

# A Review on Biochar in Agriculture: Production, Applications, and Impacts

Badmus Alao Tayo<sup>1,2,a\*</sup>, Ayodele Ebenezer Ajayi<sup>2,b</sup>,  
Oluwaseun Temitope Faloye<sup>2,c</sup>, Ayoola Olawole Jongbo<sup>3,d</sup>

<sup>1</sup>Department of Agricultural and Bioresources Engineering, Faculty of Engineering and Technology, University of Calabar, Calabar PMB 1115, Nigeria

<sup>2</sup>Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure PMB 704, Nigeria

<sup>3</sup>Programa de Pos-Graduacao em Zootecnia (PPZ), Universidade Tecnologica Federal do Parana, Campus Dois Vizinhos, 85660-000, Dois Vizinhos, Parana, Brazil

<sup>a\*</sup>tayobadmus007@gmail.com, <sup>b</sup>aeajayi@futa.edu.ng, <sup>c</sup>faloye.temitope@gmail.com, <sup>d</sup>ayoolajongbo@utfpr.edu.br

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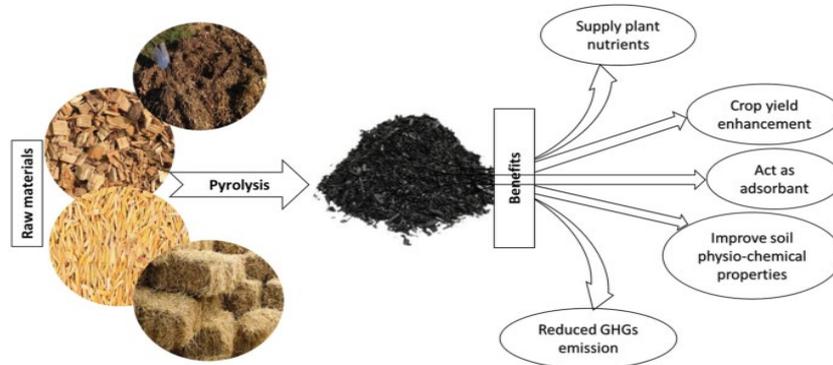
**Abstract.** Biochar, a carbon-rich material derived from biomass pyrolysis, is increasingly recognized for its potential in sustainable agriculture. Its unique physical and chemical properties enhance soil fertility, water retention, and nutrient availability, while also acting as a long-term carbon sink that mitigates greenhouse gas emissions. Despite these advantages, there remains a significant knowledge gap regarding its long-term agronomic impacts particularly on crop yield sustainability. Certain studies have observed a sustained 9% increase in maize yield even ten years after a single biochar application, while others report no yield improvement after six years. This review examines biochar production processes, emphasizing how feedstock type and pyrolysis conditions influence its properties and agricultural performance. It synthesizes evidence on biochar's role in improving soil health, boosting crop productivity, supporting microbial activity, and enhancing resilience to climate variability. Furthermore, it critically assesses the environmental benefits, potential to reduce synthetic fertilizer dependency, and constraints related to cost, scalability, and adoption. By addressing the uncertainty surrounding long-term yield outcomes, his review clarifies biochar's role in climate-resilient and sustainable farming systems and aims to guide future research and policy directions.

## 1. Introduction to Biochar and Its Agricultural Importance

Maintaining agricultural productivity is a global challenge due to the rapid depletion of soil organic matter and nutrients. With the population exceeding 8 billion, modern agroecosystems must produce more food while protecting soil, the source of nearly 99% of human food and vital ecosystem functions [140, 142, 141]. This challenge is intensified by climate change, evidenced by rising temperatures, increased atmospheric CO<sub>2</sub>, and extreme events such as droughts [143, 144, 145]. In this context, agriculture must adapt to improve resource efficiency and productivity while minimizing environmental impacts. Biochar, with its broad application potential, emerges as a promising innovation to address soil degradation, climate challenges, and environmental concerns [146, 135]. Biochar is a permeable, carbon-rich material with high resistance to decomposition and a high degree of aromatization, produced by thermal decomposition of plant or animal biomass in low-oxygen conditions [88]. Its varied industrial and agricultural applications have drawn growing interest. Biochar, produced via thermal conversion of biomass under limited oxygen, is a carbon-rich material whose physicochemical properties are governed by its feedstock and production conditions and determine its diverse applications [8, 48, 115].

