



Potential of Biochar in Improving Soil Fertility and Carbon Sequestration

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Biochar is a carbon-impact material formed through the pyrolysis of biomass and has emerged as a potential solution for improving soil fertility and addressing climate change. This review paper discusses the numerous advantages of biochar with respect of enhancement of soil physical, chemical and biological properties. Biochar's porous structure and large surface area and cation exchange capacity (CEC) improve water retention, nutrient availability, and microbial activity, thereby increasing soil health and crop productivity. It is also alkaline in nature that can neutralize acidity of soils, which enhances availability of phosphorus. Apart from agriculture, biochar acts as a permanent carbon sink and can sequester carbon for hundreds of years while decreasing greenhouse gas emissions (such as CO₂, CH₄, N₂O). Different production techniques (pyrolysis, gasification, hydrothermal carbonization, torrefaction) were discussed, emphasizing the effect of different legal parameters of the production process on the characteristics of biochar. It has shown efficacy in reducing soil bulk density (BD), elevating organic carbon (OC), and improving aggregate stability under real-world conditions across field studies. While promising, many questions remain to be answered in terms of optimal rates of application and longer-term soil effects. In fact, in

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addition to the traditional use of Biochar, there are new frontiers for the improvement of this biochar and its application in nanotechnology to create novel nanomaterials and nanostructure composites for various green environmental applications, industrial biotechnology, and renewable energy production.

Keywords: Biochar; carbon sequestration; Cation Exchange Capacity (CEC); pyrolysis; climate mitigation; torrefaction; sustainable agriculture.

1. INTRODUCTION

The depletion of soil organic matter and nutrient is one of the major global challenges to sustain agricultural productivity. The growing world population of eight billion demands that agroecosystems increase food production levels while maintaining soil health, as these systems are responsible for nearly 99% of human food supply and vital ecosystem functions (Kopittke et al., 2019; McBratney et al., 2017). Soil degradation and loss of fertility again threatens global food system sustainability (Ortiz-Bobea et al., 2021). In this context, modern agriculture must continue to innovate and adjust not only to increase agricultural production and resource-use efficiency but also to limit the negative environmental impacts of agriculture. Biochar is gaining momentum due to its plethora of application potential to combat global food shortages that crossover imminent climate challenges that are hindering environmental concern (Das et al., 2021).

Biochar emerges as a carbon-abundant porous substance which forms through thermal biomass decomposition of plant remnants, agricultural waste and wood materials under restricted oxygen conditions through the process of pyrolysis (Khan et al., 2024). Biochar represents a cost-effective carbonaceous material which offers multiple benefits for agricultural practice along with environmental applications. The application of biochar as a soil amendment leads to enhanced physical and biochemical properties of soil alongside improved productivity which becomes more substantial with time due to its effects on soil aggregation, water retention, pH elevation and microbial boost (Nepal et al., 2023). Furthermore, biochar enhances soil nutrient availability while simultaneously preventing environmental losses through leaching along with trapping lethal substances found in contaminated earth (Khan et al., 2024).

Apart from improving soil fertility, biochar is also a valuable tool for mitigating climate change (Vijay Kumar R., 2019). Biochar serves as both a

carbon source and storage point for carbon within the soil. Biochar stabilizes carbon in the soil for decades to centuries, in contrast to typical organic matter, which breaks down rapidly and releases CO₂ back into the atmosphere (Pandian et al., 2024). Biochar is more physically and chemically stable than the original carbon form due to its molecular makeup and origins. Furthermore, it is challenging to release the trapped carbon as CO₂, which makes this a viable carbon sequestration method. The introduction of biochar from forestry and agricultural waste to soil produces emission reductions of methane (CH₄) and carbon dioxide (CO₂) (Qin et al., 2018). Studies have shown that biochar application can significantly reduce greenhouse gas emissions, including methane (CH₄) and nitrous oxide (N₂O), which are potent contributors to climate change (Vijay Kumar R, 2019). These benefits position biochar as a viable strategy for enhancing soil carbon stocks while supporting sustainable agriculture and climate change mitigation (Nepal et al., 2023).

2. PROPERTIES OF BIOCHAR

Biochar shows great potential for soil restoration because of its physical structure, chemical composition together with its affinity to interact with soil components. The physical characteristics include particle density, surface area, and pore-size distributions. While, the main chemical properties include pH, total carbon and nitrogen conductivity, phosphoric acid neutralizing capacity and measures of exchangeable cations, cation exchange capacity with additional assessments of specific nutrient elements and contamination concentrations. The characteristics of biochar materials transform according to the adjustment of pyrolysis parameters viz. oxygen, highest temperature, pressure, heating period rate and resource selection (Biochar feedstock) (Elkhilfi et al., 2023; Agegnehu et al., 2017). However, soil amendment performance and carbon sequestration capabilities of soil depend directly on three key characteristics of biochar (Vijay Kumar R, 2019).

2.1 High Surface Area and Porosity

Biochar presents an outstanding trait of extensive porosity that generates extensive surface area. The porous structure of biochar plays an essential role in enhancing soil physical properties because it helps water retention and aerates while capturing nutrients (Agegnehu et al., 2017). In addition to offering soil microorganisms an ideal environment, biochar's pores boost microbial activity, which is essential for the breakdown of organic matter and the cycling of nutrients.

