Biochar - Its Role in Enhancing Soil Health and Climate Change Mitigation

Biplab, Avinaba Maji, Sovan Debnath, Badre Alam, Asha Ram, Akash Yadav, Ayyanadar Arunachalam

Soil serves as a crucial foundation for effective agricultural practices, and enhancing its quality is essential to boost both crop yields and soil fertility. One effective method to achieve this is the application of biochar. Biochar is a carbon-dense material formed through the pyrolysis of crop residues, organic waste, or wood in low-oxygen conditions. It contributes significantly to carbon sequestration and offers benefits such as recycling agricultural waste, increasing soil nutrient retention and decreasing emissions of greenhouse gases. The diverse uses of biochar support the safe and sustainable enhancement of soil health and productivity. This chapter offers a comprehensive overview of biochar's characteristics, its production processes, and its valuable contributions to agriculture. This serves as an informative tool for those studying or implementing biochar in agricultural practices.

Keywords: *Biochar, pyrolysis, soil health, climate change*

Biplab[1], Avinaba Maji[2], Sovan Debnath[1*], Badre Alam[1], Asha Ram[1], Akash Yadav[1], Ayyanadar Arunachalam[1]
[1]ICAR-Central Agroforestry Research Institute, Jhansi, Uttar Pradesh, India.
[2]Department of Agricultural Chemistry and Soil Science, Faculty of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India.

[*]Email: sovan.dta@gmail.com

Publisher: Cornous Publications LLP, Puducherry, India.
Elements of Soil Science and Recent Advances
Editor: Dr. Manik Chandra Kundu
ISBN: 978-81-986832-4-3
DOI: https://doi.org/10.37446/edibook222025/89-106

Introduction

Agricultural waste and plant residues pose a major environmental challenge worldwide due to their contribution to greenhouse gas emissions. To address this, many researchers have explored their utilization in various ways, such as soil mulching (Salem et al., 2021; Metwally et al., 2022), organic fertilizers, and biochar. Among these, biochar stands out as a more stable soil nutrient compared to other organic inputs. It significantly aids in nutrient adsorption and mineralization, thereby improving nutrient availability in the soil and supporting environmental sustainability. Being a carbon-rich material, biochar acts as a soil amendment in agriculture, helping to reduce the risks of environmental degradation and pollution (Ulusal et al., 2021).

Climate change poses a growing threat to soil health and crop productivity, emphasizing the need to maintain adequate soil organic matter to support physical, chemical, and biological functions (Srinivasarao et al., 2013). Applying biochar, a carbon-rich material derived from pyrolyzing organic waste, is an effective approach. Biochar is highly stable and can sequester carbon for centuries, aiding in the reduction of greenhouse gases while boosting soil quality (Lehmann et al., 2003). Biochar has a beneficial impact on soil characteristics, nutrient content, microbial activity, and agricultural productivity. It enhances soil health, aids in pollutant reduction, and plays a vital role in lowering greenhouse gas emissions, thereby contributing to the mitigation of global climate change (Bolan et al., 2021; Lehmann et al., 2021). Additionally, biochar can improve the hydraulic properties of soil. Its water retention capacity, large surface area, and carbon-to-nitrogen ratio are key factors that support the survival and activity of beneficial inoculant microbes in the soil (Hale et al., 2015). Currently, a major carbon imbalance exists, with land ecosystems unable to absorb the 9.5 peta-grams of carbon added to the atmosphere annually (Peters et al., 2012). Biochar offers a solution by locking carbon in stable forms while improving soil fertility and ecosystem balance (Glaser et al., 2002). When combined with fertilizers, biochar enhances soil structure, nutrient retention, crop yields, and water-retention capacity (Graber et al., 2010; Uzoma et al., 2011). Its effects depend on feedstock type, soil conditions, and crops grown (Gaskin et al., 2010). Biochar has shown positive results in crops like wheat and grapevine (Castellini et al., 2015). However, more research is needed, especially on biochar from annual crop residues and its long-term role in rainfed agriculture in regions like India. The use of biochar is growing swiftly as a sustainable approach to boost agricultural productivity and enhance food security.

Biochar: definition, preparation and its properties

Biochar is a carbon-rich, porous substance produced by heating plant-derived biomass like wood, manure, or leaves through a process called pyrolysis. This thermal decomposition takes place at temperatures between 350 and 600 °C in an environment with little or no oxygen. (Amonette and Joseph, 2009). While biochar is high in carbon content, it is not composed of pure carbon; rather, it consists of a combination of elements such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) and varying amounts of ash (Bourke et al., 2007). Among the various production techniques, slow pyrolysis at temperatures up to 500 °C and hydrothermal carbonization are considered effective methods for generating large quantities of biochar (Malghani et al., 2013).

Properties

Biochar's properties depend on the feedstock type and pyrolysis method. Wood-based biochar has higher carbon but lower nitrogen than herbaceous types. Low-oxygen pyrolysis preserves carbon, creating stable, carbon-rich biochar ideal for long-term storage. Key characteristics (Table.1) include surface area, carbon concentration, and ash content, influencing its effectiveness and applications.

Physical properties

The physical properties of biochar are largely shaped by the decomposition of fibrous biomass during the pyrolysis process. These attributes, which have both direct and indirect impacts on soil performance, include specific surface area (SSA), density, porosity, pore size and volume, thermal and heat conductivity, water-holding capacity (WHC), hydrophobic nature, and ease of grinding.

Specific surface area (SSA)

Specific surface area (SSA) is crucial for biochar’s interaction with substances, affecting its catalytic properties and reactivity. SSA increases during pyrolysis as gases escape, forming pores. It directly influences water retention and cation exchange capacity. Techniques like metal enrichment and high-temperature or CO_2-assisted pyrolysis can further enhance SSA.

Table 1. Different properties of biochar and it’s key characteristics

Property	Description
Porosity	The pore size varies by material: nano (<0.9 nm), micro (<2 nm), meso (2–50 nm), macropores (>50 nm).
Carbon content	Biochar is >65% carbon; stability and composition depend on feedstock and pyrolysis conditions.
Structure	Major elements: C, H, O, N; form the main structure.
Surface area	Increases with pyrolysis temperature; large surface area, porosity, and pore volume are beneficial.
Surface functional groups	Contains groups like -OH, $-NH_2$, -OR, -COOR, $-CH_3$, $-NO_2$, -CHO, and -COOH.
Cation exchange capacity (CEC)	Low-temperature biochar has high CEC due to oxygenated functional groups that bind metal cations.
pH	pH typically >7.0 due to alkaline salts and metals (Na, K, Ca, Mg) and $CaCO_3$.
Non-organic content	Ash content includes non-organic elements like Mg, Ca, O, N, S, and K.

Bulk density and porosity

The bulk density and compression strength of biochar initially decline with rising pyrolysis temperature but may increase at higher levels. Gas release during carbonization forms pores, reducing mass per unit volume. While porosity changes do not affect true density (which excludes voids and pores), particle density accounts solely for the solid material and any enclosed, non-accessible pores.

Hydrophobicity and WHC

These are governed by the surface chemistry and porosity of the biochar. Higher pyrolysis temperatures reduce polar surface groups, increasing hydrophobicity. This hydrophobic nature can prevent water from entering pores, affecting the biochar's ability to retain water.