## 1.1 Relevance in Modern Agriculture

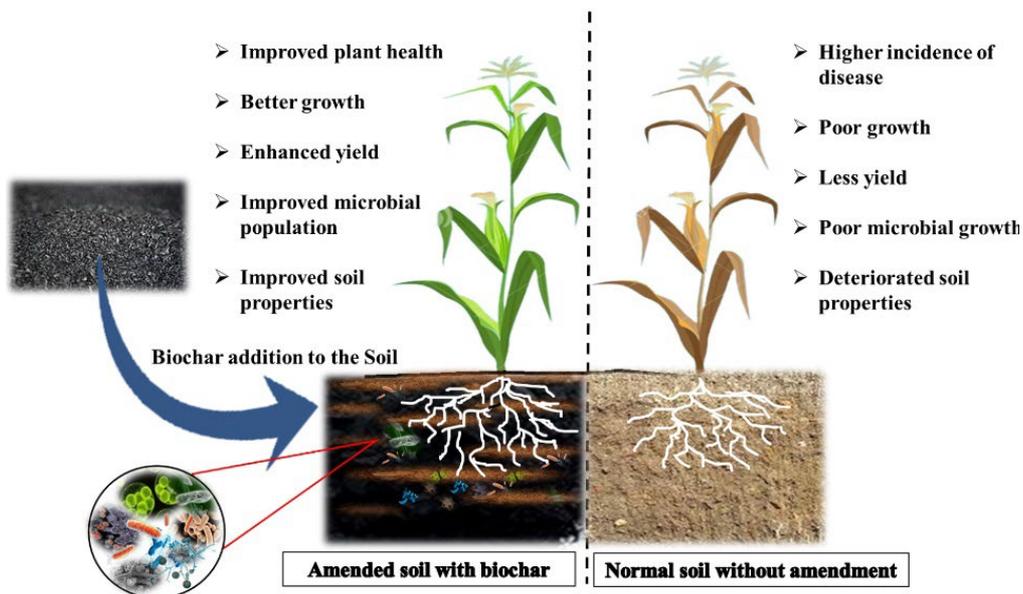
Biochar has gained attention as a soil amendment due to its cost-effectiveness and environmental benefits compared to chemical fertilizers, which can harm soil and plant health. It improves nutrient uptake, supports soil microbes, and enhances soil properties through nutrient cycling. Its diverse biomass origins provide essential nutrients and growth factors [67, 73, 52]. Figure 1 highlights biochar's role in modern agriculture.



**Fig. 1.** Applications of biochar in sustainable agriculture [40].

### 1.1.1 Contribution to Soil Health

Biochar is a versatile material with high surface area and porosity, aiding carbon sequestration, reducing nutrient leaching, and mitigating soil acidity. It supports climate change mitigation by enhancing soil health and sustainability [20]. Its addition improves soil physical, chemical, and biological properties, promoting plant growth and nutrient uptake. Benefits include improved porosity, water infiltration, water holding capacity (WHC), aggregate stability, reduced bulk density, enhanced soil strength, balanced pH, better nutrient cycling, and higher cation exchange capacity [58, 1]. Figure 2 shows biochar's impact on soil health.



**Fig. 2.** Comparison of the effects of adding biochar to soil on its physical, chemical, and biological characteristics [32].

### 1.1.2. Climate Resilience

Biochar is a climate-resilient amendment that supports sustainable agriculture and climate change mitigation. Its high carbon content and porous structure enhance soil properties and sequester CO<sub>2</sub>, aiding environmental sustainability [93]. As a carbon sink, it reduces greenhouse gas emissions and improves soil structure, fertility, and water retention, thereby enhancing nutrient availability and

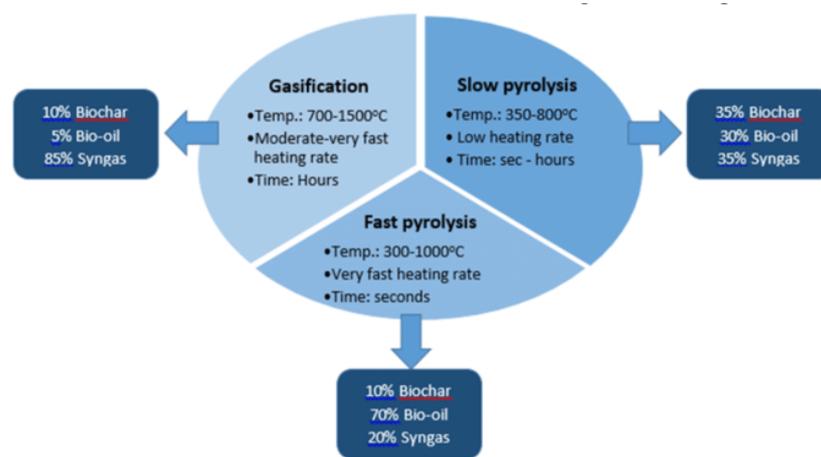
reducing leaching [92]. Its porosity supports microbial activity, promotes nutrient cycling, and suppresses disease. Biochar also improves drought resilience and reduces reliance on synthetic fertilizers, minimizing nitrogen runoff [103, 55, 86]. It further aids in restoring degraded soils and converting them into productive farmland.

