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REVIEW ARTICLE

From char to harvest: unveiling biochar's impact on soil health and crop productivity

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Abstract

Biochar is a stable carbon-rich by-product through pyrolysis of biomass under limited oxygen conditions. It has emerged as a sustainable strategy for enhancing soil health and agricultural productivity. This review synthesized recent research both on the positive and negative impacts of biochar application across different soil types and cropping systems, with particular focus on its relevance to India's agrarian economy. Biochar has been shown to improve soil physical properties such as bulk density, porosity, water retention and aggregate stability. Chemically, it enhances nutrient retention by increasing cation exchange capacity, soil pH and organic carbon content. Biologically, biochar supported microbial abundance, enzyme activities and biomass carbon, especially in nutrient-deficient or acidic soils. Consequently, numerous studies reported increased crop yields, particularly in degraded or low-fertility soils. However, adverse outcomes were also observed including nutrient immobilization, increased salinity and microbial shifts that suppress plant growth often linked to excessive dosages, incompatible soil types or unsuitable biochar characteristics. Additionally, biochar's role in long-term carbon sequestration and greenhouse gas mitigation including reductions in N_2O and CH_4 emissions was explored. While findings highlighted biochar's multifaceted potential, variability in its performance underscored the need for site-specific applications and standardized protocols. The review concluded by identifying critical research gaps and providing direction for optimizing biochar use in sustainable agriculture and climate-resilient farming systems.

Keywords: biochar; carbon sequestration; crop yield; greenhouse gas mitigation; soil health

Introduction

Around 70 % of India's population was employed in the agricultural sector. The challenge lay in adopting agricultural practices that do not deplete natural resources. India, as an agrarian country, faced the pressing need for intensive agriculture to meet the demands of its growing population (1, 2). Intensive agriculture produced more than 5 billion metric tons of agricultural residues annually worldwide (3-6). India alone generated approximately 683 million tonnes crop residues annually, with a substantial portion being underutilized or burned (3, 6). *In-situ* burning of agricultural waste led to environmental pollution, loss of biodiversity and undermining the soil's ability (7, 8). Studies indicated that greenhouse gas (GHG) emissions from open field burning increased up to 75 % between 2011 and 2020, with total CO_2-equivalent emissions rising from approximately 19340 Gg/ year to 33834 Gg/ year, thereby significantly contributing to global warming (9). From a soil health perspective, elevated temperatures caused by open burning can led to the destruction of beneficial soil microorganisms up to a depth of 70 mm (10). High temperatures caused complete sterilization of the topsoil, affecting fungi more than bacteria. This loss of microbial diversity can disturbed soil properties and essential soil functions (11).

Biochar, a carbon-rich material produced through pyrolysis of agricultural residues in an oxygen-limited environment, presented a promising solution to this multifaceted problem (12). Converting crop residues into biochar not only prevented the environmental hazards associated with open burning but also created a valuable soil amendment that enhanced soil fertility, carbon sequestration and overall agricultural productivity (13). The potential of biochar to simultaneously addressed waste management issues, mitigated GHG emissions, improved soil health and enhanced agricultural sustainability made it particularly relevant for India's predominantly agrarian economy. The Green Revolution significantly increased crop yields, but there was a need for an "evergreen revolution" to sustain productivity without harming the environment. This review focused on the positive and negative impacts of biochar on soil health, crop productivity and carbon sequestration and the reduction of greenhouse gas emissions.

Biochar and its properties

Biochar was a carbon-rich, porous material derived from the thermal decomposition of organic biomass under limited oxygen conditions. It was increasingly recognized as a sustainable solution for managing agricultural and organic waste, restoring degraded soils, improving crop productivity and mitigating climate change. When applied to soil, biochar enhanced water retention, nutrient availability, microbial activity and soil structure, leading to increased crop yields and reduced dependence on synthetic fertilizers (14). In addition to its agricultural benefits, biochar served as a long-term carbon sink. Recent studies indicate that global adoption of biochar could sequester between 0.7 and 1.8 gigatons of CO_2-equivalent annually, while reducing greenhouse gas emissions-particularly nitrous oxide from soils-by up to 50 % (15). These multifunctional benefits positioned biochar as a promising tool for achieving circular bioeconomy goals and climate resilience in agriculture. Biochar could be produced through several thermochemical processes, including slow and fast pyrolysis, hydrothermal carbonization (HTC), microwave-assisted pyrolysis and gasification. Slow pyrolysis, typically performed at 350–500 °C with long residence times, was the most common method for producing biochar with high carbon content and stability. Fast pyrolysis, operating at higher temperatures and faster heating rates, favoured the production of bio-oil over biochar (16). Hydrothermal carbonization (HTC) was a process that treated wet biomass at moderate temperature and pressure, so drying was not required. It produced hydrochar, which was similar to biochar, but had different properties. More recently, microwave-assisted pyrolysis emerged as an efficient and energy-saving method that produced biochar with high surface area and enhanced porosity, making it suitable for environmental remediation applications (17). The choice of production method significantly affected the yield, structure and functional performance of the resulting biochar. Understanding the physicochemical properties of biochar was essential for optimizing its performance in specific applications such as soil improvement, pollutant adsorption and construction. Modern analytical techniques were used to evaluate its chemical composition, surface characteristics and structural features. Elemental (CHNS) and proximate analyses helped determine carbon content, ash and volatile matter, which were indicators of biochar stability and reactivity (18). Spectroscopic tools such as Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy were used to identify surface functional groups and assess carbon structure, respectively. Scanning Electron Microscopy (SEM) provided detailed images of biochar's porous morphology, while Brunauer-Emmett-Teller (BET) analysis quantified surface area and porosity, key properties influencing adsorption and nutrient retention (17). Additionally, X-ray Photoelectron Spectroscopy (XPS) and X-ray Diffraction (XRD) offered insights into surface chemistry and crystalline phases, respectively. These characterization techniques were essential for customizing biochar for various agronomic and environmental functions. Fig. 1 showed properties and applications of biochar.

Effects of Biochar on Soil Health

Soil health was defined as the sustained ability of soil to function as a dynamic, living ecosystem that supports plant growth and productivity. It was inherently governed by the soil's physical, chemical and biological properties. Table 1 summarizes the positive and negative impacts of biochar on soil properties.

Physical properties

The alteration of soil physical properties was mainly influenced by both the inherent characteristics of the biochar and the type of soil to which it was applied. Biochar modified porosity, bulk density, aggregation, water retention and hydraulic conductivity, while reducing surface runoff.

Porosity and bulk density

Biochar reduced soil bulk density by increasing soil porosity. This was due to low density and highly porous structure, which allowed it to occupy space in the soil. When biochar was incorporated into the soil, it introduced numerous micro- and macropores both within (intrapore) and between particles (interpore). These pores increased the total volume of the soil while contributing little to its overall weight, thereby reducing bulk density. Incorporation of biochar reduced soil bulk density up to 16 % and increased in total porosity by 14 %, particularly at higher application rates (100 Mg ha^{-1}) (19). Similarly, an experiment was conducted to assess the effects of date palm-derived biochar produced at different temperatures (250 °C, 350 °C, 450 °C and 550 °C) and it was found that application of trunk-derived (550 °C) at 10 % reduced bulk density to 1.13 g/cm^3 and achieved the highest porosity of 90.28 %. This enhanced soil aeration, water retention and overall soil structure, making it an effective soil amendment (20). Conversely, a study conducted at China, investigating the effects of N-enriched biochar on subtropical paddy soil and found that applying 8 t ha^{-1} of biochar increased soil salinity and bulk density, along with lowered soil water content. Excessive application of biochar negatively affected soil structure and plant development (21). According to reports higher rates of biochar prompted macroaggregate formation, shifting from micro-aggregate dominance over time, which resulted in decreased porosity. Soils treated with mango-wood biochar (600 °C) showed no significant impact on the total porosity in sandy soil (22, 23).