2.2 Nutrient Content and Retention

The distribution of pyrolysis products is significantly influenced by the biomass' composition. Every material undergoes specific reactions during pyrolysis because of its unique composition which breaks down at specific temperatures to produce different compounds. The primary components of biochar consist of carbon, hydrogen, nitrogen together with essential plant nutrients like potassium, calcium together with magnesium and sodium (Elkhlifi et al., 2023). According to reports, using biochar improved total N, P and K availabilities, by 1.41, 2.65, and 2.60 times, respectively (Karimi et al., 2020). These nutrients function to elevate soil fertility when applied to degraded soil which holds limited nutrients. The high cation exchange capacity (CEC) of biochar enables it to attract and retain positive nutrient ions thus decreasing leaching and improving their availability for plants (Vijay Kumar R, 2019).

2.3 pH Modulation

Biochar has the ability to match its characteristics with the certain needs of the soil or soil remediation methods which gave the concept of designer Biochar. It mainly depends on the variations in the pH, ash content, surface area, and other properties of biochar (Agegnehu et al., 2017). For instance, numerous varieties of biochar have alkaline properties, making them effective in neutralizing acidic soils often found in degraded agricultural areas. By increasing the pH of these acidic soils, biochar improves the availability of nutrients, especially phosphorus, which is more accessible to plants when pH levels are elevated (Vijay Kumar R, 2019).

2.4 Carbon Stability

As it was discussed earlier, Biochar is stable for hundreds to thousands of years, in contrast to

other organic materials that are added to soil and eventually break down and release carbon dioxide back into the surrounding environment. Because of its stability, it is a great tool for long-term carbon sequestration, which helps slow down global warming by storing carbon in an inert, solid state (Pandian et al., 2024).

2.5 Surface Functional Groups

Carbonyl, hydroxyl, and carboxyl groups are among the several functional groups found in biochar. In order to give biochar its good adsorption capacity, hydrophilicity or hydrophobicity, buffering, and ion exchange capacity, the majority of these functional groups are alkaline or include oxygen (Anton and Herrero, 2018).

3. PRODUCTION PROCESS OF BIOCHAR

3.1 Thermochemical Conversion

Growing interest in globally align with biochar use cases promotes the conversion of biomass to biochar product. Generally, the conventional pathway for biochar generation is thermochemical conversion. The thermochemical conversion approach encompasses a range of conversion processes, including pyrolysis, hydrothermal carbonization, gasification, and torrefaction (Yaashikaa et al., 2020). These parameters are highly significant as they can greatly influence the physicochemical properties of biochar at the time of its production. This matters as the production of biochar will affect its chemical and physical properties. Weight loss causes the morphology of plant-derived biochar to change due to these process parameters. Loss in weight first from water is produced at about 100°C and the degradation of cellulose, hemicellulose, and lignin occurs at temperatures exceeding 220°C. Finally amongst the symptoms, weight loss occurs due to the utilization of carbonaceous wastes (Yaashikaa et al., 2020).

3.2 Pyrolysis

Pyrolysis is the thermochemical processes most frequently used to break down biomass in oxygen-limited environment at a temperature of 300–550 °C and a moderate pressure of 0.1–0.5 MPa (Chopra et al., 2022). The process represents a better option than biomass destruction because it recovers valuable

products through the production of biochar as well as syngas and bio-oil. Different temperatures trigger depolymerization and fragmentation reactions against the lignocellulosic components at specific temperatures which leads to cross-linking processes producing solid and liquid and gaseous products. The thermal process generates carbon dioxide, carbon monoxide, hydrogen and syngas as gaseous products together with the combination of bio-oil and char as solid and liquid outputs (Yaashikaa et al., 2020). The biochar yield depends on biomass type and nature, with temperature being the key factor influencing product efficiency (Wei et al., 2019). Generally, higher temperatures lead to reduced biochar yield and increased syngas production. Pyrolysis is categorized into fast, intermediate and slow processes based on heating rate, temperature, residence time, and pressure.

3.2.1 Fast pyrolysis

Fast pyrolysis functions as a direct thermochemical method to convert solid biomass into bio-oil which demonstrates significant energy content. Fast pyrolysis operates through heating feedstock materials at 500°C per min for 2 seconds or less while maintaining an oxygen-free environment (Malyan et al., 2021). Fast pyrolysis requires fume residence times to be as brief as

possible in the hot zone to produce high-quality bio-oil through quick fume cooling or quenching steps. Fast pyrolysis generates maximum bio-oil output by using heat at temperatures ranging from 500 to 550°C (Malyan et al., 2021). Fast pyrolysis serves as a preferable method to slow and intermediate methods because it blocks secondary cracking and prevents condensation while stopping intermediate polymerization (Yang et al., 2019). The primary production in fast pyrolysis yields bio-oil between 40–70% but it simultaneously generates 10–25% charcoal together with 20–40% of gaseous products.

3.2.2 Intermediate pyrolysis

Slow pyrolysis generates greater amounts of biochar output than fast and intermediate pyrolysis methods. Intermediate pyrolysis serves as the standard technique to produce equal concentrations of multiple pyrolysis products encompassing syngas, charcoal and biofuel (Malyan et al., 2021). Intermediate pyrolysis operates through residence times of 300–1000 seconds along with heating temperatures ranging from 500–600° C. Reports show that intermediate pyrolysis generates 15–25% charcoal together with 20–30% syngas and 40–60% biofuel as bioproducts (Malyan et al., 2021).

