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# *Integrating the efficiency of Biochar as an organic fertilizer-A pathway for sustainable agriculture: A Review*

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## 1. Introduction

Biochar is solid materials, rich in carbon, obtained from pyrolysis of organic biomasses. Biochar is particularly beneficial for managing the environment in a sustainable way [1]. Currently, the world is facing serious environmental issues such as environmental pollution, global warming, climate change, soil degradation, food scarcity, the continuation of them will lead to the destruction of the Earth [2]. growing population demands food security while climate change reduces agricultural yields and the nutritional value of staple crops thus it creates pressure on agricultural land to feed a large population. On the other hand, different factors such as soil degradation, depletion of nutrient and alternation in pH resulted to increase in use of fertilizers to maintain crop yield. A small amount of synthetic fertilizer (30-40%) is taken up by plants and remaining enters to the environment which have strong impact on environment in terms of water pollution, eutrophication, algae bloom, air pollution, soil pollution, alter pH of soil, harm soil microbes [3].

Because of its versatility, biochar may be used to address global issues including pollution management, soil degradation, and climate change. This aligns with sustainable development goals [4]**.** Researchers are investigating the optimal types of biomass feedstock, pyrolysis conditions, and application rates to maximize its benefits in different soil types and climates.Biochar properties mainly depend on the type of feedstock and pyrolysis temperatures. Lignin-rich biomass pyrolyzed at a wider temperature range (160–900 °C) while hemicellulose and cellulose-rich residues were pyrolyzed at a temperature of 220–315 °C and 315–400 °C, respectively. Low temperature/high-pressure (hydrothermal carbonization) and slow pyrolysis are two effective methods of biochar production from different feedstock [5].

## 2.Methods of Biochar Production

### 2.1 Feedstock Selection

Biochar properties are significantly influenced by the feedstock used, with options including agricultural residues (like rice husk and wheat straw), forestry waste (sawdust and bark), animal manure (poultry litter and cow dung), algal biomass, and sewage sludge. [6]

a. **Agricultural Residues:** These include materials like rice husk, wheat straw, maize stover, and other crop residues.
b. **Forestry Waste:** This category encompasses materials like sawdust, bark, and wood chips, which are byproducts of forestry operations.
c. **Animal Manure:** Poultry litter and cow dung are examples of animal manure that can be used as a feedstock for biochar production.
d. **Algal Biomass and Sewage Sludge:** These are also potential sources of feedstock, offering alternative pathways for biochar production.
e. **Other Feedstocks:** Other materials like grass, cassava rhizome, nut shells, fruit pits, bagasse, and other agricultural residues can also be used.

### 2.2 Pyrolysis Techniques

Biochar production involves different pyrolysis methods: slow pyrolysis (300-600 $^0$C, long durations, high-quality biochar), fast pyrolysis (500-900 $^0$C, short durations, biochar with higher volatiles), and hydrothermal carbonization (180-250 $^0$C, high pressure, wet biomass to biochar). [7]

#### 2.2.1. Slow Pyrolysis:

This method involves heating biomass at relatively moderate temperatures (300-700 ¬∞C) and long residence times in the absence of oxygen. The slower heating rates and longer residence times lead to a higher biochar yield and a lower yield of condensable liquid products due to increased cracking reactions. Slow pyrolysis is considered a robust and energy-efficient process, producing high-quality biochar with high fixed carbon content. It is often used when char is the desired primary product. Slow pyrolysis is less sensitive to the feedstock's moisture than other processes as feed dehydration is typically the first step in pyrolysis [7,8].

### 2.2.2. Fast Pyrolysis:

This method involves heating biomass at high temperatures (500-900 ¬∞C) and short residence times (seconds). Fast pyrolysis is mainly used to produce bio-oil, with biochar as a co-product. The high heating rates and temperatures lead to a higher yield of bio-oil and a lower yield of biochar. Biochar produced through fast pyrolysis may have higher levels of condensed volatiles, which can affect its performance as a soil amendment. [8]

### 2.2.3. Hydro-thermal Carbonization (HTC):

This method involves heating biomass in supercritical water at lower temperatures (180-250¬∞C) under high pressure. HTC can process high-moisture biomass without an energy-intensive drying process. The biochar produced by HTC (or hydrochar) has higher char yield, higher energy densification ratio, and more oxygen functional groups than biochar produced by pyrolysis. [9]