Soil aggregation

Biochar increased soil aggregation through a combination of physical, chemical and biological mechanisms. Physically, its porous structure and irregular surface provided sites where soil particles, organic matter and microbes can attach and bind together. Chemically, biochar had a high surface area and contained various functional groups that interacted with clay particles and soil organic matter, acting as a binding agent that enhanced particle cohesion (24). Biologically, biochar created a favourable habitat for soil microorganisms by improving aeration, moisture retention and nutrient availability. These microbes, in turn, produced substances like polysaccharides and glomalin that further helped glue soil particles into aggregates (25).

Table 1. Biochar's positive and negative impact on soil properties

S.NO.	Biochar (raw material and dose)	Temperature	Soil	Optimum dosage or temperature	Parameter	Positive Impact	Negative impact	References
1	Date Palm Biochar (5 % and 10 % by weight)	250 - 550 °C for 60 min	clay loam	450-550 °C	Bulk density	Decreased	-	(20)
					pH	Increased from 7.23 to 8.5	-	
2	Woodchips, bagasse, poultry litter and waterweed Ludwigia grandiflora. (0 % - 100 % (v/v))	450–500 °C	sandy soil		Water Retention Capacity	Increased	-	(63)
				5 % (v/v)	Readily Available Water	Increased	-	
				10 % (v/v)	Readily Available Water	Increased	-	
				75 % (v/v)	Readily Available Water	-	Decreased	
3	corn straw (9.8, 19.6 and 29.4 Mg C/ha)	400-500 °C for 4 hr	Mollisols	19.6 Mg C/ha	aggregate contents	Increased > 2mm and 0.25 2mm fractions by 56.59 % and 23.41 %, respectively	-	(26)
				19.6 Mg C/ha	F/B ratio	The F/B ratio increased 25.22 %	-	
				19.6 Mg C/ha	Gram-positive to gram-negative ratio	Increased 4.65 %	-	
4	mango-wood (2.5 % and 5 %)	600 °C	Sand and sandy loam		Water retention	Increased	-	(23)
					Porosity	Increased		
					Saturated hydraulic conductivity	Increased		
5	Apple tree branches (1.5 %, 3 % and 4.5 %)	600 °C for 120 min	loamy clay soil	1.5 %	Mean weight diameter	Higher Mean weight diameter	--	(27)
				1.5 %	Soil organic carbon	Increased 35.7 %	-	
				3 %	Aggregates	-	Negative	
				3 %	Mean weight diameter	-	Lower Mean weight diameter	
6	corn straw (0, 10, 20, or 30 t/ha.)	450 °C for 4 hr	Arenosols	20 t/ha	Aggregate mean weight diameter (MWD)	Rose 17.6 %	-	(64)
				20 t/ha	Geometric weight diameter (GMD)	Rose 24.3 %	-	
				Biochar alone	Wheat yield	Increased 6.4 - 20.2 %	-	
				Biochar + Nitrogen fertilizer	Wheat yield	Increased 20.7 - 42.7 %		
7	straw and waste sawdust (4 t/ha and 8 t/ha)	600 °C for 90 min	subtropical paddy soil	4 t/ha	Soil salinity, Soil bulk density	-	Increased	(21)
					Soil water content	-	Dcreased	
					Soil organic content	Increased	-	
8	Eucalyptus sawdust mixed with pasteurized human excreta (CaSa biochar)	500 °C	Andosols	8.3 dm³/m²	soil organic matter	Increased 17.3 %	-	(36)
					Soil organic carbon	Increased 10.0 %	-	
					soil moisture content	Increased 6.3 %	-	
9	Rice husk-derived biochar (30 t/ha, 30 t/ha,45 t/ha)	300-450 °C	Ferralsols		Soil organic carbon content	Increased	-	(35)
					small soil aggregates (< 0.25 mm)	Increased	-	
10	Switchgrass-derived biochar (SGB)	700 °C	contaminated soil		Cation exchange capacity	-	Decreased 27 %.	(34)
	Poultry litter-derived biochar (PLB)	700 °C	contaminated soil		Cation exchange capacity	Increased 91 %	-	

11	Fruit tree branches, peanut shells and cow dung (2 % (w/w))	300 °C, 450 °C and 600 °C	acidified brown soil		Soil pH	Increased by 8.48 –79.25 %.	-	(29)
					Exchangeable acidity	Decreased 56.94 – 94.95 %	-	
					Exchangeable Al	34.38 – 95.66 %	-	
					Exchangeable H	58.72 – 93.27 %	-	
12	Banana leaves biochar, Rice straw biochar, Sorghum stalks biochar and Wood chips biochar (1 %, 3 % and 5 % (w/w))	300 °C for 5 hr	Entisols (saline sandy soil)		Microbial community	Increased	-	(32)
				3 % - 5 %	Total available nitrogen	Increased	-	
				3 % - 5 %	Available potassium	Increased	--	
				3 % - 5 %	Electrical conductivity (EC)	Increased	-	
				3 % - 5 %	Cation exchange capacity	Increased	-	
				3 %	Fresh biomass of arugula	Increased	-	
13	corn-straw biochar (0,15,30 t/ha)	360 °C	saline soils		Soil organic carbon	-	Decreased in the early part of the experiment	(37)
					Soil organic carbon	Later increased 3-6 % compared to control		
					Total soil respiration rate and microbial respiration rate	-	Inhibited during the crop growing period	
					Carbon sequestration	Increased after 2 years	-	
14	Three Level Meta-Analysis (lignocellulosel biomass)	lower pyrolysis temperature			Microbial biomass carbon	Increased 26.5 %	-	(65)
					Nitrification rate	Increased 40.8 %	-	
					GHG Emission	Decreased 12.7 %	-	
					Dehydrogenase and acid phosphatase	Increased	-	
15	Swine-manure biochar (0 %, 0.5 %, 1.0 % and 2.0 %)	350 °C and 500 °C	Tea garden soil (laterite)	2 % biochar (350 °C)	Soil microbial biomass carbon	Increased 36.4 %	-	(41)
				2 % biochar (350 °C)	Soil microbial biomass nitrogen	Increased 34.3 %	-	
				2 % biochar (350 °C)	Sucrase activity	Increased 63.3 %	-	
				2 % biochar (350 °C)	Phosphatase activity	Increased 23.2 %	-	
				2 % biochar (350 °C)	Catalase activity	Increased 50.3 %	-	
				2 % biochar (350 °C)	Urease activity	Increased 27.9 %	-	
16	Sugarcane bagasse (SB), plant material (PM) and manure biomass (MB) (2 % and 4 %)	400-600 °C for 2-3 hr	Red loamy soil	2 % biochar	Microbial population	Increased 16 %	-	(38)
				4 % biochar	Microbial population	Increased 50 %	-	
					soil pH	Increased	-	
					Elemental concentrations (Mn, Zn, Cu)	Increased	-	
					Iron toxicity	Decreased	-	
17	Maize stover biochar (3.5, 6.9, 13.8 and 27.6 t/ha)	open-pit method	Plinthosol soil	27.6 t/ha	pH, N, P and K	Increased	-	(44)

