Biochar in Agriculture: A Black Gold for Sustainable Farming

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Abstract

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass, is emerging as a sustainable solution to enhance soil health and agricultural productivity. Its porous structure improves soil fertility, water retention, nutrient availability and microbial activity. Biochar also contributes to carbon sequestration, helping mitigate climate change. By converting agricultural residues into a valuable soil amendment, it supports waste management and circular agriculture. Increasing research and field adoption demonstrate that biochar can improve crop yields while reducing environmental impacts, making it a promising tool for sustainable and climate-smart farming systems.

Keywords: Biochar, Soil Fertility, Carbon Sequestration, Sustainable Agriculture, Soil Health, Climate Change, Organic Amendment

Introduction

Agriculture today faces serious challenges such as declining soil fertility, water scarcity, nutrient loss and climate change. Continuous cropping and excessive use of chemical fertilizers have degraded soil structure and reduced organic matter content. Farmers are therefore searching for eco-friendly alternatives that can restore soil health while maintaining productivity (Aslam *et al.*, 2014). Biochar has gained attention as one such innovative solution. It is a stable, carbon-rich material obtained by heating biomass such as crop residues, wood chips or animal manure in limited oxygen conditions. Unlike ordinary charcoal used as fuel, biochar is specifically produced for soil application. Historically, biochar-like materials were used in the fertile "Terra Preta" soils of the Amazon basin, which remain productive even after centuries. Modern research institutions such as the International Biochar Initiative and universities worldwide are now exploring its benefits for sustainable agriculture. Biochar not only improves soil quality but also contributes to climate change mitigation by storing carbon in the soil for long periods. Because of these multiple benefits, it is often referred to as "black gold" for agriculture (Zhang *et al.*, 2019).

Biochar: Biochar is a fine-grained, carbon-rich, porous product remaining after plant biomass which has been subjected to thermo-chemical conversion process (pyrolysis) at temperatures 350 - 600°C in an environment with little or no oxygen.

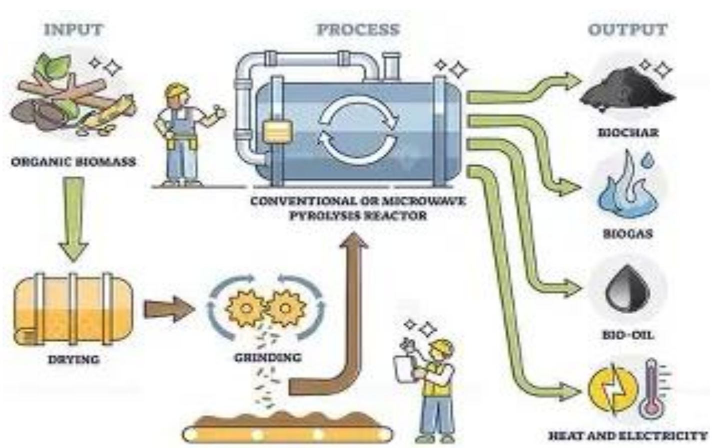
Pyrolysis is the process of breaking down organic materials at high temperatures in the absence of oxygen, resulting in the production of biochar, bio-oil and gases (Chadha *et al.*, 2020).

This process converts biomass into:

- Biochar (solid carbon-rich product)
- Bio-oil
- Syngas (fuel gas)

Common raw materials include:

- Crop residues (rice husk, maize stalk, coconut shell)
- Forestry waste
- Animal manure
- Kitchen waste



The resulting biochar has a highly porous structure, large surface area and stable carbon composition, making it suitable for soil improvement (Yusif *et al.*, 2017).

Why Biochar?

Biochar is valuable because it can:

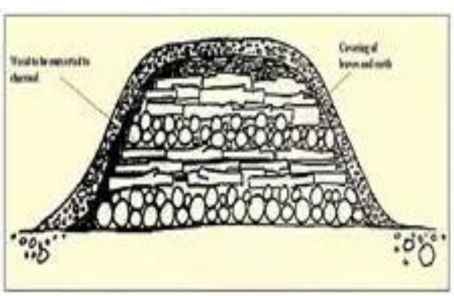
- Contribute to the conservation of natural resources
- Help lower greenhouse gas emissions in the atmosphere
- Enhance soil health and overall fertility
- Provide economic and social advantages to farming communities

How is it used?