### 1.1.3 Sustainable Agriculture Practices

To maintain groundwater quality and decrease nitrate leaching, many tactics have been proposed recently. These strategies include the implementation of drip irrigation systems [34], optimizing fertilization schedules [61], using fertilizers with a gradual release [124], and incorporating soil amendments like zeolite [78]. Among the various strategies, biochar, which is derived from organic materials through pyrolysis in low or no-oxygen conditions, is gaining recognition. Biochar offers substantial potential for use as a soil amendment, boosting sustainable farming methods, increasing the fertility of the soil and lessening the effects of abiotic and biotic stresses [5, 4].

## 2. Production, Characteristics, and Factors Influencing Biochar

Biochar is widely produced from biomass to meet growing demand across various applications [104]. Common production involves thermochemical methods such as pyrolysis, hydrothermal carbonization (HTC), gasification, and torrefaction [49, 19]. Yield optimization depends on matching the method to the biomass type and controlling factors like temperature, residence time, and heating rate [38]. These parameters affect biochar's physicochemical properties. For agricultural residues, processing conditions shape biochar structure. [91] noted initial weight loss from water at 100 °C, followed by cellulose, hemicellulose, and lignin breakdown around 220 °C. Figure 3 illustrates biochar production methods.



**Fig. 3.** Methods of biochar production and the resulting yields [147].

### 2.1 Pyrolysis Conditions

Pyrolysis is a procedure wherein organic materials are thermally disintegrated without oxygen, generally at temperatures between 250 and 900 degrees Celsius [140]. With this method, biomass waste is efficiently transformed into useful products, including biochar, syngas, and bio-oil. Depolymerization, fragmentation, and recombination are processes that lignocellulosic materials such as hemicellulose, cellulose and lignin go through at various temperatures, resulting in gaseous, liquid, and solid products [112]. The solid byproduct of pyrolysis is biochar, and the liquid produced is bio-oil. The gaseous outputs include syngas, a blend of C<sub>1</sub>-C<sub>2</sub> hydrocarbons, hydrogen (H<sub>2</sub>), carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) [43].

## 2.2 Types of Pyrolysis

Fast pyrolysis is a rapid thermochemical process that produces high-energy liquid bio oil from carbon-rich materials [43]. Biomass is heated at rates over 100 °C/min [28], with vapor residence times of 0.5 to 2 seconds at 400 to 600 °C [105, 25]. Minimizing vapor residence time is key to maximizing bio oil quality, often achieved by rapid quenching [110, 13]. In contrast, slow pyrolysis involves a heating rate of 5 to 7 °C/min and residence times over one hour, yielding more char than other methods [95].

## 2.3 Properties of Biochar

Biochar's various qualities are essential to its effectiveness in a range of applications, like agriculture and environmental restoration. This section delves into the chemical, physical and biological characteristics of biochar, emphasizing the significance of attributes like surface area, functional groups, and porosity in influencing its interactions and functions in various settings.

### a. Physical Properties

**i.** The surface area of biochar is key to its reactivity and nutrient absorption capacity. Higher pyrolysis temperatures generally produce biochar with greater surface area, enhancing its effectiveness in soil improvement and environmental applications [151]. This property supports nutrient retention and pollutant removal.

**ii.** Biochar's porosity, defined by its pore size distribution, affects soil aeration, water retention, and microbial activity. Macropores improve water flow, while micropores retain nutrients. A balanced pore structure is vital for enhancing soil quality and supporting plant growth [51], making biochar valuable for agricultural and environmental use.

**iii.** Biochar density influences nutrient retention and its persistence in soil. Low-density biochar decomposes faster, releasing nutrients, while high-density types last longer, offering sustained benefits. Optimizing density is key to achieving targeted agronomic and environmental outcomes [77, 150], supporting soil health and plant growth.