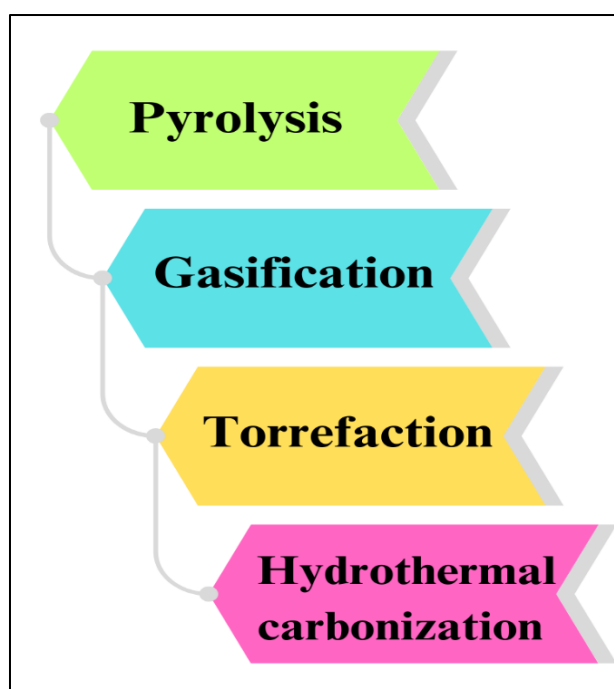


Fig. 1. Different production processes of Biochar

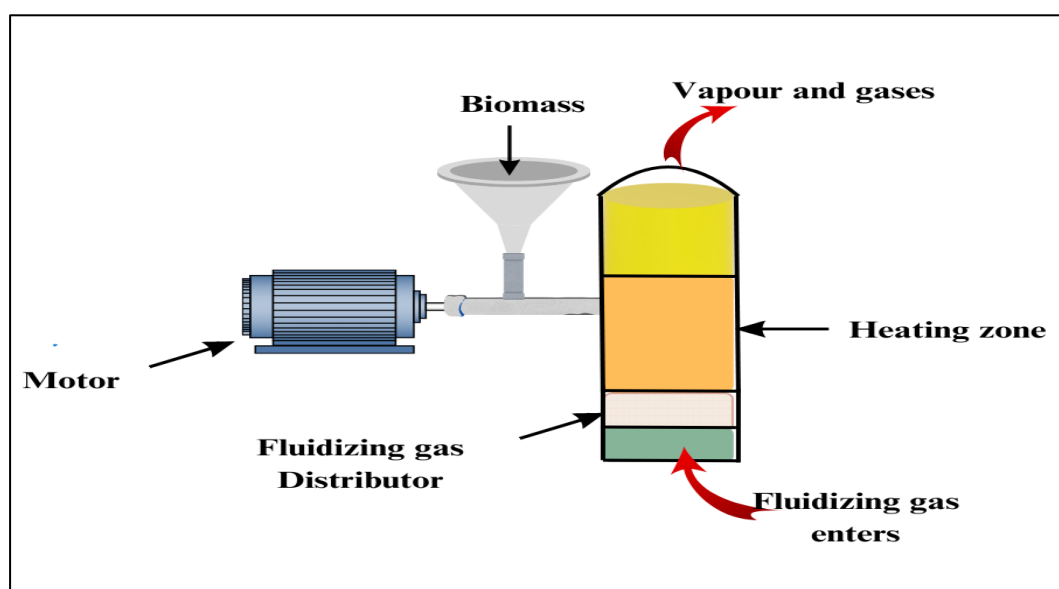


Fig. 2. Fluidized bed reactor in fast pyrolysis

3.2.3 Slow pyrolysis

The production of biochar (BC) through biomass heating using slow pyrolysis represents a conventional method. The heating period during slow pyrolysis operates at lower temperatures than fast pyrolysis by extending biomass exposure from minutes through hours. Typically the process happens at a rate of 0.1 to 0.8° C per second or at less than 50° C per minute (Roy and Dias, 2017). The production of bio-oil along with BC depends on multiple factors which include the traits of biomass feedstock and the heating speed as well as the processing temperature and gaseous conditions during the pyrolysis period.

3.3 Gasification

Gasification is a thermochemical process that uses air, steam, CO₂, or steam-oxygen mixtures to heat minuscule carbonaceous material (less than 5 mm) to >650°C in a majorly oxidative atmosphere. This process produces 3.5–10.0 MJ/Nm³ of syngas in addition to trace amounts of tar, char, and ash (Malyan et al., 2021). Char material falls into the category of secondary products with reduced output levels (Yaashikaa et al., 2020). The composition and moisture content of the feedstock affect the by-product fractions. For the formation of syngas, burn-off (30–55%) and activation temperature (700–850°C) are crucial. The gasification process contains three main phases that include, endothermic pyrolysis which converts biomass

into char and volatile matter and exothermic oxidation which produces CO₂ followed by reduction which transforms CO₂ and steam and volatiles into CO, H₂, and CH₄ that have been diluted with N₂. Pure syngas comprising CO₂, CO₂, H₂ (Limousy et al., 2017). High operating temperatures during gasification decrease biochar output compared to the production from slow pyrolysis. Additionally, the Gasification process enables the production of activated carbon for adsorption and catalytic applications and it simultaneously improves the textural qualities of charcoal during the pyrolysis process (Malyan et al., 2021).