Pore volume and size distribution

Biochar typically contains both macropores and micropores, with micropores accounting for over 80% of total pore volume. Nitrogen gas sorption is used to determine pore volume. However, extremely small pores may limit gas access, restricting adsorption capacity for certain substances.

Thermal conductivity and heat capacity

Thermal conductivity is highest when heat moves along the grain. Porous structures formed during pyrolysis reduce conductivity. However, as pyrolysis temperature increases, thermal conductivities across all directions tend to equalize due to the breakdown of complex fibrous structures, making biochar an effective thermal insulator.

Grindability

Biochar becomes more brittle during pyrolysis, improving its grindability compared to raw biomass. The Hardgrove Grindability Index (HGI) is used to quantify this, with higher values indicating better grindability.

Chemical properties

Biochar's chemical parameters elemental composition, pH, reactivity, ignition risk, energy content, and degradation rate depend on storage conditions like temperature and time (Figure 2).

Functionality

Thermal decomposition of biomass during carbonization leads to the breakdown of structural components and the release of hydrogen and oxygen. This process reduces the presence of surface functional groups, especially at higher pyrolysis temperatures, resulting in biochar with lower hydrogen-to-carbon (H/C) ratios and more aromatic structures. As temperature increases, the acidic functional groups on the biochar surface decrease, leading to a shift in its chemical nature.

pH value

The pH of biochar varies depending on its production method. Chars from pyrolysis generally differ in alkalinity compared to those from hydrothermal carbonization. The pH tends to rise with increasing alkalinity and pyrolysis temperature. This alkaline nature makes biochar particularly valuable in agriculture as a soil conditioner. Temperature is a key factor influencing biochar's pH.

Reactivity

Biochar's reactivity is critical in thermochemical applications. Its reactivity involves gas–solid interactions such as $C + CO_2 \rightarrow 2CO$, $C + H_2O \rightarrow CO + H_2$, and $4C + 3O_2 \rightarrow 2CO + 2CO_2$. These reactions occur on the biochar surface, and their rates depend on temperature and gas concentration. The accessibility of internal surfaces to gas molecules also affects reaction speed. Inorganic components in biochar can further enhance reactivity by acting as catalysts.

Elemental composition and atomic ratios

Carbonization changes the chemical composition of biomass by removing functional groups rich in hydrogen and oxygen. As pyrolysis temperature rises, both H/C and O/C atomic ratios decline. This is because oxygen is released at nearly double the rate of hydrogen during carbonization. At high temperatures, biochar can contain over 95% carbon, Oxygen is 5%; hydrogen ranges 5–7%, often under 2%.

Cation exchange capacity (CEC)

CEC refers to the biochar's ability to retain and exchange essential nutrient cations (Mg^{2+}, Na^{+}, Ca^{2+}, K^{+}). This depends on negatively charged surface areas provided by functional groups. Biochar made at lower temperatures tend to have higher CEC because they retain more surface functional groups, which contribute to soil fertility through improved nutrient exchange at plant roots.

Biochar production technique

Figure 1 shows different biomass types used in biochar production. Converting agricultural and agro-industrial waste into biochar through pyrolysis—heating in low-oxygen conditions—is a cost-effective waste management method. Common feedstocks include dry, woody residues like straw and husks, which enhance soil fertility due to their high surface area and nutrient-holding ability. Unlike open burning, which causes significant carbon loss, pyrolysis retains more carbon and produces solid, liquid, and gaseous by-products. Biochar yield (BY) is determined by dividing biochar weight by the moisture-free feedstock weight. High-quality biochar has a calorific value of 30–33 MJ/kg and typically contains about 70% fixed carbon, 21–23% volatile matter, and 1–3% ash. Nutrient-rich algae are also effective biomass sources, and cyclones are used during processing to separate different output phases. Biofuels are categorized into four generations based on lignocellulosic composition.

Torrefaction

Torrefaction involves heating food waste at 200–300 °C without oxygen to enhance energy content and carbon density. Pre-treatment, either dry or wet, removes volatiles like moisture and CO_2. Dry torrefaction yields energy-rich material quickly, while wet methods produce low-ash, high-energy output. Food waste is oven-dried, ground, and stored airtight, with nitrogen purging oxygen before heating.

Pyrolysis

Pyrolysis is a thermal process that decomposes organic matter to yield carbon-rich products like biochar. Under subcritical water conditions, it becomes hydrothermal carbonization (HTC). Factors such as temperature (400–600 °C) and heating rate influence yield, with higher values reducing biochar output. Reactors like rotary kilns or paddle kilns boost efficiency. The process may be batch or continuous, with continuous systems being more efficient. Hemicelluloses and lignin convert into biochar, vapors, gases, and bio-oil. In Europe, C4 plants are commonly used as feedstock

Dry-pyrolysis

Dry pyrolysis involves heating dry, chemical-free biomass without oxygen, where temperature, pressure, and feedstock traits like particle size, ash content, and composition affect the yield and product quality.

Slow-Pyrolysis

Slow pyrolysis is a carbon-negative method that converts biomass into biochar with low CO_2 emissions, using slow heating (~5 °C/min) at 350–700 °C, it mainly breaks down cellulose and hemicellulose, using residues like rice husks or sawdust. The biomass is oven-dried at 105 °C to remove moisture, improving heat efficiency. Unlike hydrothermal carbonization or torrefaction, slow pyrolysis prioritizes biochar yield. It uses reactors like kilns or retorts and typically produces 30–35% biochar, 40–45% liquid, and 20–25% gas.

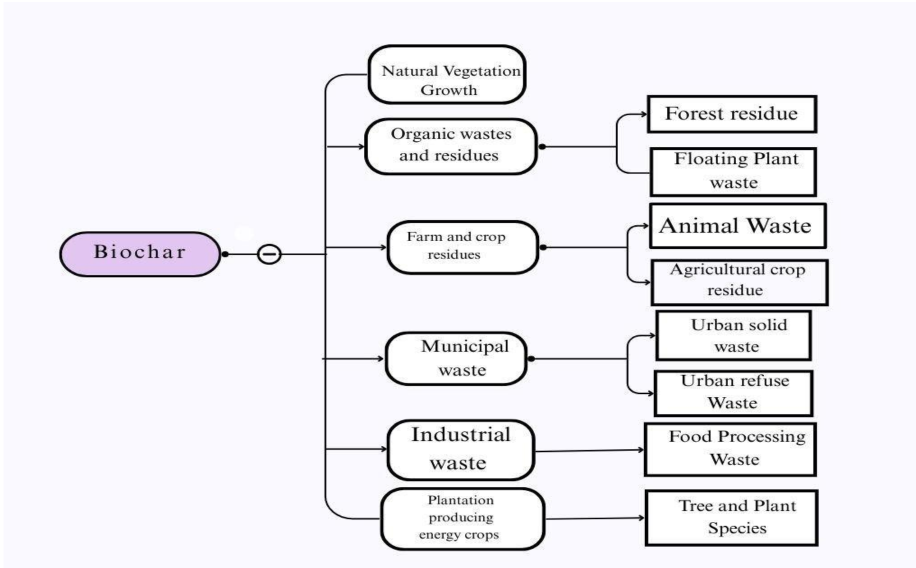


Figure 1. Categorization of different types of biomasses for biochar production (Adapted from Yadav et al., 2023)