					Soil bulk density	Increased	-	
					Soil pH	Decreased	-	
18	Straw-derived biochar (12, 24, 48 t/ha)	400-450 °C	Hapli-Udic Cambisol	24 t/ha	Available nutrients (N, K) and total nutrients (C, N, P, K)	Increased	-	(45)
					Nitrogenase activity	Increased	-	
			loamy Haplic Luvisol	20 t/ha	Soil pH	Increased 7 %	-	
19	Paper fiber sludge and grain husks (10, 20 t/ha)	550 °C for 30 min			Hydrolytic acidity	Decreased 11 %	-	(66)
					Sum of basic cations	Increased 20 %	-	
					Soil organic carbon	Increased 27 %	-	
20	wood biochar (0 to 10 t/ha)		Tropical Alfisol	2.5 t/ha lime + 5 t/ha biochar	Soil pH, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sodium (Na), magnesium (Mg) and cation exchange capacity (CEC)	Increased	-	(52)
					Exchangeable acidity	Decreased	-	

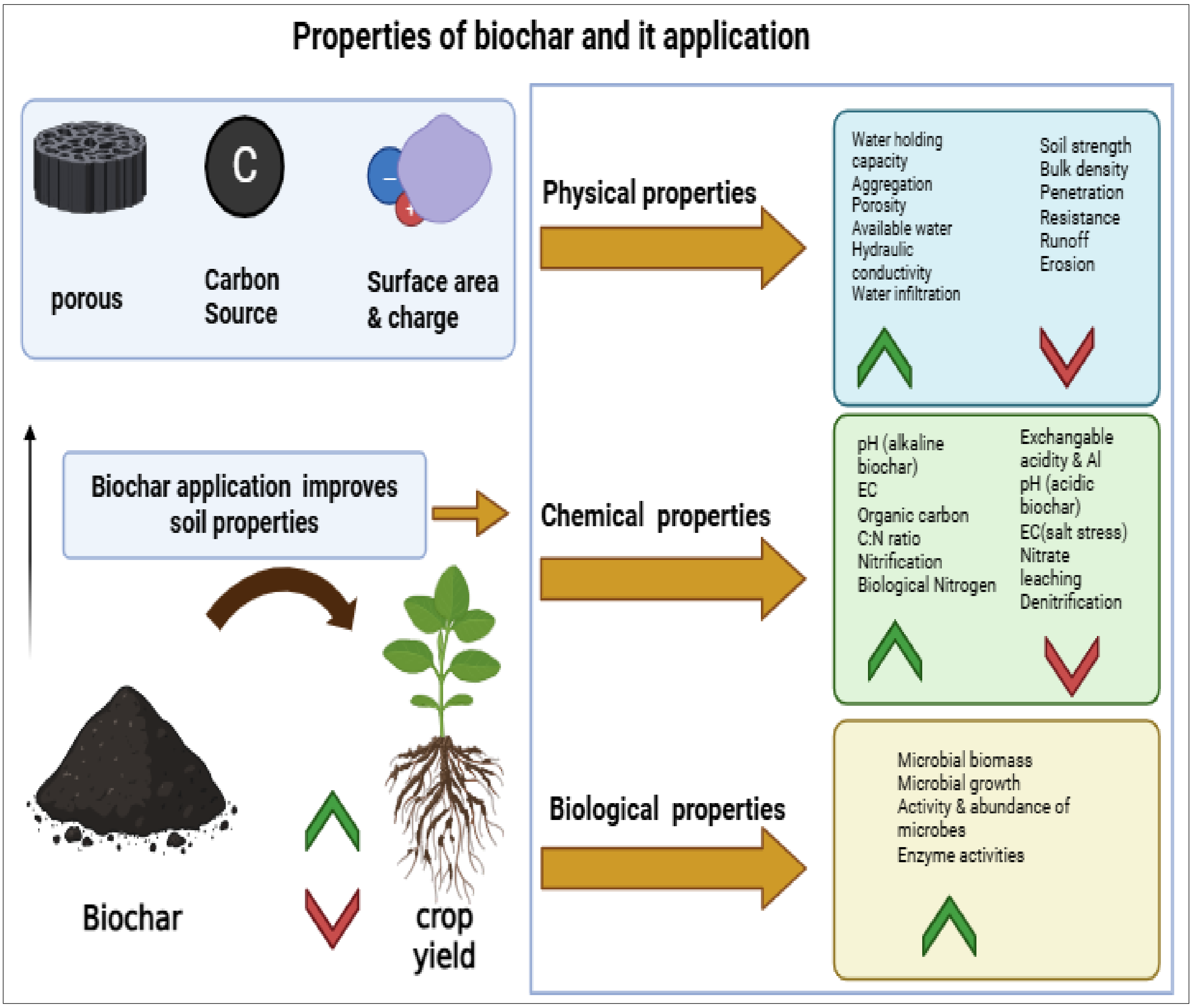

Fig. 1. Biochar properties and its application.

A long-term field study in Northeast China to evaluate the effects of corn straw-derived biochar, applied at rates of 9.8, 19.6 and 29.4 Mg C ha^{-1}, in combination with nitrogen fertilizer on Mollisols over an eight-year period (26). The study reported that biochar application at 19.6 Mg C ha^{-1} significantly increased the proportion of large soil aggregates-up to 56.6 % for the > 2 mm fraction and 23.4 % for the 0.25 - 2 mm fraction. This enhancement in aggregate stability was attributed to increased soil organic carbon content and a more favourable microbial community structure, particularly a rise in gram-positive bacteria. The authors concluded that biochar, especially when used alongside nitrogen fertilizer, effectively improved soil structure and mitigated soil degradation in Mollisols (26).

In contrast, a study reported a decreasing trend in the mean weight diameter (MWD) of soil aggregates with increasing biochar levels (27). Notably, the highest biochar application rate (4.5 %) significantly reduced the MWD to 2.18, compared to 2.74 in the control (0 %) and concluded that lower application rate (1.5 %) was more effective for preserving aggregate stability (27). These findings highlighted the need for optimized application rates tailored to soil type and environmental conditions.

Available water content & hydraulic conductivity

Application of biochar in soil created a network of micro- and mesopores that effectively retained water against gravitational forces while keeping it accessible to plant roots. Application of Miscanthus-derived biochar (1-2 % w/w) to sandy and silt loam soils increased saturated water content around 16 %, enhanced macroporosity by 78.8 % and reduced bulk density by 16.8 %. These physical changes improved the soil's ability to retain water and support plant growth, especially in coarse-textured soils that typically suffered from poor water retention. The observed effects were attributed to the biochar's porous structure and hydrophilic surface characteristics, which enabled it to retain and slowly release water within the root zone.