- As a soil amendment to improve soil properties
- For long-term carbon sequestration
- In sustainable waste management practices
- As a source of renewable energy (through by-products of production)
- As an additive in composting to improve compost quality

Methods of biochar preparation

1. Heap method



In the traditional method, a pyramid-shaped heap known as an earth kiln is constructed using wood logs and plant roots to produce charcoal. Openings or vents are created from the top downward to allow combustion gases and smoke to escape. Once the smoke emission ceases, the kiln is sealed with a layer of moist soil to initiate the cooling process. Cooling usually takes several days, after which the soil covering is removed and the produced biochar is separated from the partially carbonized material. Among earth kilns, earth-mound kilns fitted with a chimney are considered more advanced. The chimney diameter can be adjusted based on oxygen requirements, and the draft-controlled by the chimney's height-allows better regulation of airflow, resulting in improved control over the pyrolysis process.

2. Drum method

In the modified approach, biochar is produced using a pyrolysis kiln. A low-cost charring kiln by adapting used oil drums at CRIDA, Hyderabad. A cylindrical metal oil drum with a 200-litre capacity, closed at both ends, was obtained from the local market and modified for this purpose. A square opening measuring 16 cm × 16 cm was created at the centre of the top surface to load crop residues. On the bottom side, 36 holes of 4 cm^2 each were arranged in concentric circles, along with a central hole of 5 cm^2. These openings covered about 20% of the total bottom surface area, ensuring uniform air circulation from below during the charring process.

3. Stove method

a) Top-Lift Updraft Gasifier (TLUD)

There are two basic types of stoves that can be used to produce charcoal and heat, the Top-Lit Updraft Gasifier (TLUD) and the Anila stove. There are many variations on the TLUD, but the biggest distinction is between natural draft TLUDs and fanforced TLUDs. The TLUD operates as a gasifier by creating a stratified pyrolysis/combustion regime with four basic zones: raw biomass, flaming pyrolysis, gas combustion and charcoal combustion (Ghorbani *et al.*, 2019). The charcoal can be retained if it is removed at the proper time and quenched. Biomass fuel is placed between the two cylinders and a fire is ignited in the centre. Heat from the central fire pyrolyzes the concentric ring of fuel. The gases escape to the centre where they add to the cooking flame as the ring of biomass turns to char. The centre combustion chamber can be configured as either a rocket stove design (with a side opening door) or as a TLUD with primary combustion air entering from the bottom.

b) Anila stove

The modern Anila stove was designed by U.N. Ravikumar, an environmentalist and engineer associated with the Centre for Appropriate Rural Technology (CART) at India's National Institute of Engineering. The primary objectives of this design are to minimize indoor air pollution caused by traditional cooking methods and to efficiently utilize the abundant bio-residues available in rural areas of developing countries (Kim *et al.*, 2017). The stove operates on the principle of top-lit updraft gasification, where the fuel ignites from the top and burns downward while simultaneously combusting the syngas released from the biomass. Constructed from steel, the stove has an approximate weight of 10 kg.

Benefits of Biochar in Agriculture

1. Effect of Biochar on Soil Physical Properties

Bulk Density

Biochar application generally lowers soil bulk density due to its low weight and porous nature. The reduction is more noticeable in sandy soils than in clayey soils because the density difference between biochar (≈0.6 g cm^{-3}) and sandy soils is greater than with clay soils. Over time, biochar also improves soil aggregation and porosity, further decreasing bulk density.

Soil Porosity

As bulk density decreases, soil porosity increases. Biochar enhances porosity by:

- Lowering soil bulk density
- Improving soil aggregation
- Interacting with mineral particles
- Reducing soil compaction and packing

Tensile Strength

Biochar generally reduces soil tensile strength, making the soil less compact and more friable. This weakens inter-particle bonding, improves micro-structural development and enhances soil resilience to external forces (Jahidul *et al.*, 2019).

Moisture Retention

Due to its high surface area and porous structure, biochar improves soil moisture retention. It can help reduce drought stress in crops, particularly in dry regions. Its effect varies with soil type:

- May reduce water infiltration in sandy loams
- Can improve infiltration and hydraulic conductivity in clayey or compacted soils
- Has minimal effect in medium-textured soils

Soil Thermal Properties

Biochar influences soil temperature and heat movement. It can moderate temperature fluctuations, reduce thermal conductivity and alter soil surface color. These effects are linked to changes in bulk density, porosity and soil moisture content.

2. Effect of Biochar on Soil Chemical Properties

Soil pH: Low soil pH can increase the availability of toxic metals such as aluminium (Al), which harm plant roots and reduce crop growth. Biochar application generally raises soil pH due to the release of alkaline substances, thereby reducing metal toxicity and improving the availability of essential nutrients. The liming effect of biochar may gradually decline over time because of oxidation and leaching. Its pH depends on feedstock type and production temperature. Overall, biochar reduces Al saturation, neutralizes soil acidity (through H^+ adsorption and decarboxylation reactions) and improves soil chemical balance.