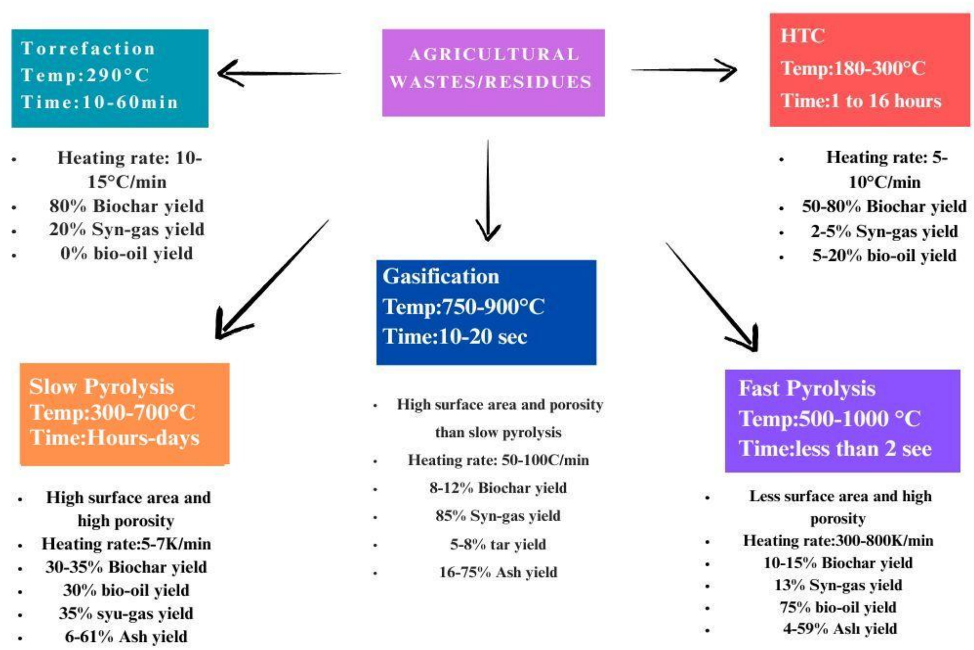


Figure 2. Biochar yield and properties vary with methods like fast/slow pyrolysis, torrefaction, HTC, and gasification. (Adapted from Yadav et al., 2023)

Fast-pyrolysis

Fast pyrolysis occurs at 800–1300 °C with a rapid heating rate (~200 °C/min) and short residence time (≤10 s), producing up to 75% bio-oil. Feedstocks include wood, grasses, and crop residues.

Hydrothermal carbonization (HTC) or Wet pyrolysis

Hydrothermal Carbonization (HTC) is a thermal method that transforms wet organic biomass into carbon-rich biochar using water under subcritical conditions (180–250 °C, 2–10 MPa). Originally developed by Friedrich Bergius and enhanced by Antonietti, HTC effectively decomposes lignin, cellulose, and hemicellulose at lower temperatures than dry pyrolysis. It suits wet feedstocks like algae and aquatic plants. Through dehydration, hydrolysis, polymerization, and decarboxylation, HTC produces biochar, liquids, and gases, including glucose and levulinic acid. It's cost-effective, energy-efficient, and ideal for small-scale applications.

Gasification

Gasification converts carbon-rich biomass into syngas (CO and H_2) at temperatures below 700 °C using limited air, oxygen, or steam. Biochar yield is about 10%, less than pyrolysis. Key factors include temperature, pressure, biomass-to-agent ratio, particle size, and residence time—temperature being most vital. Systems typically have two stages: gas generation and syngas purification. Auger reactors are often used for continuous biochar output.

Methods of biochar application

Biochar application methods can greatly influence soil dynamics, including how biochar behaves in the soil and its effects on environmental quality and soil degradation risks. However, there is limited research on the most effective application methods, as well as their implications for occupational health, safety, and cost. Generally, three primary application strategies exist: (i) topsoil incorporation, (ii) deep placement, and (iii) top-dressing. Topsoil incorporation involves applying biochar alone or mixed with organic materials like compost or manure. The level of integration into the soil depends on the cultivation approach. In traditional tillage systems, biochar and other amendments are usually evenly distributed within the top 15–30 cm of soil. Deep application, often referred to as "deep banding," targets the rhizosphere, potentially enhancing plant uptake and reducing erosion risk. This method can use pneumatic spreaders or involve placing biochar in furrows or trenches followed by surface levelling. Deep ploughing with a mould-board plough may also achieve similar results temporarily, although it creates a more continuous distribution. Top-dressing involves spreading biochar—mainly the finer particles—on the soil surface, relying on natural forces for integration. This technique is suitable for no-till farming, forests, or pastures where mechanical incorporation isn't feasible. However, it presents risks such as wind or water erosion, health hazards from dust inhalation, and potential effects on ecosystems like surface water and plant leaves. Additionally, how effectively biochar incorporates naturally varies by soil type, climate, and land use, and remains poorly understood.

Biochar application enhances soil properties

Adding biochar to agricultural soil improves (figure 3) its structure and enhances its physical, chemical, and biological properties, thereby boosting the soil's ability to retain nutrients. Among various techniques, biochar is particularly effective in adsorbing and removing heavy metals. It also helps eliminate toxic substances and organic pollutants from both soil and plants. Studies have shown that biochar can degrade or adsorb contaminants such as polychlorinated biphenyls, chlorobenzene, p-nitrophenol, PAHs, diethyl phthalate, and 2-chlorobiphenyl. Moreover, biochar enhances water retention, filtration, and moisture availability in soil, promoting-overall-soil-health.

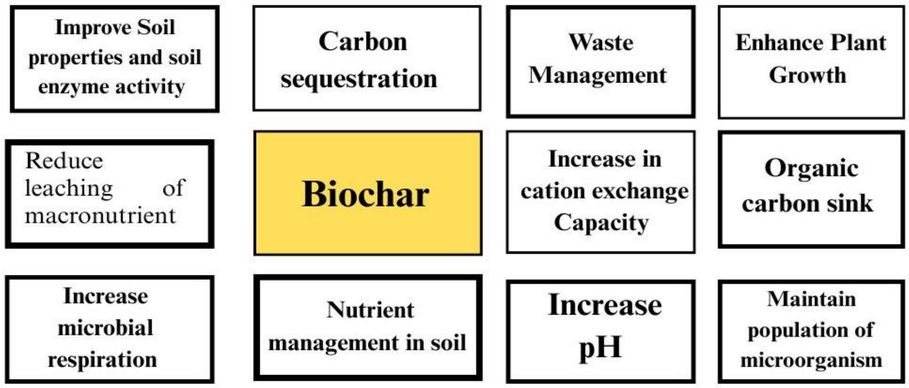


Figure 3. Advantages of adding biochar to soils with poor physicochemical characteristics (Adapted from Yadav et.al., 2023).