In contrast, in a study it was observed that applying low-temperature (500 °C) biochar produced from almond shells and spruce wood to Hanford sandy loam and Yolo silt loam soils significantly reduced saturated hydraulic conductivity (K_sat) by up to 79 % (28). This negative effect was due to the fine particles and tarry residues in low-temperature biochar, which clogged soil macropores and disrupted water flow. While high-temperature biochar showed less of this effect, the study highlighted how certain biochar types, particularly those with finer textures and lower thermal stability, could hinder water movement in soil. These contrasting findings underlined the importance of matching biochar characteristics with specific soil types and intended agronomic outcomes to ensure effective and sustainable use.

Chemical properties

Biochar application improved several chemical properties of soil. It acted as a liming agent, raised soil pH and reduced acidity, which enhanced nutrient availability. Additionally, biochar increased cation exchange capacity (CEC), thereby improving nutrient retention and minimizing leaching. Its high carbon content also contributed to increased soil organic carbon, supporting fertility and long-term carbon sequestration. The following sections discuss each of these properties in detail.

pH

Biochar typically had a liming effect that raised soil pH, especially in acidic soils. In a study it was reported that application of cow-dung and branch biochar to an acidified brown soil (rape -wheat rotation) increased soil pH up to 79.3 % (29). A recent meta-analysis found an average pH increase of 5.6 % with biochar, though it noted pH decreases under some conditions (e.g. when biochar pH was lower than soil pH (30). Conversely, in neutral to calcareous soils biochar sometimes lowered pH. For instance, adding 50t/ha low-temperature wood biochar reduced soil pH (from 7.22 to 6.49) in a loamy maize field (31). These contrasting results underscored that biochar's effect on pH depended on feedstock, pyrolysis conditions and initial soil pH.

Electrical conductivity (EC)

Biochar's impact on soil EC (a proxy for soluble salts) varied by soil and biochar type. In calcareous or non-saline soils, high-ash biochar raised EC by adding soluble ions. For example, amending a sandy desert soil with poultry-litter biochar increased EC (32). In contrast, in saline or sodic soils biochar often reduced EC by adsorbing salts and improving leaching. Similarly, a global meta-analysis reported that biochar significantly lowered soil EC by ~7.4 % on average in salt-affected soils (33). These findings underscored the context-specific nature of biochar's influence on soil salinity.

Cation exchange capacity (CEC)

Biochar generally increased soil CEC by adding high-surface-area, charged organic matter. In a research it was reported that 50t/ha of low-temperature wood biochar significantly increased the CEC of both maize and oilseed rape field soils (31). Previous research indicated that high-ash poultry-litter biochar increased the CEC by ~91 %, whereas low-ash switchgrass biochar decreased it by ~27 %, due to differences in ash and functional groups (34). Thus, while many studies reported CEC gains with biochar, some biochar especially low-ash, low-temperature types -had neutral or even negative effects on CEC.

Soil Organic Carbon (SOC)

Biochar was carbon-rich and recalcitrant, its application typically boosted soil organic carbon (OC). Adding rice-husk biochar to forest Ferralsols significantly increased SOC content and carbon density (35). Likewise, a long-term field trial in Tanzania (7 years post-application) reported a significant SOC increase from biochar (and residue) inputs (36). On the other hand, biochar initially decreased SOC stocks during the first freeze – thaw period of their 2-year saline field trial (before later gains), although overall SOC was 3 - 6 % higher than control after two years (37). These findings suggested that while biochar generally enhanced soil carbon (C) pools, transient reductions could occur due to microbial priming or rapid mineralization of labial organic matter.

Biological properties

Soil microbial population

Incorporation of biochar in soil had positive relation with microbial population. In a study it was reported that adding 2 - 4 % biochar (from sugarcane bagasse, plant material and manure feedstocks) to acidic soil increased microbial counts about a 16 % rise at 2 % biochar and up to 50 % at 4 % (38). This increase was attributed to biochar's porous structure and liming effect, which improved soil pH and enhanced the availability of micronutrients such as Zn, Mn and Cu, thereby creating a more favorable environment for microbial growth (38).

In contrast, another study, on soils containing charcoal aged 150-year or more (ancient biochar) found no significant increase in microbial biomass or activity compared to uncharred controls. They concluded that over long timescales, factor such as land management practices (e.g., fertilizer and liming) and inherent soil properties had a greater influence on microbial communities than aged biochar. Thus, ancient charcoal appeared to have limited impact on total soil microbial biomass and activity (39).

Biochar produced from nutrient-rich feedstocks (e.g., manure) and pyrolyzed at lower temperatures (~350 °C) retained more labile carbon and nutrients, which significantly boosted microbial growth. In contrast, high-temperature or gasification-derived biochar tended to be more aromatic, contained less available carbon and thus showed minimal microbial stimulation (40, 41).

Benefits were strongest in poor, acidic or sandy soils. Biochar raised pH in acidic soils and added carbon in low-C soils, which greatly stimulates microbes. In neutral/alkaline or clayey soils with high organic matter, the effect was smaller (39, 40). Moderate rates (~ 1-3 %) often maximized microbial response, whereas very high doses (≥ 5-10 %) could absorb nutrients or block pore space, sometimes reducing microbial activity (41, 42). Also, fresh biochar tended to boost microbes more than very aged char, which may have lost labile C over decades (39, 40) .

Microbial biomass carbon (MBC)

Addition of biochar influenced the microbial biomass carbon. A global meta-analysis found that biochar significantly increased soil microbial biomass on average. Across 999 observations, total microbial biomass (MBC) was higher in biochar-amended soils (40). The largest gains occurred with low-temperature, nutrient-rich biochar (as these supplied more C/N substrates) and in field studies (where longer time and plant roots helped microbes) (40). On other hand, a study found that in long-term charcoal-enriched soils there was no meaningful difference in microbial biomass C compared to reference soils - again concluding a "limited effect on total soil microbial biomass" after long durations. This implied that initial MBC boosts may have faded over time (40). In meta-analysis, MBC increases were greatest in sandy, low-organic soils (where microbes were C - limited) and in field trials rather than short incubation (40). Conversely, in fertile or clay soils much of the added C may have been retained in soil matrix or diverted to plant roots, so MBC gains were muted. The method mattered (fumigation extraction method often reported larger MBC than phospho lipid fatty acid (PLFA). Also, long-term studies suggested biochar's legacy C was very stable, so after many years microbial biomass could return to baseline (39).

Soil enzyme activity

Application of biochar influenced various soil enzymes, particularly those involved in nutrient cycling and microbial activity. Adding 2 % swine-manure biochar (pyrolyzed at 350 °C) to tea-garden soil dramatically increased enzyme activities. Urease increased 28 %, catalase 50 %, sucrase 63 % and acid phosphatase 23 % over the control (41). Microbial biomass C also increased (36 %). Moderate biochar doses and moderate pyrolysis temperature favoured enzyme stimulation; animal-manure biochar pyrolyzed at 350 °C was found to be optimal. However, one study found that hardwood biochar amendment (1-10 %) reduced the potential activity of certain soil enzymes. Leucine aminopeptidase and β-xylosidase activities were significantly lower in biochar-treated soils even before any stress exposure (42). This inhibitory effect may have occurred because biochar adsorbed or stabilized certain enzymes, thereby reducing their bioavailability or activity. Additionally, soil pH modulated enzyme responses: in acidic soils, biochar enhanced the activity of acid-sensitive enzymes, whereas in alkaline soils, the same biochar application had negligible or suppressive effects.