### b. Chemical Properties

**i. Carbon Concentration:** Biochar is rich in carbon, and its carbon content determines its stability and long-term carbon sequestration potential. High-temperature pyrolysis yields biochar with higher carbon content, making it more resistant to microbial breakdown [150]. This stability helps prevent greenhouse gas emissions and supports biochar's role in climate change mitigation.

**ii. Functional Groups:** Biochar's functional groups including hydroxyl, carboxyl, and phenolic enhance its chemical reactivity and nutrient binding. These groups improve cation exchange capacity, aiding nutrient retention and contaminant reduction. Their presence determines biochar's effectiveness in agriculture and environmental use [83].

**iii. pH:** Biochar's pH can influence soil acidity or alkalinity. Alkaline biochar, often from specific feedstocks, can neutralize acidic soils. However, its impact varies with production conditions like pyrolysis temperature and duration, affecting soil pH differently across environments [51].

### c. Biological Properties

**i. Microbial Activity:** By providing a favourable environment for advantageous microbes, biochar can have an impact on soil microbial communities. Its permeable structure provides refuge for microbes, which helps create a favourable environment for soil health and nutrient cycling. By supporting microbial activity, biochar contributes to maintaining soil fertility and promoting effective nutrient management [150].

**ii. Plant Growth Promotion:** By increasing nutrient availability, biochar encourages plant growth. Boosting water retention and boosting rhizosphere microbial activity. The presence of biochar can promote root development and increase nutrient uptake, fostering healthier and more productive plants [2]. Additionally, the capacity of biochar to influence soil microbial populations helps support plant growth through improved soil structure and nutrient cycling.

## 2.4 Factors Influencing Biochar Properties

The pyrolysis process's characteristics are crucial to the creation of biochar. The primary factors influencing the characteristics of biochar and significantly influencing its quality are feedstock type, particle size, pyrolysis temperature, and heating rate [11]. Additionally, the biomass type utilized and the particular pyrolysis conditions used affect the biochar output. Determining the applicability of biochar for different uses requires an understanding of its features. Natural materials, wood, municipal waste, and agricultural residues are only a few of the biomass sources that can be used to make biochar [94].

### 2.4.1 Feedstock

Biomass, a complex solid from organic, inorganic, or biological sources, is classified as woody or non-woody [123]. Woody biomass, like forestry residues, has low moisture and high calorific value [66, 117, 26], while non-woody biomass (e.g., agricultural waste, manure) has high moisture, low density, and low energy content [102]. Moisture reduces biochar yield and increases pyrolysis energy demands [81, 84]. Wood-based feedstocks produce carbon-rich, stable biochars [106], while grass and manure-based feedstocks yield nutrient-rich biochars ideal for N–P–K alternatives [10, 125, 41, 107]. Diverse sources include agricultural, industrial, municipal, and aquatic wastes [37, 59, 22, 23].

### 2.4.2 Resident Period

Increasing the residence time during pyrolysis at lower temperatures (300 °C) decreases biochar yield but enhances its ability to adsorb iodine and its pH. However, at higher temperatures (600 °C), increasing the residence period considerably decreases the iodine adsorption capacity while having little effect on pH or charcoal output [129].

### 2.4.3 Temperature

Pyrolysis temperature greatly affects biochar's elemental composition, pore structure, surface area, and functional groups [50]. Higher temperatures release volatiles, reducing Hydrogen-to-Carbon ratio (H/C) and Oxygen-to-Carbon ratio (O/C) ratios and increasing aromaticity and carbon content, thus enhancing stability [44]. At around 500 °C, biochar becomes more hydrophobic with greater microporosity and surface area, ideal for removing organic pollutants [91]. Lower temperatures (<500 °C) yield biochar with more oxygenated functional groups, better for capturing inorganic pollutants [94]. Higher temperatures also increase pH due to ash content [66, 84].

### 2.4.4 Pre-Treatment of Materials

Pre-pyrolysis treatment significantly influences biochar properties. Physical, chemical, or biological methods help prepare various feedstocks [114]. Techniques like particle size reduction and solvent soaking can boost yield [115]. For example, acid-treated pine wood enhanced biochar quality. Nitrogen or metal doping and vapor treatments also improve elemental composition and stability [129].