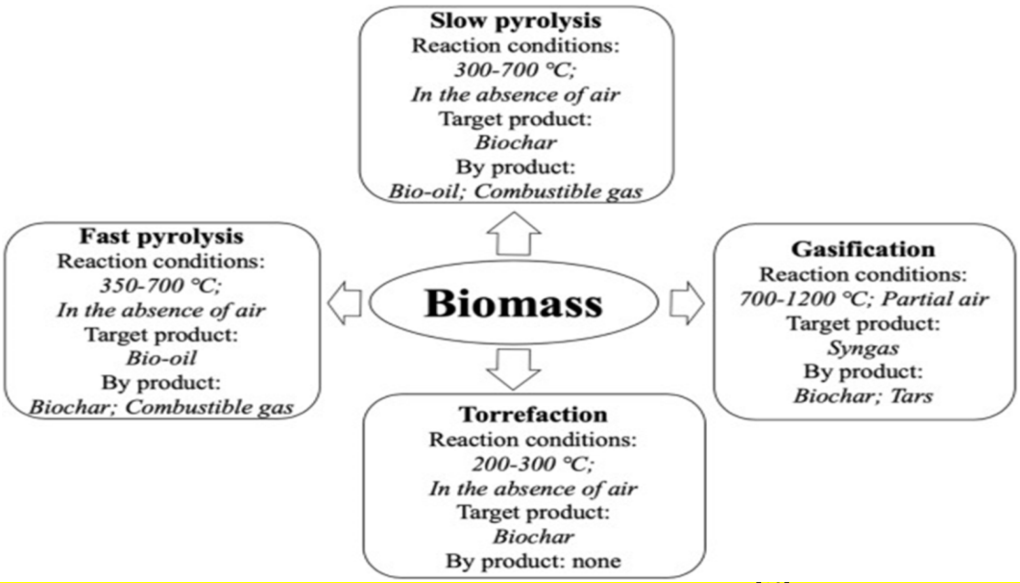


**Figure- 1: Methods of Biochar Production [10]**

## 2.3 Chemical and Physical Properties of Biochar

Biochar, produced through pyrolysis or hydrothermal carbonization, is a carbon-rich material with high porosity, large surface area, and alkaline pH, capable of adsorbing nutrients and heavy metals. It's made from biomass and contains carbon, hydrogen, oxygen, and minerals like nitrogen, phosphorus, and potassium. [11]

**2.3.1. Physical Properties:** High Surface Area and Porosity: Biochar possesses a large surface area and high porosity, enabling it to adsorb various compounds, including nutrients, organic contaminants, and some gases. Biochar has a low bulk density, making it lightweight and easy to handle and apply to soils. Biochar is primarily composed of carbon, with a typical carbon content ranging from 50 to 80%, depending on the feedstock and pyrolysis conditions. Biochar can have a neutral to high pH, which can influence soil pH and nutrient availability. [12] The high porosity and surface area of biochar contribute to its ability to retain water, which can be beneficial for soil moisture management. Biochar has a low thermal conductivity, which can help regulate soil temperature. Biochar is a renewable resource, derived from biomass, and it is also relatively stable in the environment, meaning it can persist in soil for extended periods. Biochar's high surface area and porosity give it a strong capacity to adsorb various compounds, including heavy metals, toxic chemicals, pesticides, and nutrients. [13].

**2.3.2. Chemical Properties-** Biochar has a high cation exchange capacity (CEC), meaning it can hold and exchange positively charged ions, which are essential nutrients for plant growth. The surface of biochar contains various functional groups, such as hydroxyl, carboxyl, and carbonyl groups, which can influence its interactions with other substances in the soil [14]. Biochar can contain various macronutrients, such as nitrogen, phosphorus, and potassium, which are essential for plant growth. The level of aromaticity in biochar, which refers to the presence of aromatic carbon rings, directly influences its stability in soil environments [15].