Effect of biochar on crop productivity

Well-characterized biochar, when appropriately incorporated into soil, enhanced its physical, chemical and biological properties. Improvements in overall soil health contributed significantly to increased crop productivity. Table 2 summarized both the positive and negative impacts of biochar on various crop systems.

Positive Impact

A one-time biochar amendment (at field practice rates) increased maize yields ~ 7-fold versus untreated soil in a strongly acidic (pH 3.6) Indonesian Ultisol (43). The biochar acted as lime (raising pH) and added K, Mg and P by alleviating aluminium toxicity and nutrient deficiency. This dual liming–fertility effect under very low initial pH drove the dramatic yield increase (43).

In tomato biochar application also showed positive outcomes. In highly weathered and degraded Ugandan soil, maize-stover biochar applied at rates up to 27.6 t/ha (without added fertilizers) significantly improved soil fertility, resulting in a 16 % increase in fruit yield at the highest rate (44). Higher biochar raised pH by 27 % and boosted N, P & K (exchangeable K by 57 %) (44), which sustained plant growth. The improved nutrient and pH status under low-fertility conditions explained the positive yield response.

Similarly, another study reported that applying straw-derived biochar (12, 24, 48 t/ha) to aged soybean plots without fertilizer significantly increased soybean yield over three years under continuous monocropping (45). Biochar reduced soil compaction and raised rhizosphere pH and nutrient availability (N, K, total C, N, P, K) (45) which enhanced root development (longer roots, more nodules) and N fixation. Thus, biochar overcame continuous-cropping constraints, sustainably boosting soybean productivity.

In rice, a long-term study investigated the effects of co-applying wood-derived biochar (30 t/ha) with manure in acidic paddy soils of southern China. After five years, rice yield increased by 6.3 % in the best treatment (biochar + mineral nitrogen + manure) compared to nitrogen-only controls (46). Biochar's liming effect, higher organic matter and nutrient adsorption helped offset acidification. Long-term data displayed combined biochar manure best preserved fertility and slightly increased yields.

Similarly in an arid/semi-arid rainwater-harvesting system in China, biochar application (10-20 Mg/ha) in wheat

Table 2. Biochar's positive and negative impact on crop production

S.no	Biochar source & dosage	Temperature	Soil	Plant	Optimum Dosage	Parameter	Positive	Negative	Reference
1	wood biochar (0 to 10 t/ha)		Tropical Alfisol	cowpea	2.5 t/ha lime + 5 t/ha biochar	Cowpea growth, nodulation and yield	Increased	-	(52)
					10 t/ha lime + 10 t/ha biochar	Cowpea growth, nodulation and yield	-	Decreased	
2	Maize stover biochar (3.5, 6.9, 13.8 and 27.6 t/ha.)	open-pit method	Plinthosol soil	tomato	27. 6 t / ha	Fruit yield	Increased 16.1 % compared to the control		(44)
3	wheat straw biochar (5 t/ha)	450 °C	sandplain soils	wheat, lupin and sorghum.	5 t/ha	Crop yields	Increased in the first three seasons	But declined afterward	(67)
4	pine chips, poultry litter, swine solids, switchgrass (1 %)	350 °C, 500 °C and 700 °C	sandy loam and loamy sand	carrot, lettuce, soybean and sweet corn	700 °C poultry litter biochar	Soybean shoot and pod dry weight	-	Decreased	(48)
5	straw-derived biochar (12, 24, 48 t/ha)	400-450 °C	Hapli-Udic Cambisol	soybean	-	Soybean root length, surface area, volume and exudates	Increased	-	(45)
						Nodule number, dry weight and nitrogenase activity	Increased	-	
6	wood biochar (30 t/ha)	400-600 °C	acidic paddy soil	Rice		Rice yield	Increased 6.3 %	-	(46)
7	Paper fiber sludge and grain husks (10, 20 t/ha)	550 °C for 30 min	loamy Haplic Luvisol	Maize and spring barley	20 t/ha	Grain yield	Increased	-	(66)
8	softwood pine-derived biochar (4.5 t/acre)	anoxic thermochemical conversion	Riddles-Hillsdale soil series in Ohio (USA)	Corn and soybean		Soybean yield	Increased 7.4 bushels per acre	-	(47)
9	Maize straw biochar (0, 24, 48 t/ha)	600 °C	Sandy soil	peanut	24 t/ha	Net photosynthetic rate, root length, surface area and volume, root bleeding sap	Increased	-	(51)
					24 t/ha	Peanut yield	Increased	-	
					48 t/ha	Peanut yield	-	Decreased	
10	flue-cured tobacco stem biochar (600, 900, 1200, 1800 kg/ha.)	450 °C	paddy soil and red earth soil	Flue-cured tobacco	600 kg/ha and 900 kg/ha	Leaf yield and dry matter accumulation	Increased		
					Higher dosage	Leaf yeild	-	Declined	
11	Rice straw and rice husk biochar	500 °C for 2 hr	Lou soil (Eum-Orthric Anthrosols)	winter wheat		Wheat grain yield	Increased 3.51-16.42 %	-	(47)

increased soil moisture and temperature, reduced CO_2 emissions and boosted grain yield by 3.5-16.4 % (47).

Negative Impact

Despite the numerous reported benefits, biochar application could also have negative effects on crop productivity, particularly when inappropriate types or application rates were used. In a greenhouse experiment involving carrot, lettuce, soybean and sweet corn grown in two soil types, it was found that poultry-litter biochar pyrolyzed at 700 °C, significantly reduced soybean shoots and pod dry weights in Norfolk soil compared to the control. The impact of biochar was highly dependent on its source material and the soil environment (48). This suggested that biochar effects are highly dependent on both feedstock type and soil conditions.

In another study, the influence of biochar on plant–microbe interactions using *Medicago sativa* (alfalfa) (49). The microbial inocula from biochar-treated soils reduced early plant biomass and delayed flowering. Although this effect diminished later in development, the results highlighted how biochar-induced microbial shifts could transiently suppress plant growth (49).

Another field trial evaluated the effects of varying biochar rates on flue-cured tobacco (*Nicotiana tabacum*). Plants grown without biochar outperformed those with biochar in terms of height, leaf number and leaf area, especially during early growth stages (50). High application rates (12-18 t/ha) inhibited plant development throughout the season, likely due to nitrogen immobilization caused by biochar's high C/N ratio.

Likewise, previous study examined the combined effects of biochar and irrigation on peanut yield over a three-year field experiment. While moderate biochar use (24 t/ha) improved yield, the highest application rate (48 t/ha) led to a yield reduction during the first year. This indicated that excessive biochar could negatively impact crop production under certain field conditions (51). This suggested that excessive biochar application could undesirably affect crop productivity under certain field conditions.

Similarly, a study assessed the interaction of lime and biochar on cowpea (*Vigna unguiculata*) yield. The combination of high lime (10 t/ha) and high biochar (10 t/ha) significantly reduced grain yield (85 %) compared to moderate treatments. The yield suppression was attributed to over-alkalinization, emphasizing the importance of appropriate application rates (52).