Impacts of biochar application on physical properties of soil

Applying biochar at 5 tons per hectare resulted in the highest soil moisture (figure 4) content of 11.2% at a 35 cm depth. Below this depth, moisture levels declined but remained higher than in untreated soil. In sandy loam soils, biochar's porous structure and large surface area improved rainwater infiltration and reduced runoff, particularly in Alfisols. Obia et al. (2016) found (figure 5) that in coarse-textured soils, biochar improved aggregate stability by 7–20% per percent added over two seasons. It also increased total porosity and available water capacity by 2% and 3%, while reducing bulk density by 3–5%. Similar benefits were observed in sandy loam, enhancing water retention and overall soil physical properties.

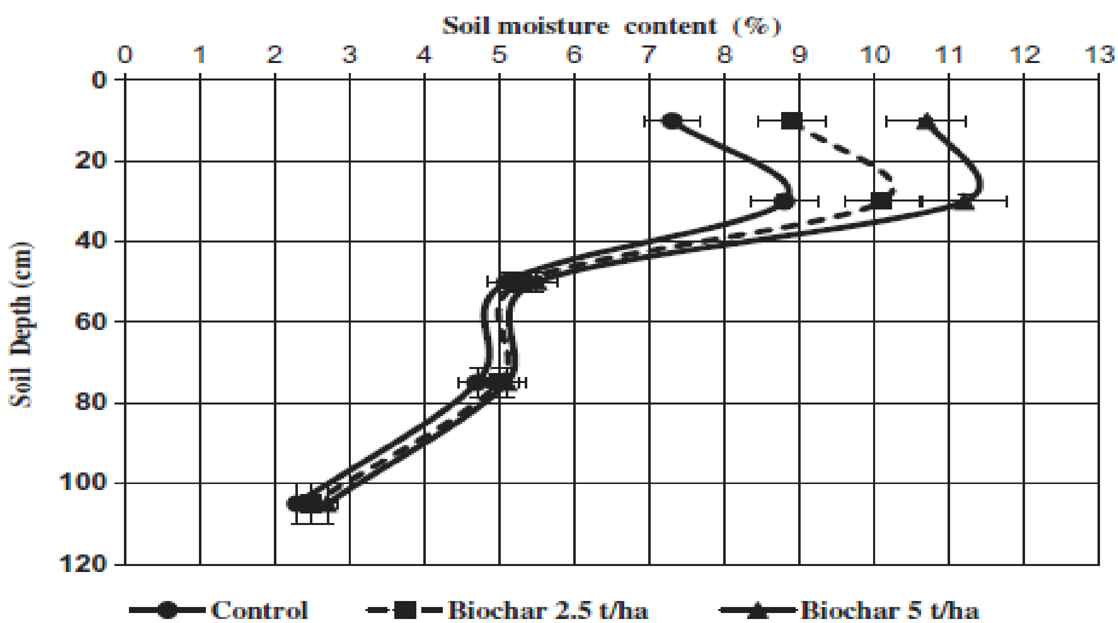


Figure 4. Impact of biochar application on soil water content variations in the soil profile of Alfisol under rainfed conditions (Adapted from Pandian et al., 2016).

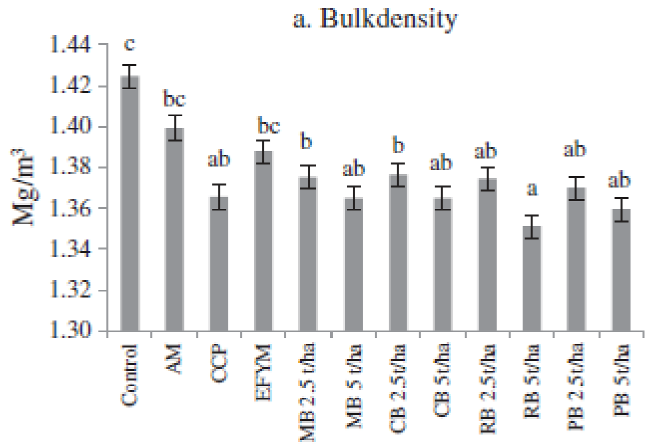


Figure 5. Impact of different biochars, application rates, and organic inputs on (a) bulk density

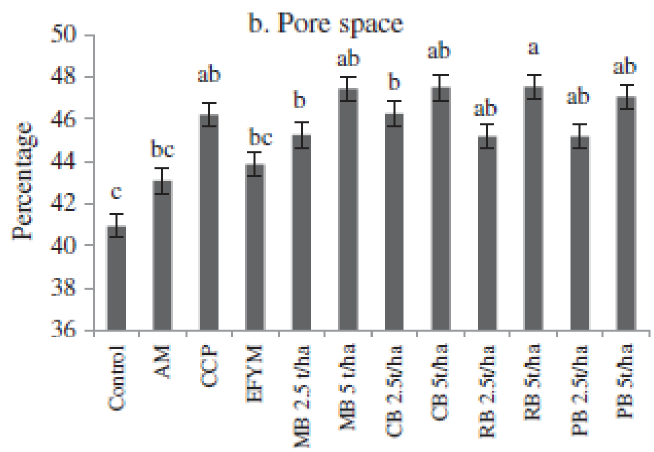


Figure 5. Impact of different biochars, application rates, and organic inputs on (b) pore space in rainfed Alfisol. Distinct lowercase letters indicate significant differences (P < 0.05); error bars show standard error (Adapted from Pandian et al., 2016).

Effect of biochar application on chemical properties of soil

The biochar's application significantly influenced soil pH, electrical conductivity (EC), and nutrient availability (Table.3). The highest soil pH (6.33) and EC (0.42 dS m^{-1}) were recorded with peanut biochar (PB) at 5 t/ha, followed by cotton stalk biochar (CSB). Biochar raised soil pH by 0.5–0.6 units in acidic red soils due to its naturally alkaline nature (pH 8.4–10.8), improving nutrient availability and boosting groundnut yields. While soil EC increased slightly, it remained within safe limits for crops due to the initially low EC levels. Nitrogen availability improved notably with maize stalk biochar (MSB) and red gram stalk biochar (RSB) at 5 t ha^{-1}, showing a 25% increase over control. This improvement stemmed from enhanced moisture retention, root growth, and nitrogen content in the biochar itself. Its ammonia adsorption ability also reduced nitrogen losses. Furthermore, nitrate retention improved, lowering the risk of nutrient leaching.

Phosphorus levels were highest in MSB- and RSB-treated soils due to biochar's efficient phosphorus adsorption–desorption behaviour. Potassium availability increased with RSB and CSB due to potassium-rich ash content. The highest cation exchange capacity (CEC) of 6.5 $cmol^{+}\ kg^{-1}$ was found in soils treated with coconut coir pith (CCP) at 10 t ha^{-1} and RSB at t ha^{-1}. Biochar also raised base saturation to 69%, a 9.5% increase over control. These benefits are largely attributed to biochar's porous structure and active functional groups like hydroxyl and carboxyl, which enhance soil nutrient dynamics and overall fertility.