3.4 Hydrothermal Carbonization

The Hydrothermal Carbonization (HTC) method is characterized as a thermochemical procedure that transforms biodegradable biomass into biochar while maintaining moisture under conditions of moderate temperature (180–350 °C) and pressure (2–10 MPa) (Lee et al., 2018). The product that is produced by the hydrothermal process is called hydrochar. The process involves filling a sealed reactor with water and biomass. To maintain stability, the temperature is increased gradually. Different products are created at different temperature ranges: hydrothermal carbonization, which produces biochar, occurs at temperatures below 250 °C (Zhang et al., 2017) hydrothermal liquefaction, which produces bio-oil between 250 and 400 °C and hydrothermal gasification, which produces gaseous products like syngas,

Table 1. Steps Involved in Biochar Production

Process	Temperature Range (°C)	Pressure (MPa)	Main Products	References
Pyrolysis	300–550	0.1–0.5	Biochar, Syngas, Bio-oil	(Chopra et al., 2022; Yaashikaa et al., 2020)
Fast Pyrolysis	500–550	Atmospheric	Bio-oil (40–70%), Char (10–25%), Gases (20–40%)	(Malyan et al., 2021; Yang et al., 2019)
Intermediate Pyrolysis	500–600	Atmospheric	Char (15–25%), Syngas (20–30%), Biofuel (40–60%)	(Malyan et al., 2021)
Slow Pyrolysis	<500	Atmospheric	Higher biochar yield, Low bio-oil & gas	(Roy and Dias, 2017)
Gasification	>650	Varies	Syngas (3.5–10.0 MJ/Nm ³), Minor char & tar	(Malyan et al., 2021; Yaashikaa et al., 2020)
Hydrothermal Carbonization (HTC)	180–350	2–10	Hydrochar, Bio-oil, Syngas	(Lee et al., 2018; Zhang et al., 2017)
Torrefaction	200–300	Atmospheric	Biochar with altered properties	(Yu et al., 2017; Khan et al., 2024)

including CO, CO₂, H₂, and CH₄. The hydrolyzed product undergoes a number of processes, including isomerization, fragmentation, and dehydration, to produce 5-hydroxymethylfurfural and its derivatives as an intermediate product. In order to create the hydrochar, the reaction also goes through condensation, polymerization, and intramolecular dehydration (Bakraoui et al., 2019). Through repolymerization and intermediary crosslinking, the ultimate product carbon is created.

3.5 Torrefaction

Torrefaction is an innovative method for producing biochar that uses low heating rates and gentle pyrolysis. This process extracts oxygen, moisture, and carbon dioxide from biomass at a temperature of 300°C in an inert atmospheric environment (Yu et al., 2017). It alters characteristics such as particle size, moisture levels, surface area, heating rate, and energy density. The procedure can be carried out using steam, wet, or oxidative techniques. It is an incomplete pyrolysis process and requires temperatures ranging from 200 to 300°C, with residence times of less than 30 minutes and heating rates below 50°C/min (Khan et al., 2024).

4. IMPACT OF BIOCHAR ON SOIL FERTILITY

Biochar as a soil amendment has many benefits for enhancing soil fertility and supporting

sustainable crop production. Biochar can help overcome this by increasing nutrient availability and reducing leaching losses, allowing plants to thrive with reduced fertilizer inputs while still accessing more available nutrients. It also promotes helpful microbial populations and improves their functional abilities in soil ecosystem (Diatta et al., 2020). Due to the unique properties including high porosity, specific surface area, and the stability of carbon content, they have been proven to be effective soil supplements (Zhang et al., 2021). According to literature, biochar is known to enhance the physical, chemical and biological properties of soil, especially with time of its application (Joseph et al., 2021). Thus, adding biochar to soil can improve its fertility through specific mechanisms, making it a great option for this purpose and improving a variety of soil fertility characteristics (Zubairu et al., 2023).

4.1 Effect of Biochar Application on Soil Physical Properties

4.1.1 Bulk density

The incorporation of biochar into the soil causes decreased bulk density because its natural density values are lower than those of mineral soils. The bulk density of biochar spans from 0.08 g cm⁻³ to 0.43 g cm⁻³ and exceeds typical mineral soil density which falls within 1.16–2.00 g cm⁻³ (Diatta et al., 2020). Increased biochar application decreases soil bulk density while

improving soil aeration (Khan et al., 2024). The addition of biochar at 4% to degraded tropical soils reduced bulk density by 5% according to REF, whereas simultaneous application of biochar and compost at 1% brought an extra 16% reduction in bulk density (Khan et al., 2024). Studies have proven that using biochar derived from crop residues can successfully decrease soil compaction (Nepal et al., 2023). Similarly, Pandian et al. (2016) reported that applying 5 t ha⁻¹ of *Prosopis* biochar to red soil reduced soil bulk density by 3–5% compared to the control (0 and 2.5 t ha⁻¹). Likewise, a three-year study concluded that adding 5 t ha⁻¹ of *Prosopis* biochar to sandy soil reduced its bulk density from 1.41 to 1.38 Mg m⁻³ (Kannan et al., 2021).