Soil Salinity

High soil salinity limits plant growth by restricting water uptake and disturbing ion balance. Biochar can adsorb soluble salts and help reduce salt stress in crops. Its ability to increase cation exchange capacity (CEC) also helps minimize soil salinization, making it useful in saline and degraded soils (Ranjitha *et al.*, 2023).

Cation Exchange Capacity (CEC)

Most biochars are neutral to alkaline, and their application can increase soil pH and CEC. The presence of carboxyl and other oxygen-containing functional groups on biochar surfaces enhances nutrient retention and reduces leaching losses. By increasing CEC, biochar improves the soil's ability to retain important nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+). Its surface charge properties also help buffer soil pH and maintain nutrient availability.

3. Effect of Biochar on Soil Biological Properties

Biological Nitrogen Fixation (BNF)

Biochar application has been shown to enhance biological nitrogen fixation in legume crops. This improvement is attributed to:

- Temporary immobilization of nitrogen
- Increased nodulation
- Improved phosphorus availability
- Rise in soil pH
- Supply of essential macro- and micronutrients

These factors together create favorable conditions for symbiotic nitrogen-fixing bacteria.

Effect on Soil Microorganisms

The porous structure of biochar provides a suitable habitat for soil microorganisms by retaining nutrients such as nitrate and ammonium (Shaaban *et al.*, 2018). It can increase microbial population, especially in acidic soils, by raising soil pH. Biochar also supports beneficial fungi such as arbuscular mycorrhiza (AM) and ectomycorrhiza (EM), improving root–microbe interactions. Enhanced microbial biomass and enzyme activity can promote nutrient cycling and organic matter decomposition (Elwahed *et al.*, 2019).

4. Role of Biochar in Pollutant Reduction

Organic Pollutants

Biochar can adsorb organic pollutants such as pesticides, reducing their mobility and environmental risk. However, strong adsorption may sometimes lower herbicide effectiveness. Sorption efficiency generally increases with higher biochar production temperatures.

Inorganic Pollutants

Biochar is effective in remediating metal-contaminated soils. It reduces the bioavailability of heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn) and arsenic (As) by forming stable surface complexes. However, its effectiveness may decline over time due to pore blockage.

Climate Change Mitigation

Biochar is recognized as a promising tool for climate change mitigation. Its stable carbon structure allows long-term carbon sequestration in soils, reducing carbon dioxide (CO_2) emissions. Additionally, biochar can influence soil emissions of other greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4), contributing to a lower overall carbon footprint.

Application Methods

- Direct soil incorporation before sowing
- Blending with compost or manure
- Use in nursery media and potting mixtures
- Band placement near root zones

Application rates vary from 2–10 tons per hectare depending on soil type and crop.

Challenges in Adoption

- High Initial Cost: Production units and transport can be expensive.
- Lack of Awareness: Many farmers are unfamiliar with its preparation and benefits.
- Variation in Quality: Biochar properties depend on feedstock and production temperature.
- Yields may decline because of the sorption of water and nutrients by the biochar, which reduces the availability of these resources for the crops.
- The sorption of pesticides and herbicides by the biochar can reduce their efficacy.
- Some biochar's can act as a source of contaminants, such as heavy metals, VOCs (Volatile Organic Compounds), PAHs (Polycyclic Aromatic Hydrocarbons).
- The fine ash associated with biochar is the perfect source for dust, posing a risk for respiratory diseases.

Recommendations in the Adoption of Biochar

- Promote low-cost biochar production technologies at village level.
- Provide training through agricultural extension services.
- Integrate biochar with integrated nutrient management practices.
- Support research and policy initiatives encouraging climate-resilient farming.

Future Perspectives and Opportunities

Biochar holds strong potential in sustainable agriculture. With growing concerns about soil degradation and climate change, its use is expected to expand. Integration of biochar with precision agriculture and organic farming systems can further enhance its effectiveness. Government support, farmer awareness programs and continued scientific research will be key to unlocking its full potential.

Conclusion

Biochar represents a promising, eco-friendly innovation for improving soil health and ensuring sustainable agricultural production. By enhancing nutrient retention, water availability and microbial activity, it supports higher crop productivity. Additionally, its role in long-term carbon sequestration makes it an important tool in combating climate change. With proper awareness, research support and policy encouragement, biochar can become a cornerstone of climate-smart and sustainable farming systems worldwide.

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