Effect of biochar application on soil organic matter content

Application of biochar at two different rates significantly improved soil organic carbon (OC) in Alfisol after three years (Table.4). While the control plot had an OC of 3.6 g kg^{-1}, treated plots varies from 4.4 to 4.8 g kg^{-1}, with the highest values in maize stalk biochar (MSB) and red gram stalk biochar (RSB) at 5 t ha^{-1}. This increase is due to biochar's stable, carbon-rich nature. Higher doses also raised water-soluble carbon (WSC) and biomass carbon (BMC), with MSB at 5 t ha^{-1} recording the highest WSC (56 mg kg^{-1}) and BMC (321 mg kg^{-1}), compared to 30 mg $kg^{-1}$and 225 mg kg^{-1}in the control. At 0.3 m depth, carbon stock reached 21.4 t ha^{-1}in RSB plots, versus 16.2 t ha^{-1} in controls. Overall, biochar improved OC, WSC by 73%, and BMC by 37%, supported by microbial activity and root exudates.

Effect of biochar application on soil microbial biomass carbon and nitrogen

A significant difference in MBC and MBN was observed (Table.2) only between the B8 treatment and the control. The application of 8% biochar showed in a 10.8% enhances in MBC compared to the control value of 75.1 mg kg^{-1}, while MBN showed a 7.5% rise relative to the control value of 8.2 mg kg^{-1}.

Table 2. Soil physicochemical parameters, microbial biomass and nitrogen under different biochar treatments (Adapted from Xu et al., 2016)

Parameters	**Control (0 t ha^{-1})**	**Biochar (40 t ha^{-1})**	**Biochar (80 t ha^{-1})**	**Biochar (160 t ha^{-1})**
pH	7.84 ± 0.18^{c}	8.17 ± 0.20^{b}	8.21 ± 0.14^{a}	8.25 ± 0.12^{a}
Microbial biomass carbon (mg kg^{-1})	75.12 ± 4.63^{b}	79.45 ± 4.27^{ab}	75.31 ± 4.21^{b}	83.27 ± 5.01^{a}
Microbial biomass nitrogen (mg kg^{-1})	8.24 ± 0.31^{b}	8.56 ± 0.50^{ab}	8.59 ± 0.42^{ab}	8.86 ± 0.30^{a}
Soil basal respiration (mg CO_2 $kg^{-1}\ d^{-1}$)	70.68 ± 5.23^{b}	89.19 ± 5.76^{a}	96.86 ± 6.31^{a}	94.53 ± 5.89^{a}
Substrate induced respiration (mg $CO_2\ kg^{-1}\ d^{-1}$)	152.95 ± 12.81^{c}	186.41 ± 10.35^{b}	214.58 ± 10.41^{a}	189.51 ± 9.58^{b}
Soil metabolic quotient (d^{-1})	0.94 ± 0.04^{b}	1.12 ± 0.11^{a}	1.29 ± 0.12^{a}	1.14 ± 0.03^{a}
Net N mineralization (mg $kg^{-1}\ d^{-1}$)	1.28 ± 0.19^{c}	1.80 ± 0.19^{a}	1.72 ± 0.15^{a}	1.51 ± 0.12^{b}

Distinct lowercase letters indicate significant differences ($P < 0.05$)

Table 3. Effect of various types of biochar's rate of application, and organics on soil pH, EC, CEC, and nutrients availability (3-year average) (Adapted from Pandian et al., 2016)

Treatment details	EC (dS m^{-1})	pH	Av. N (kg ha^{-1})	Av. P (kg ha^{-1})	Av. K (kg ha^{-1})	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	CEC ($cmol^{+}$ kg^{-1})	BS (%)
Control	0.22^{d}	5.72^{b}	158^{c}	23^{c}	179^{c}	0.02	0.01	2.5	1.0	5.6^{b}	63^{c}

Arbuscular mycorrhizae (AM) 100 kg ha^{-1}	0.26^{c}	5.79^{b}	162b^{c}	30^{ab}	191^{ab}	0.03	0.01	2.8	1.0	5.8^{b}	66^{b}
Composted coir pith (CCP) 10 t ha^{-1}	0.26^{c}	6.23^{ab}	179^{a}	28^{ab}	198^{a}	0.03	0.01	3.1	1.3	6.5^{a}	68^{ab}
Enriched FYM (EFYM) 0.75 t ha^{-1}	0.26^{c}	5.99^{ab}	168^{b}	26^{b}	188^{b}	0.03	0.01	3.0	1.0	6.0^{ab}	67^{ab}
Maize stalk biochar (MB) 2.5 t ha^{-1}	0.35^{b}	6.08^{ab}	166^{b}	28^{ab}	191^{ab}	0.03	0.01	2.5	1.3	6.0^{ab}	67^{ab}
Maize stalk biochar (MB) 5 t ha^{-1}	0.42^{a}	6.31^{ab}	172^{ab}	32^{a}	195^{ab}	0.03	0.02	3.0	1.5	6.4^{ab}	69^{a}
Cotton stalk biochar (CB) 2.5 t ha^{-1}	0.29^{c}	6.14^{ab}	168^{b}	25^{b}	190^{ab}	0.03	0.01	3.0	1.0	6.0^{ab}	67^{ab}
Cotton stalk biochar (CB) 5 t ha^{-1}	0.35^{b}	6.30^{ab}	174^{ab}	29^{ab}	196^{ab}	0.04	0.02	2.8	1.5	6.4^{ab}	69^{a}
Red gram stalk (RB) biochar 2.5 t ha^{-1}	0.32^{b}	6.19^{ab}	166^{b}	28^{ab}	192^{ab}	0.03	0.02	2.8	1.2	6.0^{ab}	67^{ab}
Red gram stalk (RB) biochar 5 t ha^{-1}	0.41^{ab}	6.28^{ab}	178^{a}	31^{a}	197^{a}	0.03	0.01	3.0	1.5	6.5^{a}	69^{a}
Prosopis biochar (PB) 2.5 t ha^{-1}	0.30^{b}	6.23^{ab}	160^{c}	26^{b}	188^{b}	0.03	0.01	2.5	1.6	6.1^{ab}	67^{ab}
Prosopis biochar (PB) 5 t ha^{-1}	0.42^{a}	6.33^{a}	168^{b}	27^{b}	193^{ab}	0.03	0.01	2.8	1.6	6.4^{ab}	69^{a}
S.Em. ±	0.02	0.1	3	1.5	3	0.002	0.001	0.1	0.1	0.2	1.1
C.D. ($P < 0.05$)	0.06	0.4	8	4.3	9	0.004	0.002	0.4	0.2	0.5	3.1