## 3. Biochar's Effects on the Health of Soils

Biochar is a stable porous carbon from biomass that can improve soil structure and water retention, raise pH and cation exchange capacity, and support microbes, thereby enhancing soil fertility and reducing nutrient losses. Effects vary with feedstock, pyrolysis conditions, application rate, soil type, and time since application.

### 3.1 Impact on Water Retention/WHC

Biochar's large surface area and porosity improve soil water retention, acting like a sponge, absorbing excess water and slowly releasing it during dry periods [57]. This supports plant growth, enhances drought tolerance, and reduces irrigation needs, especially in arid regions. Its effectiveness depends on biochar type, application rate, soil properties, and environmental conditions, all of which must be considered for optimal use [57].

### 3.2 Impact on Nutrient Retention/Availability

Biochar enhances nutrient retention through its porous structure and large surface area, reducing leaching and ensuring long-term availability of nutrients like potassium, phosphorus, and nitrogen. It improves cation exchange capacity, supporting plant growth and minimizing nutrient loss [119, 120, 118, 35, 80, 31]. This reduces fertilizer demand and promotes efficient nutrient use in agriculture [126].

### 3.3 Impact on Soil Structure/Texture

Biochar improves soil structure by enhancing aggregation, porosity, and stability [126]. This boosts water infiltration, retention, and nutrient availability, creating favorable conditions for microbes and root growth. It also reduces compaction, especially in clay soils (Blanco-Canqui, 2021). Long-term use further enhances soil structure and supports sustainable farming [57].

### 3.4 Impact on the PH of Soil

Plant growth and health depend heavily on the soil pH. By limiting the availability of nutrients, making plants more susceptible to pests, and limiting growth, acidic soils impede plant development [33]. [33] state that biochar buffers pH variations and releases alkaline substances like potassium and calcium carbonate to help balance soil acidity and give plants more stable growing conditions. Biochar, however, may have a detrimental impact on pH in alkaline soils [21]. Soil pH is influenced by the type of feedstock, pyrolysis conditions, and soil composition [125].

### 3.5 Impact on Soil Porosity

Soil porosity is key to water retention, nutrient uptake, and plant growth [87]. Biochar enhances porosity by creating channels that improve air and water flow, boosting crop yield and aiding CO<sub>2</sub> and contaminant retention [72, 15]. Biochar increased capillary and total porosity by 23% and 24% [127], and by 65% in sandy loam soil at 30 t ha<sup>-1</sup> over two years [1]. Meta-analysis shows biochar raises porosity by 14–64% and lowers bulk density by 3–31% [15]. [85] also reported an 8.4% increase.

### 3.6 Concentration of Organic Carbon in Soil

Soil organic carbon (SOC) is essential for soil fertility, structure, water retention, and carbon sequestration [42]. Biochar's impact on SOC depends on soil type, application rate, and biochar type. Biochar increased SOC from 4.0% to 26.7% over two years [99] and by 11.02–22.13% over four years at 6–12 t ha<sup>-1</sup> [128]. Rates from 1 to 100 Mg ha<sup>-1</sup> averaged a 29% SOC rise. In pot studies, 5–200 g kg<sup>-1</sup> raised SOC by 75% in 3.5 years [42]. Short-term gains include a rise from 34.5% to 38.0% in five days [152] and from 3.1 to 4.9 mg/kg [125].

#### 3.6.1 Biochar Effects on Soil Physical and Chemical Properties

To synthesize the literature, Table 1 compiles representative studies by feedstock, pyrolysis conditions, experiment type and duration, soil type, application rate and crop, the soil characteristics measured, and the observed effects with references. Overall, the studies most often report increases in soil pH, cation exchange capacity, aggregation, water holding capacity, and soil organic carbon, and decreases in bulk density. These effects tend to be stronger in acidic or coarse textured soils.

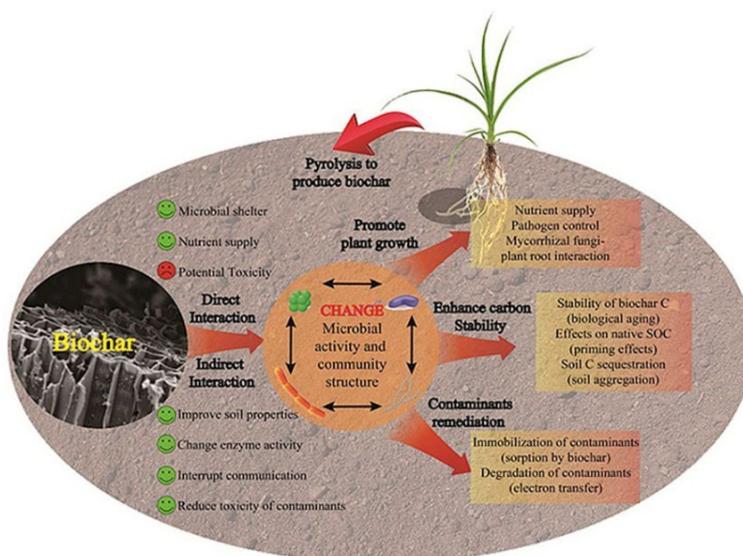
**Table 1.** Biochar effect on soil physical and chemical properties across different experiments.