**2.3.3. Effects of biochar on soil-** biochar can affects soil physical, chemical and microbial properties-Biochar application has shown a differential effect on soil physical properties like bulk density ($\rho_b$), porosity, hydraulic conductivity, and soil color under diverse soil and climate types. Biochar's porous structure and low density help to reduce soil bulk density. This reduction in bulk density, in turn, increases soil porosity and aeration, allowing for better oxygen exchange between the soil and the atmosphere. Improved aeration is crucial for root respiration and overall plant health. [16] Biochar's porous structure and large surface area increase the soil's ability to retain water. This improved water retention can be particularly beneficial in arid and semi-arid regions, or during periods of drought. Biochar can also enhance water infiltration by creating larger pores in the soil, allowing water to move more easily through the soil profile [17]. Biochar can improve soil aggregation and structure, making it more resistant to erosion. The improved water retention capacity of biochar-amended soils can also reduce runoff and erosion by allowing more water to infiltrate and less to flow over the surface. Studies have shown that biochar application can reduce runoff and soil erosion by 25% and 16% respectively. Vegetated areas with biochar amendments have shown double the reduction in erosion compared to bare soil [18].

Biochar is carbon rich material having high percentage of aromatic carbon structures, contributing to its stability and chemical resistance. Biochar, with its high surface area and porosity, enhances the soil's ability to hold and exchange positively charged nutrients (cations) like calcium, magnesium, and potassium, leading to better nutrient availability for plants. Biochar can increase the availability of nutrients like phosphorus and nitrogen by reducing their leaching and gaseous loss, respectively. Biochar's porous structure and high surface area allow it to effectively adsorb and immobilize heavy metals and pollutants, reducing their bioavailability and potential harm to plants and the environment. This adsorption process can help remediate contaminated soils and prevent the leaching of pollutants into groundwater. [19]. Biochar stimulates enzymatic activity, crucial for nutrient cycling and organic matter decomposition, while also fostering beneficial microbes like nitrogen-fixing bacteria and mycorrhizal fungi, essential for plant nutrition and soil health. Additionally, biochar promotes microbial biomass growth, creating a healthier and more resilient soil ecosystem [20]

The interactions between biochar and soil microbes play a crucial role in determining its impact on soil health and fertility. Studies are investigating how biochar affects microbial communities, nutrient cycling, and soil carbon dynamics, with implications for sustainable agriculture and ecosystem functioning. The soil biological properties play a crucial role in nutrients mineralization, which is the basis for plant nutrients availability [21**].** The biochar surface adsorbed the bacteria, making them less susceptible to leaching, and thus increased the population of bacteria in the soil. The biochar application increased the nitrogen fixation capacity by increasing the number of N-fixing bacteria [22].

Biochar application significantly enhanced the soil MBC and MBN. Biochar alters the soil enzymatic reaction; however, the intensity of the soil enzymatic alterations depends upon the feedstock nature from which biochar has been developed. [21, 23].

## 3.Biochar and Crop Productivity

Numerous studies have demonstrated the positive effects of biochar on soil fertility and crop yield. research has shown that biochar application can improve soil structure, increase water retention, enhance nutrient availability, and stimulate microbial activity, leading to higher crop yields [24]. The magnitude of these effects varies depending on factors such as biochar type, application rate, soil type, and crop species. Biochar has been found to have a high surface area and porosity, which enable it to adsorb and retain nutrients such as nitrogen, phosphorus, potassium, and micronutrients in the soil. Additionally, biochar can serve as a reservoir for slow-release of nutrients, providing a sustained supply to plants over time. [21, 24].

**Table-1**

| Crop | feedstock | Pyrolysis temp. °C | Type of soil | dose | Yield | reference |
|---|---|---|---|---|---|---|
| Rice | Rice husk biochar | 300-700 °C | Acidic soil | (20 Mg $ha^{-1}$) | 6% economic yield enhancement over control | **25** |
| Maize | Cacao shell biochar | 400 and 500 °C | Acidic soil (sandy loams) | (15 Mg $ha^{-1}$) | Cacao shell biochar recorded 8.6 times by alleviation of soil acidity. | **25** |
| Maize | Rice husk | 300-700 °C | Acidic soil | (2 Mg $ha^{-1}$) | 27% increment in grain and shoot biomass yield over control. | **26** |
| Maize | sorghum | 300-500 °C | Acidic soil | (2 Mg $ha^{-1}$) | 16% increment in grain and shoot biomass yield over control. | **26** |

### 3.1. Bio-char and Stress tolerance of crop

Biochar has been shown to improve soil water retention and infiltration rates, particularly in sandy or degraded soils. This can help mitigate the effects of drought and improve crop resilience to water stress. Biochar can alleviation of various kinds of abiotic stress, such as salt and drought [27]. It improves drought resilience by enhancing soil water retention and reducing water loss, while its ability to adsorb and immobilize salts mitigates salinity stress, enhancing nutrient uptake. Additionally, biochar binds heavy metals, preventing their bioavailability and protecting plant roots [28].