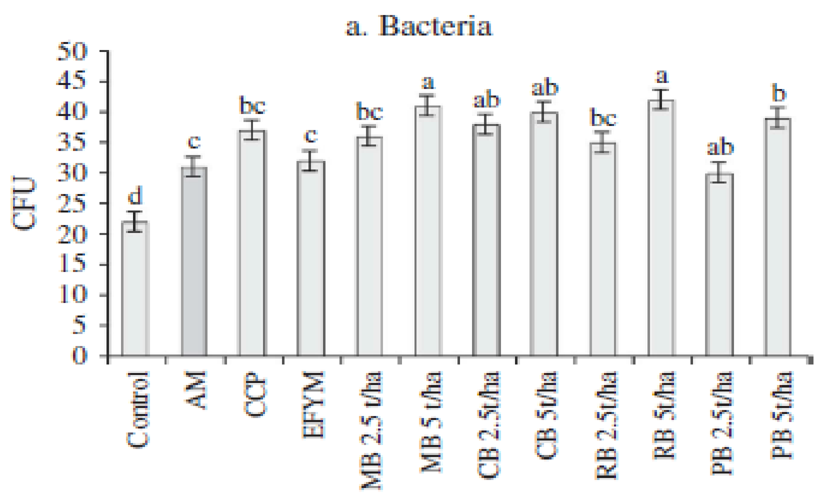
EC-electrical conductivity; CEC-cation exchange capacity; BS-base saturation, S.Em.-standard errors mean; C.D-critical Difference, Av.- Available, Ex.- Exchangeable. Distinct lowercase letters indicate significant differences ($P < 0.05$)

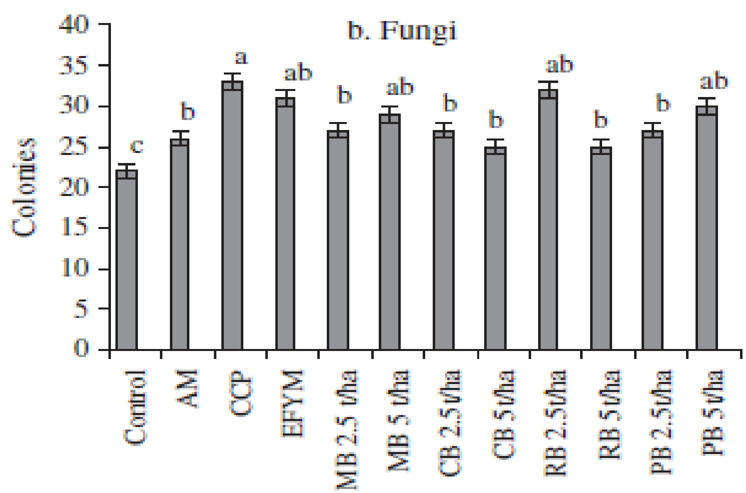
Microbial population

Detailed analysis of soil microbial data showed that biochar application significantly influenced microbial populations over time (Figure 7). The highest bacterial count was recorded in RSB at 5 t/ha (42×10^6 CFU), followed by MSB at 2.5 t/ha (41×10^6 CFU). For fungi, the peak population (33×10^3 CFU) was found in CCP at 10 t/ha and RSB at 2.5 t/ha. Actinomycetes were most abundant in CSB at 5 t/ha (30×10^4 CFU). This enhancement in microbial load is attributed to biochar's surface compounds, such as sugars and aldehydes, formed during pyrolysis (Painter 2001; Rillig et al., 2011). Additionally, biochar's porous structure offers shelter for microbes, while improved moisture, aeration, and aggregation further promote microbial activity.

Soil enzymatic activities

On the 90th day of incubation, the activities of 11 soil enzymes associated with carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) cycling were analyzed (Figure 8). β-glucosidase and β-cellobiosidase activities were significantly elevated in both CK and U + 0.5% MC treatments, with no notable difference between them ($P > 0.05$). β-xylosidase and α-glucosidase activities peaked in CK soils compared to urea-treated variants. Most C-cycling enzymes, except β-xylosidase, and sulfatase initially increased at low MC levels (0.5%) but declined at higher doses, suggesting excessive MC suppresses enzyme function. N-acetyl-glucosaminidase, peroxidase, and phenol oxidase showed similar reductions. In contrast, L-leucine aminopeptidase and urease increased with more MC, indicating enhanced N-related enzyme activity. Phosphatase was highest in CK and decreased with higher MC additions under urea treatments.





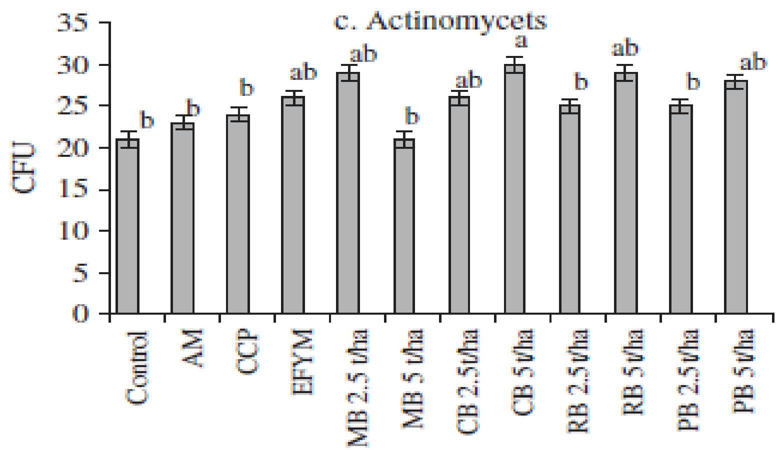


Figure 7. Impact of biochar's rate of application and organics on a) soil bacteria, b) soil fungi c) and soil actinomycetes culturable microbial population in Alfisol under rainfed climatic condition. (ref. Pandian et al., **2016)**

Table 4. Impact of various biochar's rate of application, and organics on soil organic carbon fractions in Alfisol (3-year average) (Adapted from Pandian et al., 2016)

Treatment details	**Rate of application (t ha^{-1})**	**Water soluble carbon (mg kg^{-1})**	**Biomass carbon (mg kg^{-1})**	**Organic carbon (g kg^{-1})**	**Carbon stock (t ha^{-1})**
Control	–	30^{e}	225^{e}	3.6^{e}	16.2^{e}
Arbuscular mycorrhiza (AM)	0.10	34^{d}	280^{c}	3.9^{d}	17.4^{d}
Composted coir pith (CCP)	10.0	44^{bc}	305^{ab}	4.5^{b}	19.8^{b}
Enriched farmyard manure (EFYM)	0.75	36^{d}	253^{d}	4.0^{d}	17.9^{c}
Maize stalk biochar (MB)	2.5	41^{c}	292^{b}	4.4^{b}	19.9^{b}
Maize stalk biochar (MB)	5.0	56^{a}	321^{a}	4.8^{a}	21.1^{ab}
Cotton stalk biochar (CB)	2.5	41^{c}	293^{b}	4.4^{b}	19.6^{b}
Cotton stalk biochar (CB)	5.0	51^{ab}	313^{a}	4.7^{ab}	20.7^{ab}
Red gram stalk biochar (RB)	2.5	43^{bc}	292^{b}	4.4^{b}	19.8^{b}
Red gram stalk biochar (RB)	5.0	54^{ab}	311^{ab}	4.8^{a}	21.4^{a}
Prosopis biochar (PB)	2.5	42^{c}	265^{c}	4.3^{c}	19.4^{b}
Prosopis biochar (PB)	5.0	48^{b}	291^{b}	4.6^{ab}	20.7^{ab}
S. Em.±		2	7	0.1	0.2
C.D. ($p < 0.05$)		5	20	0.2	0.7

Distinct lowercase letters indicate significant differences ($P < 0.05$)