SN	Biochar source	Biochar pH	Pyrolysis temperatures (°C)	No. of years	Soil type	Application rate	Crops grown	Soil characteristics measured	Effect on soil	References
1	Wood chip, wheat straw, vineyard pruning	8.3–9.7	400 (vineyard pruning) and 525 (wood chip, wheat straw, vineyard pruning)	(crop), 2 (fallow)	Chernozem and Cambisol (fine textured), Planosol (coarse textured)	0, 3% by weight	Mustard ( <i>Sinapis alba</i> L.), barley ( <i>Hordeum vulgare</i> L. cv. Xandú) and red clover ( <i>Trifolium pratense</i> L.)	Bulk density, aggregate stability, plant available water	Coarse-textured soil > fine-textured soil (soil structure and aggregate stability); straw biochar > wood chip biochar (aggregate stability in coarse-textured soil)	[154]
2	Forest shrub	9.3	450–500	3	Inceptisols (moderately acidic silty loam)	0, 5, 10, 15, 25, 40 [t ha <sup>-1</sup> ]	Maize ( <i>Zea mays</i> ) – Mustard ( <i>Brassica</i> spp.)	Plant available phosphorus (PAP) and water (PAW); soil pH, CEC, base saturation (BS), soil organic carbon (SOC)	PAP increased at 10 and 40 t ha <sup>-1</sup> ; PAW at 40 t ha <sup>-1</sup> ; increase in soil pH, EC and BS; additive effect on SOC	[155]
3	Wheat straw biochar	10.35	350–550	1	Upland red soil	0, 2.5, 5, 10, 20, 30 and 40 [t ha <sup>-1</sup> ]	Rapeseed and sweet potato	Soil particle size, aggregate stability, organic carbon, total N content and C:N ratio	Increase in soil aggregation, microaggregate content, SOC, total N and C:N ratio	[156]
SN	Biochar source	Biochar pH	Pyrolysis temperatures (°C)	No. of years	Soil type	Application rate	Crops grown	Soil characteristics measured	Effect on soil	References
4	Cacao shell	10.2	300–450	1	Typic Kanhapludult (Ultisol; sandy loam)	0, 22.5 [t ha <sup>-1</sup> ]	Maize ( <i>Zea mays</i> )	pH, Al <sup>3+</sup> concentration, macronutrients	Increase in soil P and K availability; raised soil pH; reduced Al <sup>3+</sup> concentration	[157]
5	Mixed woody feedstock	10.1–10.5	620	10 days	Sandy and sandy loam	0, 1, 5, 10% and 20% (by volume)	Soil incubation	Bulk density and water holding capacity	Biochar decreased soil BD and increased maximum WHC; stronger effect on sandy (coarse-textured) soil and with finer biochar	[158]
6	Soft and hard wood	9.7	600–700 (softwood), 900 (hardwood)	Multiple scales - including 6-year corn–tomato rotation	Sandy; silty clay	0, 0.5, 1% [w/w]	Corn–tomato rotation	Soil water retention (SWR), wilting point (WP), field capacity (FC), plant available water (PAW)	High-surface-area biochar increased FC and SWR (sandy soil); no significant effects on WP or on silty-clay soil	[159]

7	Corn stover feedstock	7.4–10.6	350 and 650	<1	Sandy loam	0, 1, 2% and 4%	Incubation/pot	Soil water retention capacity, bulk density, porosity, soil organic carbon (SOC)	Biochar increased soil porosity, reduced bulk density, and increased SOC ( $\text{g kg}^{-1}$ )	[160]
8	Eucalyptus woodstock	6.52, 8.92	350 and 800	<1	Coarse-textured (Al-rich Ultisol) and fine-textured (Mn-rich Oxisol)	0, 1, 2% and 4%	3 consecutive corn crops	Soil organic carbon (SOC) stability (soil C remaining relative to initial soil C)	Ultisol: SOC stability increased at 2% application; Oxisol: SOC stability decreased at 2% & 4% application of high-temperature biochar	[161]