Effect of biochar on carbon sequestration and GHG emission reduction

In general, biochar tended to enhance long-term soil C storage under favourable conditions. Field trials found substantial SOC increases (especially in recalcitrant pools) when biochar was applied at high rates (35, 53). Meta-analyses confirmed average SOC gains (61 %) (54). These gains are primarily attributed to biochar's stable aromatic carbon structure, its negative priming effect (suppression of native carbon mineralization) and the formation of stable microbial residues (55).

However, field results varied based in soil texture. Fine-textured (loamy) soils-maintained SOC gains better than coarse (sandy) soils. Analogously, Long term data showed that a substantial increase in SOC persistent in loamy soil even after 11 years, whereas sandy soils lost most of additional SOC over time (56). In some cases biochar has triggered short-term positive priming effects or enhanced microbial activity, partially offsetting these carbon gains (53). Thus, biochar's SOC effect depended strongly on soil texture, amendment rate, feedstock quality and time: high-quality (low-volatile) biochar and co-amendment with organics tended to sequester more C, whereas in poor or aged conditions the net gain could diminish (54, 56).

Numerous studies documented reductions in nitrous oxide (N_2O) and methane (CH_4) emissions following biochar application, especially in wet or fertilized soils. Biochar increased soil pH and reduced N_2O by up to 50 % in an acidic soils (57). In rice paddy trials, straw derived biochar decreased CH_4 emissions by 43 % and CO_2 emission by ~37 % (58). Likewise, Meta-analyses agreed that biochar-amended soils typically emitted ~ 18 % less N_2O and a few percent less CH_4 (59). These reductions are attributed to biochar's promotion of complete denitrification (more N_2 relative to N_2O), enhanced soil aeration and pH-driven shifts in microbial genes (e.g. more *nosZ* bacteria) (57, 59).

However, biochar's effects were not uniformly positive. Under some conditions it showed no GHG mitigation or even increases. For instance, no change in N_2O emissions was observed when biochar was added to digestate-amended fields although brief CH_4 spikes occurred (60). High biochar application rates input labile carbon could prime CO_2 release. For example, applying biochar at 45 t/ha increased soil CO_2 flux by stimulating microbial respiration in forest soil (61). Similarly, in a two-year maize-wheat field trail, biochar alone nearly doubled N_2O emissions during maize cultivation but had no significant effect during wheat growth (62). Biochar tended to reduce N_2O mainly in well-fertilized or alkaline soils, but could have little effect or increase emissions, if nitrogen was already limiting or in low pH conditions. Biochar generally suppressed N_2O and CH_4, but its net GHG mitigation depended on climate, soil chemistry and management.

Conclusion

Biochar emerged as a promising soil amendment with the potential to improve soil health, sequester carbon and improve crop productivity. This review emphasized the importance of optimizing biochar production techniques such as: pyrolysis temperature and feedstock type, to tailor its properties for specific agricultural applications. While biochar provided several agronomic and environmental benefits, including improved soil structure, water retention, nutrient availability and microbial activity, it could also have negative effects when misapplied, such as altering soil pH or immobilizing nutrients. These contrasting outcomes highlighted the need for site and crop-specific assessments. To ensure the effective use of biochar, future research should prioritized long-term field studies across diverse agroecosystems, established standardized production and application protocols and developed practical decision-support tools for farmers. By integrating biochar with sustainable soil management practices, it contributed significantly to building resilient agricultural systems and addressing climate change.

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Authors' contributions

KS wrote the manuscript. JP provided guidance during writing process. SS, RUS, MLM, TSK, SK and MR reviewed the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

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References

1. Verma P, Singh D, Pathania IP, Aggarwal K. Strategies to improve agriculture sustainability, soil fertility and enhancement of farmers' income for the economic development. In: Meena RS, editor. Soil fertility management for sustainable development. Singapore: Springer; 2019:43–70. https://doi.org/10.1007/978-981-13-5904-0_4
2. Malone CC, Johnson SE. The intensive agricultural development program in India: Washington (DC): United States Department of Agriculture, Economic Research Service; 1971.
3. Devi RU, Balakrishna K. Crop waste management: perspectives on alternative uses in India. CABI Rev. 2022. https://doi.org/10.1079/cabireviews202217022
4. Kumawat A, Meena RS, Rashmi I, Kumar A, Bamboriya S, Yadav D, et al. Crop residue management: a novel technique for restoring soil health and sustainable intensification in India. In: Meena RS, editor. Sustainable Intensification for Agroecosystem Services and Management. Singapore: Springer; 2021:229–65. https://doi.org/10.1007/978-981-16-3207-5_8
5. Krishna W, Mkondiwa M. Economics of crop residue management. Annu Rev Resour Econ. 2023;15(1):19–39. https://doi.org/10.1146/annurev-resource-101422-090019
6. Jain N, Pathak H, Bhatia A. Sustainable management of crop residues in India. Curr Adv Agric Sci. 2014;6(1):1–9.

7. Pereira P, Bogunovic I, Inacio M, Zhao W, Barcelo D, editors. Agriculture intensification impacts on soil and water ecosystem services. EGU Gen Assem Conf Abstr;2023. https://doi.org/10.5194/egusphere-egu23-1423

8. Scheper J, Badenhausser I, Kantelhardt J, Kirchweger S, Bartomeus I, Bretagnolle V, et al. Biodiversity and pollination benefits trade off against profit in an intensive farming system. Proc Natl Acad Sci U S A. 2023;120(28):e2212124120. https://doi.org/10.1073/pnas.2212124120

9. Deshpande MV, Kumar N, Pillai D, Krishna W, Jain M. Greenhouse gas emissions from agricultural residue burning have increased by 75% since 2011 across India. Sci Total Environ. 2023;904:166944. https://doi.org/10.1016/j.scitotenv.2023.166944

10. Deka H, Mishra P. Effect of fuel burning on the microbial population of soil. Folia Microbiol (Praha). 1984;29(4):330–6. https://doi.org/10.1007/BF02875966

11. Mataix-Solera J, Guerrero C, García-Orenes F, Bárcenas GM, Torres MP. Forest fire effects on soil microbiology. In: Cerda A, Robichaud PR, editors. Fire effects on soils and restoration strategies: Boca Raton (FL): CRC press; 2009. p. 149–92. https://doi.org/10.1201/9781439843338-c5

12. Divyangkumar N, Panwar NL, Agrawal C, Gupta T, Meena G, Singh M. Cradle-to-gate analyses of biochar produced from agricultural crop residues by vacuum pyrolysis. Clean Energy. 2024;8(6):1–15. https://doi.org/10.1093/ce/zkae069

13. Xu M, Wu J, Zhang X, Yang G. Impact of biochar application on carbon sequestration, soil fertility and crop productivity. Acta Ecol Sin. 2018;38(2):393–404. https://doi.org/10.5846/stxb201610112058

14. Babu S, Singh R, Kumar S, Rathore SS, Yadav D, Yadav SK, et al. Biochar implications in cleaner agricultural production and environmental sustainability. Environ Sci Adv. 2023;2(8):1042–59. https://doi.org/10.1039/D2VA00324D

15. Zhu H, An Q, Nasir ASM, Babin A, Saucedo SL, Vallenas A, et al. Emerging applications of biochar: a review on techno-environmental-economic aspects. Bioresour Technol. 2023;388:129745. https://doi.org/10.1016/j.biortech.2023.129745

