Carbon sequestration refers to the long-term storage of atmospheric carbon in stable reservoirs. Biochar has emerged as one of the most effective agricultural tools for carbon sequestration because it converts unstable biomass carbon into a highly stable form that resists decomposition.

Instead of allowing crop residues to decompose rapidly or be burned in the field, pyrolysis transforms a substantial portion of the biomass carbon into stable biochar. When incorporated into soil, this carbon can remain stored for many decades or even centuries.

biochar contributes to climate change mitigation by storing carbon in soil, reducing greenhouse gas emissions, and lowering emissions associated with crop residue burning. It also cites research indicating that the production of one tonne of biochar has the potential to avoid approximately 2.2 tonnes of carbon dioxide emissions under appropriate conditions.

Through these mechanisms, biochar supports both sustainable soil management and global efforts to reduce atmospheric greenhouse gas concentrations.

15. Effect of Biochar on Crop Productivity

Crop productivity depends largely on soil health, nutrient availability, water supply, and root development. Since biochar improves all of these factors simultaneously, its application has been associated with improved crop growth and yield in many agricultural systems.

biochar enhances soil fertility, improves nutrient availability, increases microbial activity, and conserves soil moisture, all of which contribute to higher crop productivity. It also cites studies indicating that biochar application can increase yields of cereals, pulses, and vegetables by 10–20% under suitable soil and crop conditions. In one example, rice production increased by approximately 15% following biochar application.

However, crop response depends on several factors, including:

- Soil type
- Feedstock used for biochar production
- Pyrolysis temperature
- Biochar application rate
- Crop species
- Fertilizer management
- Climatic conditions

16. Charged Biochar

Freshly prepared biochar contains numerous pores and adsorption sites but relatively few plant nutrients. Consequently, direct application of untreated biochar may temporarily immobilize nutrients until the pores become enriched.

To overcome this limitation, preparing **charged biochar** by mixing fresh biochar with farmyard manure, compost, or cow urine and allowing the mixture to mature for **15–20 days** before field application. This enrichment process loads the pores of the biochar with nutrients and beneficial microorganisms. charged biochar is considerably more effective than freshly prepared biochar because it supplies nutrients immediately after application while retaining the long-term benefits of stable carbon.

17. Methods of Biochar Application

Biochar can be incorporated into agricultural systems through several methods depending on crop type, farming practice, and equipment availability.

application methods include:

17.1 Surface Broadcasting and Incorporation

Biochar is uniformly spread over the soil surface and incorporated during land preparation. This method is suitable for field crops and ensures even distribution within the root zone.

17.2 Band or Trench Application

Biochar is placed directly in planting rows or trenches where crop roots develop. This localized placement improves nutrient availability around the root system while reducing the quantity of biochar required.

17.3 Mixing with Compost or Fertilizers

Biochar may be blended with compost, organic manures, or fertilizers before application. This practice enhances nutrient retention and reduces nutrient losses through leaching.

17.4 Potting Media

Biochar can also be incorporated into nursery and potting media to improve aeration, moisture retention, and root development.

17.5 Slurry or Liquid Application

The source document also describes the use of biochar slurry, particularly in systems equipped with fertigation or manure management practices.

17.6 Integration with Livestock Manure Management

Biochar may be incorporated into livestock bedding or manure storage systems. According to the document, this approach helps reduce ammonia emissions, conserves nutrients during manure storage, and produces nutrient-rich compost after decomposition.

18. Recommended Biochar Application Rates

The quantity of biochar required depends primarily on soil type, texture, soil properties and soil condition.

Soil Type	Recommended Rate	Expected Benefits
Sandy soils	20–50 t ha^{-1}	Improved water-holding capacity and nutrient retention
Clay soils	10–30 t ha^{-1}	Reduced compaction and improved aeration
Loamy soils	5–20 t ha^{-1}	Maintenance of balanced soil structure

Crop-based recommendations:

- Cereals: 200–300 kg $acre^{-1}$
- Vegetables: 150–200 kg $acre^{-1}$
- Fruit trees: 3–5 kg per tree
- Rainfed agriculture: 400–500 kg $acre^{-1}$

These recommendations should be adjusted according to local soil characteristics, cropping systems, and nutrient management plans.

19. Environmental Benefits of Biochar

Biochar contributes significantly to sustainable agriculture and environmental protection.

The source document highlights several important environmental benefits:

- Reduces crop residue burning.
- Conserves carbon within agricultural soils.
- Lowers greenhouse gas emissions.
- Improves air quality by reducing smoke and particulate emissions.
- Enhances soil carbon storage.
- Supports climate-smart agriculture.

Instead of releasing carbon immediately through open burning, pyrolysis converts a substantial portion of biomass carbon into a stable form that remains in the soil for extended periods.

20. Limitations and Precautions

Although biochar has numerous advantages, proper production and application are essential.

- Use dry biomass.
- Avoid excess oxygen during carbonization.
- Ensure complete carbonization.
- Do not cool the biochar abruptly with excessive water.
- Select appropriate feedstocks.
- Apply recommended doses rather than excessive quantities.

It also recommends combining biochar with organic or chemical fertilizers to maximize crop response in tropical soils.

21. Future Prospects

Increasing concern over declining soil fertility, climate change, water scarcity, and sustainable crop production has positioned biochar as an important component of climate-smart agriculture.

Future opportunities include:

- Sustainable crop residue management.
- Long-term soil carbon restoration.
- Carbon sequestration initiatives.
- Integrated nutrient management.
- Regenerative agriculture.
- Circular bioeconomy approaches based on agricultural biomass.

Further research is needed to optimize biochar

production technologies, identify crop-specific recommendations, and evaluate long-term impacts under diverse agroecological conditions.

22. Conclusion

Biochar represents a scientifically validated and environmentally sustainable technology for restoring soil health while simultaneously addressing crop residue management and climate change mitigation. Produced through the pyrolysis of biomass under oxygen-limited conditions, biochar possesses unique physical and chemical properties that improve soil structure, enhance water-holding capacity, increase nutrient-use efficiency, stimulate beneficial microbial activity, and sequester carbon in stable forms.

biochar is particularly valuable for degraded, low-organic-carbon, and rainfed agricultural soils, where improvements in soil quality translate into enhanced crop productivity and greater resilience to climatic stress. When produced correctly and applied at appropriate rates preferably after enrichment with compost or farmyard manure biochar can become an integral component of sustainable soil management strategies.

As agriculture seeks solutions that simultaneously improve productivity, conserve natural resources, and reduce greenhouse gas emissions, biochar offers a practical pathway toward resilient and climate-smart farming systems.