Biochar application has been found to promote soil health by enhancing microbial diversity and activity in the rhizosphere. This can lead to improved nutrient cycling, disease suppression, and overall soil resilience. However, the effects of biochar on soil microbial communities may vary depending on factors such as biochar properties, soil type, and management practices. In terms of biotic stress, biochar fosters beneficial soil microbes that suppress pests and diseases, while also promoting plant vigor, making crops more resilient [29].

**Table-2**

| **Crop** | **feedstock** | **Pyrolysis temp $^0$C** | **dose** | **Type of stress** | **Stress tolerance** | **reference** |
|---|---|---|---|---|---|---|
| **Rice** | Rapeseed stover biochar | 300-700 °C | 40 g $kg^{-1}$ soil | **Abiotic stress** | Reduced heat stress, regulating heat shock protein in roots and leaves. | **25** |
| Maize | Crofton weed biochar | 400 °C and 500 °C | 37.18 g $kg^{-1}$ soil | **Abiotic stress** | Increased nutrient availability in acidic soils in nutrient deficient condition | **30** |
| Wheat | Wheat straw biochar | 400–600 °C | 20 g $kg^{-1}$ soil | **Abiotic stress** | Drought stress resistance by enhancing water use efficiency by 19.30%. | **31** |
| Soybean | Wheat straw biochar | 400–600 °C | 10 g $kg^{-1}$ soil | **Abiotic stress** | Drought stress resistance by enhancing water use efficiency by 27.5%. | **32** |
| Pea | Sawdust and rice husk biochar | 350–700 °C | | Abiotic stress | Reduces oxidative and osmotic stress | **33** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Tomato | Pepper plant waste biochar | 300-700 °C | 30 g $kg^{-1}$ soil | Biotic Stress | Enhanced resistance against fungus- *Fusarium oxysporum* f. sp. *radicis lycopersici* | **34** |
| Brinjal | Oak and pine biochar | 450-600 °C | (12.5 kg) | Abiotic stress | Increased stomatal conductance and photosynthetic rate, as well as reduced leaf temperature and electrolyte leakage, to reduce salinity stress in plants | **35** |
| Lupin | maize and wood biochar | 600 °C<br>850 °C<br>(at 210 °C HTC**)** | 1%-3% | Biotic Stress | Immunized bacteria *Pseudomonas putida* and *Stenotrophomonas pavanii*. | **36** |

## 3.2. Bio-char and Climate Change Mitigation

### 3.2.1. Carbon Sequestration

Biochar significantly contributes to carbon sequestration and soil health by mitigating abiotic stresses, enhancing biotic resistance, improving nutrient availability, and promoting soil structure. Its stable carbon structure allows for long-term carbon storage, reducing atmospheric $CO_2$ levels, while its ability to enhance soil structure improves aeration, water retention, and infiltration [37]. By increasing cation exchange capacity (CEC), biochar helps retain essential nutrients, making them more available to plants, and buffers soil pH, improving conditions for growth. It also adsorbs and immobilizes heavy metals and pollutants, minimizing environmental contamination. In terms of plant growth, biochar strengthens resilience against abiotic stresses like drought, salinity, and heavy metal toxicity, while also suppressing pests and diseases, thereby enhancing biotic stress resistance [38]. Acting as a slow-release fertilizer, it improves the availability of key nutrients such as nitrogen, phosphorus, and potassium, while fostering microbial diversity by supporting nitrogen-fixing bacteria and mycorrhizal fungi. Additionally, biochar boosts soil organic matter decomposition, further enriching soil fertility. Its benefits extend to specific crops, increasing rice yields in acidic soils, improving maize grain yields in biochar-amended fields, and enhancing drought resistance and water efficiency in wheat, making it a powerful tool for sustainable agriculture [39].

#### 3.2.2. Reduction of Greenhouse Gas Emissions

Biochar, a charcoal-like material derived from biomass, plays a vital role in mitigating greenhouse gas emissions and enhancing soil health by sequestering carbon, improving fertility, and increasing plant resilience [24].