16. Ibitoye SE, Loha C, Mahamood RM, Jen T-C, Alam M, Sarkar I, et al. An overview of biochar production techniques and application in iron and steel industries. Bioresour Bioproc. 2024;11(1):65. https://doi.org/10.1186/s40643-024-00779-z

17. Varkolu M, Gundekari S, Palla VCS, Kumar P, Bhattacharjee S, Vinodkumar T. Recent Advances in biochar production, Characterization and environmental applications. Catalysts. 2025;15(3):243. https://doi.org/10.3390/catal15030243

18. Zhang J, Li C. Biochar for sustainable farming and recultivation. Basel: MDPI; 2023. p. 2421. https://doi.org/10.3390/agronomy13092421

19. Sun Z, Arthur E, de Jonge LW, Elsgaard L, Moldrup P. Pore structure characteristics after 2 years of biochar application to a sandy loam field. Soil Sci. 2015;180(2):41–6. https://doi.org/10.1097/SS.0000000000000111

20. Tahir A, Al-Ani F, Al Obaidy A. Effect of date palm derived biochar on soil's bulk density, pH and nitrogen content. Eng Technol J. 2022;40(11):1358–64. https://doi.org/10.30684/etj.2021.132003.1082

21. Liu X, Wang W, Peñuelas J, Sardans J, Chen X, Fang Y, et al. Effects of nitrogen-enriched biochar on subtropical paddy soil organic carbon pool dynamics. Sci Total Environ. 2022;851:158322. https://doi.org/10.1016/j.scitotenv.2022.158322

22. Acharya BS, Dodla S, Wang JJ, Pavuluri K, Darapuneni M, Dattamudi S, et al. Biochar impacts on soil water dynamics: knowns, unknowns and research directions. Biochar. 2024;6(1):34. https://doi.org/10.1007/s42773-024-00323-4

23. Villagra-Mendoza K, Horn R. Effect of biochar addition on hydraulic functions of two textural soils. Geoderma. 2018;326:88–95. https://doi.org/10.1016/j.geoderma.2018.03.021

24. Situ G, Zhao Y, Zhang L, Yang X, Chen D, Li S, et al. Linking the chemical nature of soil organic carbon and biological binding agent in aggregates to soil aggregate stability following biochar amendment in a rice paddy. Sci Total Environ. 2022;847:157460. https://doi.org/10.1016/j.scitotenv.2022.157460

25. Costa OY, Raaijmakers JM, Kuramae EE. Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. Front Microbiol. 2018;9:1636. https://doi.org/10.3389/fmicb.2018.01636

26. Sun J, Lu X, Chen G, Luo N, Zhang Q, Li X. Biochar promotes soil aggregate stability and associated organic carbon sequestration and regulates microbial community structures in Mollisols from northeast China. Soil. 2023;9(1):261–75. https://doi.org/10.5194/soil-9-261-2023

27. Sheng M-h, Ai X-y, Huang B-c, Zhu M-k, Liu Z-y, Ai Y-w. Effects of biochar additions on the mechanical stability of soil aggregates and their role in the dynamic renewal of aggregates in slope ecological restoration. Sci Total Environ. 2023;898:165478. https://doi.org/10.1016/j.scitotenv.2023.165478

28. Baethgen. Ecosystem dynamics of crop-pasture rotations in a fifty-year field experiment in southern South America: Century model and field results (vol 85, p. 423, 2021). Soil Sci Soc Am J. 2021;85(5):1866. https://doi.org/10.1002/saj2.20316

29. Geng N, Kang X, Yan X, Yin N, Wang H, Pan H, et al. Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. Ecotoxicol Environ Saf. 2022;232:113241. https://doi.org/10.1016/j.ecoenv.2022.113241

30. Zhang N, Xing J, Wei L, Liu C, Zhao W, Liu Z, et al. The potential of biochar to mitigate soil acidification: a global meta-analysis. Biochar. 2025;7(1):49. https://doi.org/10.1007/s42773-025-00451-5

31. Gruss I, Twardowski JP, Latawiec A, Medyńska-Juraszek A, Królczyk J. Risk assessment of low-temperature biochar used as soil amendment on soil mesofauna. Environ Sci Pollut Res. 2019;26:18230–9. https://doi.org/10.1007/s11356-019-05153-7

32. ELsaman NK, Amin AE-EAZ, El-Razek MA, Roshdy NMK. Comparative effects of different types and doses of biochar on soil quality indicators and arugula growth under saline conditions. Sci Rep. 2025;15(1):10046. https://doi.org/10.1038/s41598-025-92816-w

33. Su Z, Liu X, Wang Z, Wang J. Biochar effects on salt-affected soil properties and plant productivity: A global meta-analysis. J Environ Manag. 2024;366:121653. https://doi.org/10.1038/s41598-025-92816-w

34. Antonangelo JA, Culman S, Zhang H. Comparative analysis and prediction of cation exchange capacity via summation: influence of biochar type and nutrient ratios. Front Soil Sci. 2024;4:1371777. https://doi.org/10.3389/fsoil.2024.1371777

35. Wei J, Li Y, Li J, Yan W, Yin Q, Jiang H, et al. A 2-year pure biochar addition enhances soil carbon sequestration and reduces aggregate stability in understory conditions. Sci Rep. 2024;14(1):1–10. https://doi.org/10.1038/s41598-024-81232-1

36. Ernest B, Yanda PZ, Hansson A, Fridahl M. Long-term effects of adding biochar to soils on organic matter content, persistent carbon storage and moisture content in Karagwe, Tanzania. Sci Rep. 2024;14(1):30565. https://doi.org/10.1038/s41598-024-83372-w

37. Zhang R, Qu Z, Yang W, Wang L, Zhang D, Liu L, et al. Biochar addition enhances annual carbon stocks and ecosystem carbon sink intensity in saline soils of the Hetao Irrigation District, Inner Mongolia. Plant, Soil Environ. 2024;70(5). https://doi.org/10.17221/121/2023-PSE

38. Ullah Z, Ali S, Muhammad N, Khan N, Rizwan M, Khan MD, et al. Biochar impact on microbial population and elemental composition of red soil. Arabian J Geosci. 2020;13:1–9. https://doi.org/10.1007/s12517-020-05671-6

39. Hardy B, Sleutel S, Dufey JE, Cornelis J-T. The long-term effect of biochar on soil microbial abundance, activity and community structure is overwritten by land management. Front Environ Sci. 2019;7:110. https://doi.org/10.3389/fenvs.2019.00110

40. Li X, Wang T, Chang SX, Jiang X, Song Y. Biochar increases soil microbial biomass but has variable effects on microbial diversity: a meta-analysis. Sci Total Environ. 2020;749:141593. https://doi.org/10.1016/j.scitotenv.2020.141593

41. Jiang Y, Wang X, Zhao Y, Zhang C, Jin Z, Shan S, et al. Effects of biochar application on enzyme activities in tea garden soil. Front Bioeng Biotechnol. 2021;9:728530. https://doi.org/10.3389/fbioe.2021.728530

42. Elzobair KA, Stromberger ME, Ippolito JA. Stabilizing effect of biochar on soil extracellular enzymes after a denaturing stress. Chemosphere. 2016;142:114–9. https://doi.org/10.1016/j.chemosphere.2015.03.018