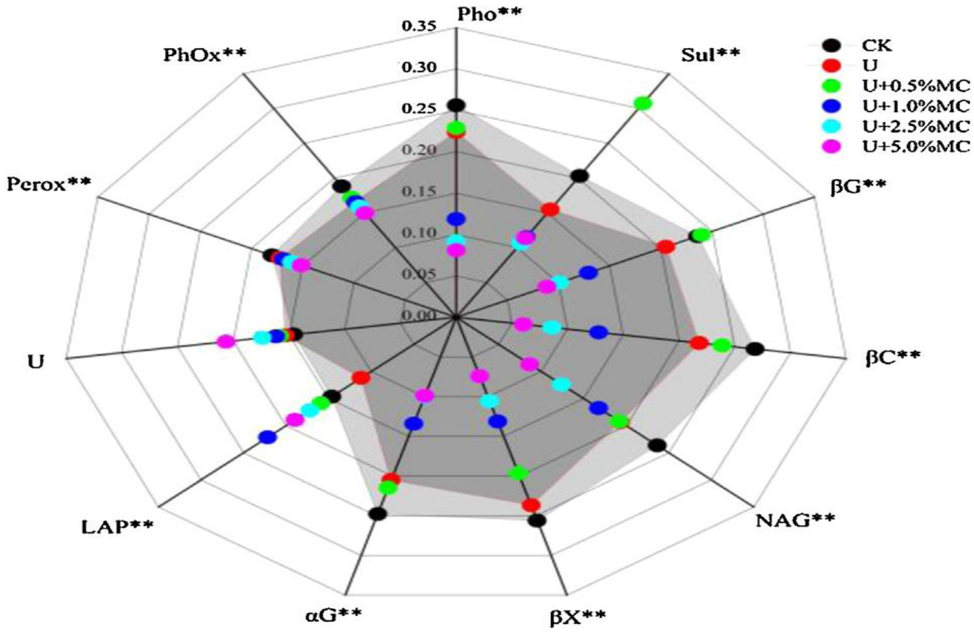


Figure 8. Radar chart showing normalized enzyme activity responses to biochar and urea applications.

Asterisks denote significant treatment differences (Fisher's LSD: *$P < 0.05$, **$P < 0.01$). CK-Control, U-Urea, MC- Maize Biochar. Enzyme abbreviations: Pho-phosphomonoesterase; Sul-sulfatase; βG-β -glucosidase; βC-β -cellobiosidase; NAG, N-acetyl glucosaminidase; PhOx-phenol oxidase βX-β-xylosidase; LAP-L-leucine aminopeptidase; Perox- peroxidase, U-urease; and αG-α-glucosidase

Effect of biochar application on soil fertility

Biochar application improves soil fertility by enhancing its physical, chemical, and biological properties. In saline soils, it helps plants absorb water and nutrients by reducing salinity and improving ion exchange. Biochar adsorbs excess sodium, allowing beneficial calcium and magnesium to replace it, thus lowering soil alkalinity. It also serves as a nutrient source, improves nutrient retention, and supports nutrient cycling. Rich in essential elements, biochar minimizes nitrogen loss and holds nutrients like potassium, nitrogen, phosphorus, and organic matter. Specifically, BC200 biochar increases inorganic nitrogen and enhances iron, copper, and zinc availability in calcareous soils.

Remediation of heavy metals toxicity in soil

Soil contamination from industrial, household, and chemical activities has become a major global concern, often disrupting essential microbial functions. One effective and eco-friendly method for soil remediation is the use of biochar, which is derived from organic waste materials (Table 2). Its affordability and sustainability make it suitable for restoring polluted soils. With its large surface area, high porosity, and strong water retention, biochar helps reduce soil pollutants. Numerous studies have shown its effectiveness in immobilizing heavy metals and metalloids. For example, biochar produced from *Carya* species effectively adsorbs and limits the leaching of herbicides like sodium bis-pyribac and clomazone.

Effect of biochar application on climate change mitigation

Global warming, mainly caused by increasing greenhouse gas emissions, is a key environmental issue. The carbon cycle is crucial in both its cause and potential solution. Biochar, due to its stable physical and chemical characteristics, offers promising environmental benefits. It can bind transition metals, serving as a catalyst in contaminant breakdown. Converting organic waste into biochar reduces methane emissions from landfills and energy sectors, aiding climate change mitigation. Producing 0.49 Gt C of biochar annually could remove the same amount of carbon from the atmosphere, requiring 2.2 Gt C of biomass. Biochar or pyrolyzed animal manure also helps reduce phosphate and nitrate leaching, limiting nutrient runoff in agriculture. Its resistance to decomposition results in less carbon dioxide release than untreated organic matter, making it an effective tool for long-term carbon storage. By adhering to soil particles, biochar prevents CO_2 loss, contributing to carbon sequestration and GHG emission reduction.

Carbon sequestration

Biochar was originally proposed as a soil amendment to promote carbon sequestration, as it contains a stable form of carbon that can persist in soils over time. This stability makes biochar a promising option for reducing greenhouse gas emissions through long-term carbon storage. When used with proper waste management strategies, biochar can preserve organic carbon that would otherwise decompose or be incinerated, offering a sustainable alternative to traditional disposal methods. Additionally, biochar composites have shown potential to enhance carbon retention and stability compared to unmodified biochar. Producing biochar from agricultural and food industry residues not only supports effective carbon storage but also improves soil health and contributes to environmental sustainability.

Mitigate greenhouse gas emissions

Global application of biochar is projected to reduce greenhouse gas (GHG) emissions by up to 12%. Recent studies indicate that incorporating biochar composites into soil, rather than using raw biochar alone, can improve climate change mitigation in two main ways. First, combining biochar with compost increases stable carbon input and produces a nutrient-rich, eco-friendly product that overcomes the low macronutrient levels and methane emissions linked to traditional pyrolysis biochar. Second, biochar improves soil organic matter and lowers emissions of potent GHGs like methane (CH_4) and nitrous oxide (N_2O). For biochar systems to be more climate-friendly than simply using it as fuel, they must enhance plant growth or cut soil GHG emissions. Additionally, in rice fields, biochar helps reduce methane release by encouraging methanotrophic bacteria that consume methane and limiting methane-producing methanogens, further supporting its effectiveness in emission reduction strategies.

Constraints

When incorporated into soils, biochar can interact with agrochemicals such as herbicides, pesticides, and soil nutrients by adsorbing or deactivating them, sometimes reducing their effectiveness for targeted weed or pest control and nutrient availability. Certain biochars have demonstrated the ability to slow methane oxidation and mitigate nitrous oxide (N_2O) emissions, contributing to greenhouse gas reduction. However, some biochars may contain phytotoxic compounds, including volatile organic compounds (VOCs), phenolics, or polyaromatic residues, which can hinder seed germination and early seedling growth. From a physicochemical perspective, although biochar improves overall soil porosity and water-holding capacity, it can disrupt pore continuity, affect hydraulic conductivity, and, in some cases, increase soil bulk density. Excessive application rates may elevate soil electrical conductivity (EC) and pH, potentially causing osmotic stress, nutrient imbalances, and shifts in soil microbial activity. Its fragile, dusty nature leads to handling and application difficulties, as fine particles are easily lost to wind erosion or washed away by rain before incorporation. Once integrated into soil, biochar's recalcitrant carbon structure ensures long-term persistence, making remediation of adverse effects difficult. Certain biochars may also leach or release toxic substances such as heavy metals (Cd, Pb, As, Zn) and polycyclic aromatic hydrocarbons (PAHs), especially if derived from contaminated or improperly processed feedstocks. Additionally, not all agricultural or forestry residues are suitable for biochar production some generate biochars with poor nutrient retention capacity or rapid decomposition, limiting their effectiveness. Environmental risks include potential alteration of native soil microbial communities, unintentional impacts on soil fauna, and off-site transport of biochar particles that could affect aquatic ecosystems.