4.1.2 Soil Porosity and water holding capacity

Soil porosity, water holding capacity, and hydraulic conductivity are all significantly influenced by biochar. Biochar morphology, application rate, internal pore structure (intrapores), interpores (pores connecting biochar to soil particles), and particle size distribution are the key factors affecting soil porosity (Yi et al., 2020). Carbon (C), nitrogen (N), and hydrogen (H) from biochar regulate porosity, WHC, hydraulic conductivity, and soil respiration in biochar-amended soils all together. Various field experiments demonstrated that biochar improves soil porosity and retention of water (Randolph et al., 2017). A meta-analysis of 74 studies concluded that biochar increases soil porosity by 8.4% and increases water retention by 15.1% and saturated hydraulic conductivity by 25% (Omondi et al., 2016). The retention capacity of biochar can be explained by its internal pore structure, as pores below 10 µm can entrap water, contributing to reduced hydraulic conductivity and improved soil moisture retention (Suliman et al., 2017).

In addition, biochar works as a binder, enhancing soil porosity, water retention and strength of aggregates (Jien et al., 2021). When 6% biochar was added to clay soil, it altered the soil's pore structure, strengthened the soil, and encouraged the formation of macroaggregates (REF). The mesopores (pores between the biochar particles and the soil) are reduced when biochar is applied because big aggregates smaller than 0.25 mm obstruct the biochar's surface pores (Khan et al., 2024). Yet for large aggregates (< 0.25 mm) these may occlude biochar inner pores, causing a decrease in mesopores. Biochar also helps to increase and

retain soil moisture significantly. Likewise, (Lateef et al., 2019) reported that the water retention of the biochar treated soil after 20 days was 67.17% vs 55.5% for untreated soil. Similarly, (Liu et al., 2018) reported that soil treated with biochar retained more water than unamended soil, which may be due to greater soil organic matter content and more optimally-sized pores.

4.1.3 Soil aggregate stability

Increasing the stability of soil aggregates is one of the most important benefits of using biochar as a soil amendment (Yan et al., 2022). During a one-year mustard–red clover cropping cycle followed by two years of fallow, biochars derived from wood chips, wheat straw, and vineyard prunings (pH 8.3–9.7; applied at 3% by soil weight) improved soil structure and aggregate stability, with more pronounced effects observed in coarse-textured soils compared to fine-textured ones (Burrell et al., 2016). Similarly, in a rice-wheat rotation system, six years of continuous straw plus a biochar amendment made from straw improved soil aggregation in the top 0–40 cm (Zhang et al., 2020). Likewise, when applied to highland red soil for a year in a rapeseed-potato farming system, wheat straw biochar (pH 10.35, application rate 2–40 t ha⁻¹) improved the soil aggregate stability and microaggregate content while raising the yields of sweet potatoes and rapeseed (Nepal et al., 2023).

4.2 Effect of Biochar Application on Soil Chemical Properties

The application of biochar significantly affects the chemical characteristics of the soil, including pH, EC, CEC, and the quantity of soil organic matter (Pandian et al., 2024).

4.2.1 Soil pH

Owing to its high alkalinity and highly buffering capacities and functional groups (Naggar *et al.*, 2019), biochar can be used to mitigate soil acidification. Moreover, it elevates soil pH, enhances the accessibility of nutrients to plants, and releases minerals from the charcoal in the form of cations such as potassium, magnesium, calcium, and sodium (Khan et al., 2024). After four years of 20 tons per hectare of biochar applied, the pH went from 3.89 to 4.05 showing the latter benefits of the material. In another study where 20 tons of ha⁻¹ biochar was applied in Sumatra, Indonesia, it helped to raise the pH

from 3.9 to 5.1 and reduced Al^{3+} concentrations, which are toxic to plants. A study conducted to investigate the potential benefits of using biochar in banana production evidenced increases in soil pH and potassium uptake, with no effect on fruit yield (Khan et al., 2024). So, biochar fertilizer carrier can be a sustainable long-term management strategy for acidic soil problems. Another incubation study conducted by (Zhao et al., 2022) showed that various crop straw-derived biochar (pH 7.69 to 10.26) incorporated into Ultisol (pH 4.31) at a rate of 1% and 2% w/w significantly increased the soil pH. Adding biochar from paddy straw (pH 10.50) to sandy soil (pH 5.24) raised the pH a whopping 4.5 units compared to control (Naggar et al., 2018). Similarly, the pH of acidic red soil was increased from 5.7 to 6.0 after additions of 5 t ha⁻¹ cotton stalk biochar (Pandian et al., 2016).

4.2.2 Cation exchange capacity and nutrient retention

Cation exchange capacity (CEC): The soil's ability to hold onto cations in an exchangeable form that plants can utilize. Soils characterized by higher CEC can hold more nutrients in a way that allows plants to access them and prevents soluble nutrients from leaching out or being taken immediately by plants (Khan et al., 2024). With soil ageing and weathering, biochar application to agricultural soils improves CEC via surface oxidation and the formation of surface functional groups bearing permanent negative charges. Thus, with its porous structure and larger surface area, along with the increased presence of these functional groups, leads to an increase in CEC over time (Diatta et al., 2020).