43. Hale SE, Nurida NL, Mulder J, Sørmo E, Silvani L, Abiven S, et al. The effect of biochar, lime and ash on maize yield in a long-term field trial in a Ultisol in the humid tropics. Sci Total Environ. 2020;719:137455. https://doi.org/10.1016/j.scitotenv.2020.137455

44. Wacal C, Basalirwa D, Byalebeka J, Tsubo M, Nishihara E. Low cost maize stover biochar as an alternative to inorganic fertilizer for improvement of soil chemical properties, growth and yield of tomatoes on degraded soil of Northern Uganda. BMC Plant Biol. 2023;23(1):473. https://doi.org/10.1186/s12870-023-04468-5

45. Wu D, Zhang W, Xiu L, Sun Y, Gu W, Wang Y, et al. Soybean yield response of biochar-regulated soil properties and root growth strategy. Agronomy. 2022;12(6):1412. https://doi.org/10.3390/agronomy12061412

46. Liang D, Ning Y, Ji C, Zhang Y, Wu H, Ma H, et al. Biochar and manure co-application increases rice yield in low productive acid soil by increasing soil pH, organic carbon and nutrient retention and availability. Plants. 2024;13(7):973. https://doi.org/10.3390/plants13070973

47. Ma X, Lv M, Huang F, Zhang P, Cai T, Jia Z. Effects of biochar application on soil hydrothermal environment, carbon emissions and crop yield in wheat fields under ridge–furrow rainwater harvesting planting mode. Agriculture. 2022;12(10):1704. https://doi.org/10.3390/agriculture12101704

48. Olszyk D, Shiroyama T, Novak J, Cantrell K, Sigua G, Watts D, et al. Biochar affects growth and shoot nitrogen in four crops for two soils. Agrosyst Geosci Environ. 2020;3(1):e20067. https://doi.org/10.1002/agg2.20067

49. Hol WG, Vestergård M, ten Hooven F, Duyts H, van de Voorde TF, Bezemer TM. Transient negative biochar effects on plant growth are strongest after microbial species loss. Soil Biol Biochem. 2017;115:442–51. https://doi.org/10.1016/j.soilbio.2017.09.016

50. Yang Y, Ahmed W, Ye C, Yang L, Wu L, Dai Z, et al. Exploring the effect of different application rates of biochar on the accumulation of nutrients and growth of flue-cured tobacco (Nicotiana tabacum). Front Plant Sci. 2024;15:1225031. https://doi.org/10.3389/fpls.2024.1225031

51. Zhang J, Liu X, Wu Q, Qiu Y, Chi D, Xia G, et al. Mulched drip irrigation and maize straw biochar increase peanut yield by regulating soil nitrogen, photosynthesis and root in arid regions. Agric Water Manag. 2023;289:108565. https://doi.org/10.1016/j.agwat.2023.108565

52. Adekiya AO, Ayorinde BB, Ogunbode T. Combined lime and biochar application enhances cowpea growth and yield in tropical Alfisol. Sci Rep. 2024;14(1):1389. https://doi.org/10.1038/s41598-024-52102-7

53. Ding X, Li G, Zhao X, Lin Q, Wang X. Biochar application significantly increases soil organic carbon under conservation tillage: an 11-year field experiment. Biochar. 2023;5(1):28. https://doi.org/10.1007/s42773-023-00226-w

54. Bekchanova M, Kuppens T, Cuypers A, Jozefczak M, Malina R. Biochar's effect on the soil carbon cycle: a rapid review and meta-analysis. Biochar. 2024;6(1):1–19. https://doi.org/10.1007/s42773-024-00381-8

55. Kalu S, Seppänen A, Mganga KZ, Sietiö O-M, Glaser B, Karhu K. Biochar reduced the mineralization of native and added soil organic carbon: evidence of negative priming and enhanced microbial carbon use efficiency. Biochar. 2024;6(1):7. https://doi.org/10.1007/s42773-023-00294-y

56. Gross A, Bromm T, Polifka S, Fischer D, Glaser B. Long-term biochar and soil organic carbon stability–Evidence from field experiments in Germany. Sci Total Environ. 2024;954:176340. https://doi.org/10.1016/j.scitotenv.2024.176340

57. Lin F, Wang H, Shaghaleh H, Ali Adam Hamad A, Zhang Y, Yang B, et al. Effects of biochar amendment on N2O emissions from soils with different pH levels. Atmosphere. 2024;15(1):68. https://doi.org/10.3390/atmos15010068

58. Somboon S, Rossopa B, Yodda S, Sukitprapanon T-S, Chidthaisong A, Lawongsa P. Mitigating methane emissions and global warming potential while increasing rice yield using biochar derived from leftover rice straw in a tropical paddy soil. Sci Rep. 2024;14(1):8706. https://doi.org/10.1038/s41598-024-59352-5

59. Shrestha RK, Jacinthe PA, Lal R, Lorenz K, Singh MP, Demyan SM, et al. Biochar as a negative emission technology: a synthesis of field research on greenhouse gas emissions. J Environ Qual. 2023;52(4):769–98. https://doi.org/10.1002/jeq2.20475

60. Efosa N, Krause H-M, Hüppi R, Krauss M, Vaucher N, Zourek F, et al. Emissions of nitrous oxide and methane after field application of liquid organic fertilizers and biochar. Agric Ecosyst Environ. 2023;356:108642. https://doi.org/10.1016/j.agee.2023.108642

61. Zu H, Deng Z, Liu X, Luo J, Chen Y, Yi M, et al. Effects of biochar on soil respiration mediated by rainfall events: evidence from one-year field experiment in an urban forest. Ecol Process. 2025;14(1):1. https://doi.org/10.1186/s13717-024-00571-z

62. Niu Y, Chen Z, Müller C, Zaman MM, Kim D, Yu H, et al. Yield-scaled N2O emissions were effectively reduced by biochar amendment of sandy loam soil under maize-wheat rotation in the North China Plain. Atmos Environ. 2017;170:58–70. https://doi.org/10.1016/j.atmosenv.2017.09.050

63. Ndede EO, Kurebito S, Idowu O, Tokunari T, Jindo K. The potential of biochar to enhance the water retention properties of sandy agricultural soils. Agronomy. 2022;12(2):311. https://doi.org/10.3390/agronomy12020311

64. Yang W, Wang Z, Zhao H, Li D, Jia H, Xu W. Biochar application influences the stability of soil aggregates and wheat yields. Plant Soil Environ. 2024;70(3):125. https://doi.org/10.17221/199/2023-PSE

65. Kerner P, Struhs E, Mirkouei A, Aho K, Lohse KA, Dungan RS, et al. crobial responses to biochar soil amendment and influential factors: a three-level meta-analysis. Environ Sci Technol. 2023;57(48):19838–48. https://doi.org/10.1021/acs.est.3c04201

66. Aydin E, Šimanský V, Horák J, Igaz D. Potential of biochar to alternate soil properties and crop yields 3 and 4 years after the application. Agronomy. 2020;10(6):889. https://doi.org/10.3390/agronomy10060889

67. Hall D, Bell R. Biochar and compost increase crop yields but the effect is short term on sandplain soils. Pedosphere. 2015;25(5):720–8. 2015. https://doi.org/10.1016/S1002-0160(15)30053-9

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