Socioeconomic barriers further limit its widespread adoption: high production and transportation costs, labour-intensive application, need for specialized spreading equipment, and lack of farmer awareness of appropriate application methods and dosages. Market uncertainties, absence of standardized quality control protocols, policy gaps, and limited financial incentives also constrain biochar use on a larger scale. Therefore, site-specific evaluation of feedstock type, pyrolysis conditions, and application rates is crucial to maximize benefits while minimizing adverse impacts.

Research gaps and future prospects

To advance biochar use as a soil enhancer and a climate mitigation strategy, focused efforts on research, development, and demonstration are essential. There is a need to create cost-effective biochar kilns that small and marginal farmers can afford. ICAR-Central Research Institute on Dryland Agriculture (CRIDA) has developed a portable, farmer-friendly kiln for converting castor, cotton, and pigeon pea stalks into biochar. However, current designs lack mechanisms for capturing emissions during production. Modifications are underway to integrate systems that can reduce gas emissions. Additionally, studies indicate the potential of carbon-rich biochar for sustainable enhancement of soil health and productivity, especially in rainfed systems. Moving forward, interdisciplinary and location-specific long-term research is necessary to assess biochar's residual effects on different soil types, nutrient dynamics, microbial activity, carbon storage potential, crop yields, and greenhouse gas reduction.

Conclusion

India faces a growing challenge in managing large volumes of unused and excess crop and agroforestry residues due to inefficient residue management practices. Of the 523 million tonnes of crop residues generated annually, around 127 million tonnes remain unutilized or underutilized due to various limitations. While direct incorporation of these residues into soil can help conserve organic carbon and nutrients, it also poses crop management issues due to slow decomposition. Converting surplus crop residues into biochar through slow pyrolysis is emerging as an effective and economical alternative. Biochar not only offers a sustainable solution for residue disposal but also enhances soil quality, sequesters carbon, reduces agricultural waste, and increases crop productivity. Global research, including in India, confirms the positive impact of biochar on improving soil health and reducing greenhouse gas emissions. Early findings suggest that using biochar as a soil amendment can significantly improve soil fertility and agricultural yields.

References

Beyer, L., Wachendorf, C., Elsner, D. C., & Knabe, R. (1993). Suitability of dehydrogenase activity assay as an index of soil biological activity. *Biology and Fertility of Soils*, *16*(1), 52-56.

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., & Van Zwieten, L. (2022). Multifunctional applications of biochar beyond carbon storage. *International Materials Reviews*, *67*(2), 150-200.

Bourke, J. (2007). *Preparation and properties of natural, demineralized, pure, and doped carbons from biomass; Model of the chemical structure of carbonized charcoal* (Doctoral dissertation, The University of Waikato).

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., & Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*, *154*, 1-13.

El–Metwally, I., Geries, L., & Saudy, H. (2022). Interactive effect of soil mulching and irrigation regime on yield, irrigation water use efficiency and weeds of trickle–irrigated onion. *Archives of Agronomy and Soil Science*, *68*(8), 1103-1116.

Gaskin, J. W., Speir, R. A., Harris, K., Das, K. C., Lee, R. D., Morris, L. A., & Fisher, D. S. (2010). Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. *Agronomy Journal*, *102*(2), 623-633.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. *Biology and Fertility of Soils*, *35*(4), 219-230.

Graber ER, Meller Harel Y, Kolton M, Cytryn E, Silber A, Rav David D, Tsechansky L, Borenshtein M, & Elad Y. (2010). Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil*, *337*(1), 481–496.

Hale, L., Luth, M., & Crowley, D. (2015). Biochar characteristics relate to its utility as an alternative soil inoculum carrier to peat and vermiculite. *Soil Biology and Biochemistry, 81*, 228-235.

Lehmann, J., & Rondon, M. (2006). Bio-char soil management on highly weathered soils in the humid tropics. *Biological Approaches to Sustainable Soil Systems*, *113*(517), e530.

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, *14*(12), 883-892.

Lehmann, J., Pereira da Silva Jr, J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, *249*(2), 343-357.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil Biology and Biochemistry*, *43*(9), 1812-1836.

Malghani, S., Gleixner, G., & Trumbore, S. E. (2013). Chars produced by slow pyrolysis and hydrothermal carbonization vary in carbon sequestration potential and greenhouse gases emissions. *Soil Biology and Biochemistry*, *62*, 137-146.

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., & Børresen, T. (2016). In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research*, *155*, 35-44.

Painter, T. J. (2001). Carbohydrate polymers in food preservation: an integrated view of the Maillard reaction with special reference to the discoveries of preserved foods in Sphagnum dominated peat bogs. *Carbohydrate Polymers*, *36*, 335–347.

Pandian, K., Subramaniayan, P., Gnasekaran, P., & Chitraputhirapillai, S. (2016). Effect of biochar amendment on soil physical, chemical and biological properties and groundnut yield in rainfed Alfisol of semi-arid tropics. *Archives of Agronomy and Soil Science*, *62*(9), 1293-1310.

Peters, G. P., Davis, S. J., & Andrew, R. (2012). A synthesis of carbon in international trade. *Biogeosciences*, *9*(8), 3247-3276.

Properties, M., Amonette, J. E., & Joseph, S. (2009). Characteristics of Biochar. *Biochar for Environmental Management: Science and Technology*, *33*.

Salem, E. M., Kenawey, K. M., Saudy, H. S., & Mubarak, M. (2021). Soil mulching and deficit irrigation effect on sustainability of nutrients availability and uptake, and productivity of maize grown in calcareous soils. *Communications in Soil Science and Plant Analysis*, *52*(15), 1745-1761.

Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A. K., & Kundu, S. (2013). Sustainable management of soils of dryland ecosystems for enhancing agronomic productivity and sequestering carbon. *Advances in Agronomy*, *121*, 254–329.

Ulusal, A., Apaydın Varol, E., Bruckman, V. J., & Uzun, B. B. (2021). Opportunity for sustainable biomass valorization to produce biochar for improving soil characteristics. *Biomass Conversion and Biorefinery*, *11*(3), 1041-1051.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and Management*, *27*, 205–212.

Wang, X., Song, D., Liang, G., Zhang, Q., Ai, C., & Zhou, W. (2015). Maize biochar addition rate influences soil enzyme activity and microbial community composition in a fluvo-aquic soil. *Applied Soil Ecology*, *96*, 265-272.

Xu, N., Tan, G., Wang, H., & Gai, X. (2016). Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *European Journal of Soil Biology*, *74*, 1-8.

Yadav, S. P. S., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., ... & Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, 100498.