Table 2. Influence of Biochar Application on Soil Chemical Attributes

Soil Chemical Property	Biochar Application Rate	Effect Observed	Reference
Soil pH	20 t/ha (4 years)	Increased from 3.89 to 4.05	Khan et al., 2024
	20 t/ha (Sumatra, Indonesia)	Increased from 3.9 to 5.1, reduced Al^{3+} concentration	Khan et al., 2024
	Crop straw biochar (pH 7.69-10.26) at 1% & 2% w/w in Ultisol (pH 4.31)	Increased soil pH significantly	Zhao et al., 2022
	Paddy straw biochar (pH 10.50) in sandy soil (pH 5.24)	Increased soil pH by 4.5 units	Naggar et al., 2018
	5 t/ha cotton stalk biochar	Increased acidic red soil pH from 5.7 to 6.0	Pandian et al., 2016
Cation Exchange Capacity (CEC)	General effect of biochar	Increases CEC over time	Diatta et al., 2020
	1% & 3% rice husk biochar in loamy sandy soil	CEC increased by 20% (1%) and 30% (3%)	Ghorbani et al., 2019
	1% & 3% rice husk biochar in clay soil	CEC increased by 9% (1%) and 19% (3%)	Ghorbani et al., 2019
Electrical Conductivity (EC)	High-temperature pyrolyzed biochar	Higher EC values	Zhao et al., 2022
	10% (w/w) cassava stalk biochar	Increased EC significantly	Prapagdee & Tawinteung, 2017
	30 t/ha rice straw + 50 t/ha silver grass biochar	Increased EC by 38.5%	Naggar et al., 2018
	5 t/ha Prosopis biochar in Alfisol	Increased soil EC to 0.42 dS/m	Pandian et al., 2016
Soil Organic Carbon (SOC)	General impact of biochar	Increases SOC, soil fertility	Pandian et al., 2024
	5 t/ha red gram stalk biochar	SOC increased from 3.6 g/kg to 4.8 g/kg	Pandian et al., 2016
	12 t/ha rice husk biochar	Increased organic matter to 26 g/kg	Oladele SO, 2019
	10.9 t/ha biochar + compost + residue	SOC increased by 0.17%, 0.11%, 0.17%	Hose et al., 2020

The high CEC of biochar is especially beneficial in improving low-fertility soils. A study by (Ghorbani et al., 2019) investigated the effect of rice husk biochar on two soil types (clay and loamy sand) and three levels (0%, 1%, and 3% w/w). The results indicated that the application of biochar at 1% and 3% led to 20% and 30% increase in the CEC of the loamy sandy soil and 9% and 19% increase in the clay soil, respectively. Similarly, (Zubairu et al., 2023) reported that the CEC increased from 88.4 mmolc kg⁻¹ in biochar-unamended soil to 211.3 mmolc kg⁻¹ in biochar-amended soil. However, the way that BC influences soil CEC may depend on a number of factors, including as the type of soil, BC-production conditions, and the dosage rate (Zubairu et al., 2023). The increase in soil CEC leads to further improvement in nutrient retention in soil which adds to the potential of biochar in sustainable soil management (Diatta et al., 2020).

4.2.3 Electrical conductivity

The addition of biochar to soil raises its EC. Biochars produced at greater pyrolysis temperatures, particularly those made from waste paper and wood, have been shown to have higher EC (Zhao et al., 2022). According to (Prapagdee and Tawintung, 2017) adding 10% (w/w) of cassava stalk biochar raised the EC of the soil. Likewise, adding rice straw (30 t ha⁻¹) and biochar made from silver grass residue (50 t ha⁻¹) to sandy soil (EC = 0.07 dSm⁻¹) increased the EC by 38.5% (Naggar et al., 2018). Similarly, Prosopis biochar applied at a rate of 5 t ha⁻¹ increased soil pH to 6.33 and EC to 0.42 dS m⁻¹ in a semiarid tropical Alfisol (Pandian et al., 2016).

4.2.4 Soil organic carbon

Biochar naturally raises the amount of organic carbon in soils because it is a carbon-rich substance. The temperature during pyrolysis and the feedstock have significant impact on the amount of carbon in biochar (Naggar et al., 2018). For low-fertile soils, biochar has become a useful additive to increase SOC content and slow down climate change (Sarfraz et al., 2022). Red gram stalk biochar applied at 5 t ha⁻¹ increased SOC by 4.8 g kg⁻¹ in comparison to the control (3.6 g kg⁻¹) (Pandian et al., 2016). Likewise, (Oladele SO, 2019) reported that applying rice husk biochar at a rate of 12 t ha⁻¹ led to a notable rise in the amount of organic matter (26 g kg⁻¹). When applied at 10.9 t ha⁻¹,

biochar, compost, and biochar-blended crop residue considerably raised SOC by 0.17, 0.11, and 0.17% in comparison to control (Hose et al., 2020). Thus, applying biochar enhances soil health by increasing organic and total carbon, which benefits the microbiome, nutrient availability, and physical health of the soil (Pandian et al., 2024).

4.3 Effect of Biochar Application on Soil Biological Properties

Through the same characteristics that improve soil physical and chemical properties—porous structure, high CEC, and high sorption capacity—biochar has the ability to increase the richness and activity of soil microbial communities (Zheng et al., 2013). The inherent qualities of biochar may improve nutrient availability and retention for microorganisms and affect how soil, plant, and microorganism components interact. Microorganisms can find a suitable home in the pore spaces of biochar, hence the biochar with the maximum microporosity would be best for habitat (Diatta et al., 2020).