### 3.7 Mechanisms of Interaction with Biochar

Biochar interacts with soil through processes that enhance porosity, water retention, and aeration, supporting plant and microbial activity [30, 7, 71]. Its high surface area aids in nutrient and contaminant retention, improving soil fertility. Cation exchange capacity, influenced by biochar's pH and surface charge, boosts nutrient availability and soil health [31]. Biochar also supports microbial activity, nutrient cycling, and aggregate formation, leading to lasting soil improvements [126]. Figure 4 illustrates these interactions.



**Fig. 4.** Mechanisms and effects of interactions between microbes and biochar in lowering pollutants and enhancing soil quality [130].

## 4. Biochar Applications

Biochar is gaining attention for its eco friendliness, wide biomass availability, and versatile thermochemical production [111]. Pyrolysis temperature affects how well biochar removes pollutants. Higher temperatures produce carbon rich biochar that is more effective at adsorbing organic pollutants [3, 27, 55], while lower temperatures are better for removing inorganic pollutants due to the presence of more oxygen containing functional groups [113]. Factors like pH and residence time also affect biochar's performance [38]. Biochar is used in soil amendment, energy, composting, catalysis, wastewater treatment, and carbon storage [9]. It offers a cost effective alternative to activated carbon for removing pollutants [100], with performance shaped by its surface area, porosity, ion exchange, and feedstock pyrolysis conditions [39, 79, 102].

#### 4.1. Soil Amendment

Soil amendment with biochar is considered one of the important approaches to enhance soil nutrient and water retention, promote soil ecological functions, and serve as a significant tool to address climate change by storing CO<sub>2</sub> in the soil [131, 132, 133]. Owing to its highly stable carbon content, high porosity, and large specific surface area, biochar application offers multiple benefits as a soil amendment [146, 135, 137]. Studies have shown that biochar improves the physical, chemical, and biological properties of soil [138, 139, 137], particularly with long term application [55], thereby enhancing agricultural productivity [136]. The effects of biochar on soil may persist for years due to its biochemical stability, and long term impacts on crop yield have been documented in some field experiments. For example, [149] reported a consistent 9% increase in maize yield even a decade after a single biochar application, whereas [153] found that rice yield was no longer influenced by biochar six years after application. Such differences often arise from variations in environmental conditions and agricultural practices across field trials, resulting in diverse long term effects of biochar on crop yield. However, few meta-analyses have investigated these long term impacts, and the driving factors behind the spatial variation in biochar effects still need to be identified to optimize biochar soil amendment strategies.

#### 5. Environmental Impact and Future Research

Biochar has diverse applications, but its environmental impact must be assessed carefully. Stability is crucial and depends on the strength, condensation, and aromaticity of its carbon structure [99, 65, 98, 115, 148]. Biochars derived from wood and grasses can act as sinks for PAHs [60]. However, because their properties vary, they must be evaluated; if unstable, they can release dissolved organic compounds and pose environmental risks [14]. Figure 5 shows biochar's environmental and climate benefits.

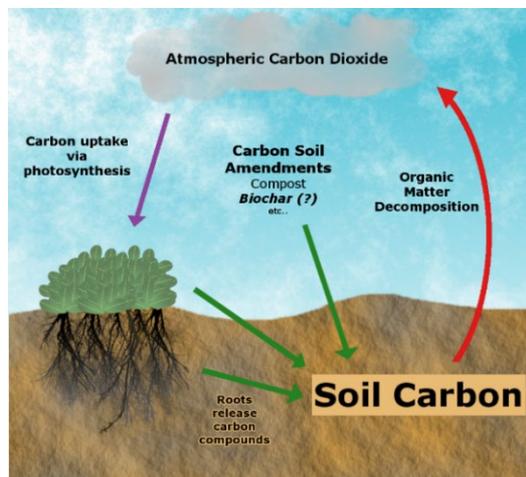


Fig. 5. Biochar and carbon sequestration [24].