## 4.Challenges and Future Prospects

### 4.1. Challenges in Large-Scale Adoption

Despite its numerous benefits, biochar faces challenges in large-scale adoption due to high production costs, lack of standardized regulations, and variability in its properties. The initial cost of biochar production remains a significant barrier, while the absence of quality control measures leads to inconsistent performance. Additionally, biochar characteristics vary based on feedstock and pyrolysis conditions, making its effects unpredictable. However, its advantages outweigh these challenges—it mitigates abiotic stresses like drought, salinity, and heavy metal contamination, enhances biotic resistance against pests and diseases, and improves soil fertility by increasing nutrient availability and cation exchange capacity (CEC) [40]. Biochar also enhances soil structure by reducing bulk density, improving aeration, retaining moisture, and preventing erosion. It supports microbial life, fostering nitrogen-fixing bacteria and mycorrhizal fungi, while buffering soil pH and immobilizing heavy metals and pollutants. Crop-specific benefits include a 6% yield increase in rice (acidic soils), a 27% yield boost in maize, and improved drought resilience in wheat. Moreover, biochar contributes to carbon sequestration and greenhouse gas reduction, making it a promising tool for sustainable agriculture and environmental conservation [41].

## 5.Future Directions

Policy supports for biochar-based fertilizers is crucial for promoting sustainable agriculture, enhancing soil health, and mitigating climate change. Governments should implement subsidies and financial incentives to offset high production costs and encourage large-scale adoption among farmers [19]. Standardized regulations and quality control frameworks must be established to ensure consistent biochar properties, efficacy, and safety. Research funding should be allocated to optimize biochar formulations, improve application techniques, and study long-term soil impacts. Integration of biochar into national soil health and carbon sequestration policies can enhance its role in climate change mitigation by promoting its carbon capture potential and reducing greenhouse gas emissions [42]. Policymakers should incentivize collaborations between research institutions, agricultural industries, and farmers to develop region-specific biochar-based fertilizers tailored to different soil types and crops. Public awareness campaigns and training programs can educate farmers on the benefits of biochar, its correct application methods, and its potential to enhance soil fertility and crop resilience [43].

Additionally, biochar should be incorporated into organic farming policies and sustainable land management practices, aligning with global environmental goals such as the UN's Sustainable Development Goals (SDGs). International cooperation on biochar policies can facilitate knowledge exchange, standardization, and investment in biochar-based innovations [44]. Furthermore, carbon credit programs should recognize biochar's contribution to carbon sequestration, allowing farmers to benefit financially from its use. By integrating biochar-based fertilizers into national and global agricultural policies, governments can support sustainable farming, improve food security, and contribute to long-term environmental conservation[45]

## 6. Conclusion

Biochar presents a viable, eco-friendly alternative to synthetic fertilizers, offering benefits for soil health, crop productivity, and climate change mitigation. Its ability to improve soil structure, retain nutrients, and sequester carbon makes it a valuable tool in sustainable agriculture. Future research and policy support can further enhance biochar's role in global food security and environmental conservation [20]. Biochar production offers a sustainable solution for managing organic waste streams such as agricultural residues, forestry waste, and municipal solid waste. This can help reduce fertilizer requirements and nutrient leaching, contributing to improved nutrient use efficiency and reduced environmental pollution [19]**.** Biochar application to agricultural soils represents a potential strategy for sequestering carbon from the atmosphere and mitigating climate change. Studies have estimated that widespread adoption of biochar could contribute to significant carbon storage in soils globally, helping to offset greenhouse gas emissions from agriculture and other sectors [47, 48].It plays a crucial role in pollutant remediation by adsorbing and immobilizing heavy metals and other pollutants, reducing their bioavailability and potential harm to plants and the environment. Additionally, by improving soil structure and water retention, biochar helps prevent soil erosion, further supporting long-term soil health and sustainability [49].

Overall, agricultural data related to biochar highlight its potential to improve soil fertility, crop productivity, and environmental sustainability, while providing economic benefits to farmers and contributing to climate change mitigation efforts. However, further research is needed to fully understand the agronomic and environmental impacts of biochar across different agroecosystems and to optimize its application for maximum benefit [48]. Despite the various claimed benefits of biochar in the agricultural and environmental sustainability, its field level uses are very low. Hence, the availability of feedstock, permanency of biochar application, economic feasibility, and demand and supply of biochar need to be evaluated for large-scale adoption [50].

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