High rates of biochar application can promote bacterial (as opposed to fungal) dominant communities in the soil microbial composition (Li et al., 2015). According to (Zhang et al., 2018), the incorporation of biochar also raised the microbial biomass and activity as well as the ratios of Gram-positive to Gram-negative bacteria (G+/G-negative) (G+/G-1). Biochar incorporation can also affect the activity of the microbial population by affecting the activities of enzymes including peroxidase, cellulase, and protease (Du et al., 2019). Applying biochar shields soil-dwelling microorganisms from natural predators and provides them with an accommodation (Yang et al., 2019). According to (Guenet et al., 2019) applying biochar made from Eichornia biomass at a rate of 20 kg ha⁻¹ led to notable increases in enzyme activity; dehydrogenase activity rose by 21%, while acid phosphatase and alkaline phosphatase activity rose by 32% and 22.8%, respectively. Applying biochar prolongs the function of mycorrhizal fungi in a number of ways, including (i) changing the physicochemical characteristics of the soil, (ii) indirectly influencing mycorrhizae by changing the surrounding microbial environment, (iii) interfering with plant-fungus signaling and allelochemical detoxification on biochar, and (iv) offering protection from fungal grazers (Liu et al., 2018).

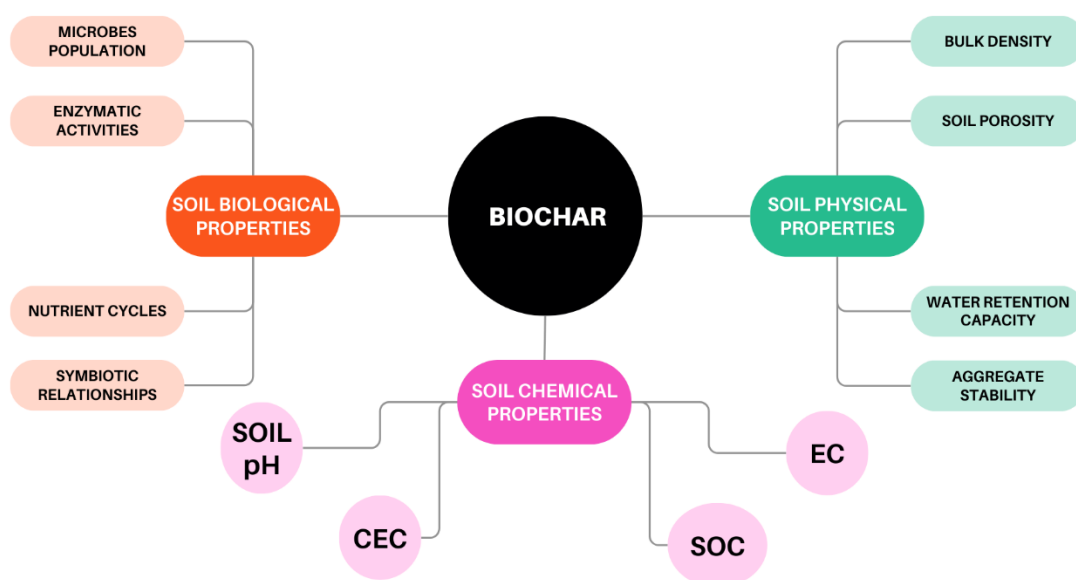


Fig. 3. Effect of Biochar on different soil properties that helps in improving soil fertility

5. ROLE OF BIOCHAR IN CARBON SEQUESTRATION

Soil carbon sequestration, a technique for absorbing and storing carbon in soil to prevent it from entering the atmosphere, is a key tactic for mitigating the consequences of human-caused climate change (Oliveira et al., 2021). A study done by (Oo et al., 2018) also highlighted that by storing carbon in soil and displacing the use of fossil fuels, biochar may be utilized to fight climate change. Biochar, which is formed from forestry and agricultural waste and stays in the soil for a long time, has the potential to lower CO₂ and methane (CH₄) emissions (Pandian et al., 2024). Biochar made from maize stalks applied at a rate of 16 tons per hectare greatly enhanced carbon sequestration in coastal saline environments (-3.84 to -3.17 t CO₂ -eq. ha⁻¹ t⁻¹C) without substantially raising greenhouse gas emissions while boosting soil fertility (Lin et al., 2015). It has been found that applying biochar at a rate of 2% to 5% greatly increases the carbon sequestration from rice and beet fields by 46% to 58% (Nepal et al., 2020). In a two-year study conducted in China's Loess Plateau, biochar made from apple wood scraps and reapplied in apple orchards enhanced the soil organic carbon sequestration, increasing it by 316.52% to 354.78% (Han et al., 2022). According to a most recent global meta-analysis study on the use of biochar worldwide, applying biochar both alone and in conjunction with chemical fertilization increased the potential for sequestering soil organic carbon (SOC) by 32%

to 35% and by as much as 40% (Nepal et al., 2020). Although there was a notable variance based on the soil qualities, land-use type, agricultural practice, and other biochar features, the results indicate that the biochar with a higher pH (8–9) had a more positive increase of SOC sequestration (Liu et al., 2016). Overall, findings from lab-based research showed that biochar has a greater potential for sequestering soil carbon than in field settings because of distinct interactions and management techniques (Xu et al., 2021).