##### i. Potential for Carbon Sequestration

Growing climate concerns have increased focus on reducing atmospheric CO<sub>2</sub>. Soil, a major carbon sink, plays a key role in climate regulation [29]. Biochar, with its stable aromatic structure, resists biodegradation and enhances soil carbon sequestration [6]. However, its effects on CO<sub>2</sub> emissions vary, with studies reporting both increases and decreases [127, 102]. Wood-derived biochar reduces carbon mineralization [43, 53], while combustion-based inputs may increase organic carbon turnover [76], suggesting that sequestration depends more on biochar's stability than fertility improvement. CO<sub>2</sub>, a key greenhouse gas, reached 412 ppm in 2020 [36] and is projected to hit 54–56 Gt by 2030, surpassing the 42 Gt limit for a 2°C target [74]. Biochar's long-term stability makes it a promising carbon storage tool [116, 121]. Agricultural residue biochar can sequester up to 1.2 t C ha<sup>-1</sup> year<sup>-1</sup>

[122], while manure-based types reach up to  $0.6 \text{ t C ha}^{-1} \text{ year}^{-1}$  [89], with other studies reporting  $0.8 \text{ t C ha}^{-1} \text{ year}^{-1}$ , supporting its role in climate mitigation.

## ii. Reduction of Greenhouse Gas Emissions

Applying stable carbon as biochar in agricultural soils is an effective strategy for enhancing carbon sequestration and mitigating climate change [64, 90]. Some biochars also reduce emissions of greenhouse gases like methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ). Meta-analyses show mixed  $\text{CH}_4$  results, reduced  $\text{N}_2\text{O}$ , and increased  $\text{CO}_2$ , depending on feedstock, pyrolysis conditions, application rate, and environment, mostly from lab studies [96, 46].  $\text{N}_2\text{O}$ , a potent greenhouse gas with nearly 300 times the warming potential of  $\text{CO}_2$  over 100 years, mainly comes from fertilizer and manure use [47]. Biochar reduces  $\text{N}_2\text{O}$  by improving soil pH, reducing compaction, and enhancing microbial activity, particularly in sandy loam soils [82]. Biochar also helps cut  $\text{CH}_4$  emissions from landfills, rice paddies, and manure by adsorption and microbial oxidation. Spruce wood biochar at  $10 \text{ t ha}^{-1}$  over seven years reduced  $\text{CH}_4$  by 43% [56], while a meta-analysis of 43 studies showed an average 37.9%  $\text{CH}_4$  reduction in East Asian rice fields [63].

## 5.1 Future Research

Future research on biochar in agriculture could delve into several critical areas to enhance its utility and evaluate its long-term implications:

### a. Optimizing Biochar Production

Explore how variations in feedstock types, pyrolysis temperatures, and residence times influence biochar properties suited for specific agricultural needs. Develop energy-efficient and advanced pyrolysis techniques to improve biochar yield and functionality.

### b. Soil-Biochar Interactions

Analyse how biochar affects soil microbial ecosystems and their function in nutrient cycling in the long term. Analyse how biochar affects the dynamics of organic matter in the soil and stabilising carbon storage.

### c. Crop-Specific Applications

Assess biochar's influence on diverse crops under different soil conditions and climates. Identify biochar formulations optimised for nutrient retention and water management, particularly in arid regions.

### d. Greenhouse Gas Mitigation

Evaluate the effectiveness of biochar in lowering emissions of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  from agricultural soils. Address possible trade-offs, such as the release of  $\text{CO}_2$  during biochar production or application.

### e. Sustainable Farming Integration

Combine biochar with practices like composting, organic farming, or precision agriculture to explore synergistic effects. Study its role in regenerative agriculture to boost soil health and ecosystem resilience.

### f. Economic and Policy Frameworks

Analyse the economic viability of producing and using biochar for smallholder and large-scale farming. Examine policy measures to encourage biochar adoption, including subsidies, carbon credits, or sustainability incentives.

### g. Reduction of Climate Change

Assess the global potential of biochar in mitigating greenhouse gas emissions through carbon storage and reducing the need for fertilisers. Investigate its role in mitigating climate change over the long run strategy by integrating biochar into national and international carbon offset programs. This

comprehensive approach will ensure biochar is optimized as a sustainable solution for modern agricultural challenges.

## 5.2 Conclusion

Biochar stands at the intersection of agricultural innovation and environmental stewardship, offering a multifunctional tool for enhancing soil health, mitigating climate change, and building resilient farming systems. By addressing production challenges and promoting widespread adoption through research and policy initiatives, food security and ecological balance for future generations could be ensured by using biochar to make agriculture a more climate-adaptive and sustainable enterprise.

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