Apart from CO₂, the soil's release of CH₄ and nitrous oxide (N₂O) can also affect the climate (Oo et al., 2018). Biochar has the potential to reduce greenhouse gas emissions in a number of ways. In anaerobic environments, soil microbes use methanogenesis to create CH₄. When compared to CO₂, CH₄ has a far higher ability to retain thermal energy in the Earth's troposphere, which contributes to the phenomena of global warming (Pandian et al., 2024). When 2% of biochar was added to the soil, an insignificant amount of CH₄ was released (Weng et al., 2017). Due to its innate persistence, biochar's long-term presence in the soil reduces greenhouse gases (GHG) emissions.

Likewise, soil microorganisms generate N₂O through two processes: nitrification and denitrification. Adding biochar to soil improves soil aeration and lowers N₂O emissions by giving the soil low-density and porous properties in

comparison to the soil. According to (Cai and Akiyama, 2017) adding biochar to soil immobilizes bioavailable nitrogen, whether it be in organic or inorganic form, which lowers N₂O emissions. Biochar's high carbon-to-nitrogen ratios and low nitrogen concentrations facilitate the biological immobilization of inorganic nitrogen. This mechanism aids in the soil system's nitrogen retention, which reduces ammonia volatilization (Pandian et al., 2024).

Furthermore, biochar affects the transport and orientation of pollutants by adsorbing a variety of organic pollutants such as phenols, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and naphthalenes (Chen et al., 2019). The four main adsorption mechanisms of biochar on organic contaminants are micropore adsorption, pore retention, surface adsorption and partitioning (Huang et al., 2018). Yet a few mechanisms usually collaborate to regulate the adsorption process. All these attributes of biochar, including, but not limited to, the extent of aromatization, carbonaceous materials, elemental composition, pH, pore structure, surface chemistry, and others, affect its ability to adsorb organic pollutants. The differences of properties of various biochar also lead to the complex adsorption mechanisms for different types of organic pollutants (Chen et al., 2019).

6. CONCLUSION

Biochar has become a revolutionary remedy to solve major issues of soil fertility and to reduce climate change. Such features of biochar include improved soil physical properties (porosity, soil water retention, soil aggregation) and chemical properties (pH buffering, CEC) etc. This in turn creates an ideal habitat for microorganisms, enhancing soil health and productivity. Biochar is also a viable candidate for long-term carbon sequestration and leads to decreased emission of greenhouse gases like CO₂, CH₄, and N₂O due to biochar's stable carbon structure.

Though it holds great promise, challenges remain, including figuring out the optimal application rates and how it interacts with soil over the long term, as well as the fact that biochar properties can vary based on how the biochar is produced. Future studies should address these gaps, as well as investigate more advanced applications such as nano-biochar for improved environmental remediation or nutrient delivery. Combining biochar with additional sustainable practices, like composting or

precision agriculture, might additively amplify its benefits.

In summary, biochar is an effective and adaptable method to enrich soil fertility, increase crop yield, and address climate change. placed in proper context with continued innovation, agronomy and policy support, their adoption can be pivotal in global food security and environmental sustainability. As an intermediary between science and practice, biochar holds significant potential for building resilient agricultural systems and a healthy planet.

7. FUTURE PROSPECTIVE

Biochar is a carbon-heavy material produced through the pyrolysis of biological biomass and has gained significant interest for a variety of applications in climate change mitigation, environmental remediation, and agriculture. Biochar has a bright future of potential expansions in to additional industries and advancements in manufacturing techniques, as long as the research technology continues to advance.

This is a low-cost and environmentally friendly one that has a great potential to be used in agriculture and the environment in the field of soil quality improvement, soil fertility improvement, soil and water remediation, soil carbon sequestration, and greenhouse gas mitigation. And, above all, the advantages from applying biochars for agricultural purposes depend on the type of biochar, soil properties, management practices, etc, so it is important to treat each biochar as unique; and characterize it, and evaluate it in methods of crop-soil management (particularly when applying it on a large scale) (Nepal et al., 2023). Nano biochar is widely generated for the implementation of short-period improvement in the effectiveness of carbonaceous material in the field using the implementation of advanced technologies, especially nanotechnology. The reduced size of biochar, all the way down to the nanoscale, is likely to have great potential for the environmental remediation of contaminated soil and water systems, due to its vastly increased specific surface area available for the adsorption and chemical reaction of pollutants (Nepal et al., 2023). It remains to be seen if this type of nano-biochar will be suitable for soil carbon sequestration and greenhouse gas mitigation often associated with biochar's more recalcitrant carbon. Over the years, biochar (which is carbon

neutral and acts as a low-cost source of pollution management) has demonstrated the use of its unique adsorption capacity for this purpose in the environmental application in soil and water systems. As nanotechnology develops, we can explore interactions of biochar with specific metal(loid)s, organic pollutants, microplastics, and many others in soil, water, and air, thereby broadening the venue of biochar applications. For the application of universal biochar in treating wastewater streams from municipal waste, potable water sources, and landfill environments, a definitive protocol and capture and filtration of contaminants were likely necessary. Biochar can help reduce environmental hazards due to both poor rainwater management practices as well as the global production and usage of numerous hazardous chemicals. This could then reduce the related risks to human health (Nepal et al., 2023).

To date, much information vacuum still exists on the long-term stability, optimal application rate, influence of soil carbon stock, and effects of biochar on soil biotic properties. Future studies should focus on identifying soil quality markers, estimating carbon sequestration potential and understanding the synergies of different carbon sources (Nepal et al., 2023).

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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