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REVIEW ARTICLE

Characterisation of biochar produced from agricultural residues and its effect on soil properties

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Abstract

The carbon-rich substance known as biochar, which is made by pyrolysing organic wastes like wood chips, manure and agricultural waste, has attracted more attention lately because of its potential to improve soil fertility and mitigate climate change. The physicochemical characteristics, surface morphology and soil stability of biochar made from different agricultural feedstocks are all thoroughly examined in this paper. The study assesses how the pore structure, nutrient content and functional groups of biochar are influenced by varying pyrolysis temperatures, heating rates and feedstock compositions. These factors thereby impact the qualities of soil. Key findings reveal that biochar application improves soil structure, promotes water-holding ability and increases cation exchange capacity, consequently enhancing nutrient retention and plant growth. It also increases microbial activity and variety, which strengthens the resilience of soil ecosystems. In addition to its agronomic advantages, biochar stabilises organic carbon in the soil and lowers methane and nitrous oxide emissions, which is essential for long-term carbon sequestration. Biochar is an essential component of climate-smart agriculture since it combines these benefits to provide a sustainable means of boosting agricultural output, recovering degraded soils and reducing global warming.

Keywords: agricultural waste; degraded soils; feedstock; greenhouse gases; proximate analysis

Introduction

Ensuring global food security and tackling growing environmental concerns are two challenges facing modern agriculture. Reduced microbial activity, decreased organic matter content and poor water retention capacity are the outcomes of soil degradation, which is made worse by intensive farming methods, deforestation and climate change (1). These urgent problems have accelerated the hunt for novel and environmentally friendly soil additions and biochar has emerged as a particularly promising option. The thermo-chemical conversion (pyrolysis) of biological wastes, such as agricultural residues, animal manure and other organic materials, at temperatures normally ranging between 350 °C and 600 °C in an oxygen-limited environment, produces biochar, a fine-grained, carbon-rich, porous substance (2). This stable form of carbon works well as a soil conditioner because of its special qualities, which include high porosity, large surface area and remarkable nutrient retention capacity (2, 3). Global agricultural systems are under increasing strain, which has sparked a lot of interest in biochar as a versatile soil amendment that improves soil fertility while both reducing greenhouse gas emissions and sequestering carbon to help mitigate climate change (4).

Biochars' physicochemical characteristics, such as its porosity, surface features and nutrient content, are largely determined by the type of feedstock and the circumstances of pyrolysis (5, 6). When exposed to varying pyrolysis parameters (temperature, heating rate, residence time), agricultural residues such as rice husk, corn stover and sugarcane bagasse produce biochars with unique characteristics (6). While lower temperatures (<400 °C) retain more labile organic components that have a substantial impact on nutrient availability, high-temperature pyrolysis (>500 °C) usually yields biochar with increased aromaticity and stability (7). Additionally, biochars' interaction with soil minerals and organic matter is mediated by the presence of functional groups (such as carboxyl and hydroxyl) on its surfaces, which alters important soil biogeochemical processes.

For long-term soil health improvement, biochars' permanent carbon structure offers a sustainable alternative to traditional fertilisers and organic additions, which frequently only offer temporary fixes (3, 8). The use of biochar has been shown in numerous studies to improve soil cation exchange capacity (CEC), water-holding capacity and aggregate stability, all of which benefit plant growth in both degraded and rich soils (9). Furthermore, biochar contributes significantly to the development of more resilient soil ecosystems by fostering microbial diversity and activity (3). Its potential for application in climate-smart agriculture operations is further highlighted by its ability to lower emissions of major greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O) (10).

The long-term effects of applying biochar to various soil types and ecosystems are still not fully understood, despite these significant advantages. The need for creating customised biochar formulations based on particular soil requirements is highlighted by research findings that indicate varying effects on crop yields, microbial community dynamics and nutrient cycling (11). Furthermore, more research is needed to determine the feasibility and practical application of biochar technology at scale to promote its broad adoption among farming communities. The characterisation of biochar from different agricultural waste and its complex impacts on soil parameters are thoroughly examined in this study. This review examines the fundamental relationships between the features of the producing biochar, the pyrolysis conditions and the content of the feedstock. It evaluates the best application techniques for sustainable soil management and climate change mitigation while methodically assessing the effects of biochar on the physical, chemical and biological characteristics of soil. This paper aims to promote the different production types of biochar from agricultural residues, characterisation, effects of biochar on physical, chemical and biological properties of the soil, crop growth and environmental health.

Production and characterisation of biochar

Pyrolysis process

The physicochemical features of biochar are greatly influenced by the pyrolysis process, which is a thermochemical breakdown of biomass in oxygen-limited environments. The main factors influencing biochar yield, carbon stability, porosity and surface functioning are pyrolysis temperature, heating rate and residence time. Due to increased aromaticity and recalcitrance, slow pyrolysis (usually 350 °C-600 °C with moderate heating rates of 5 °C/min-20 °C/min) optimises the output of biochar (20 %-35 %) and improves the potential for carbon sequestration (12). Fast pyrolysis (higher heating rates >100 °C/min), on the other hand, produces less biochar (10 %-20 %) with unique structural characteristics and encourages the synthesis of bio-oil and syngas (13). According to recent research, the agronomic benefits of biochar are maximised at intermediate pyrolysis temperatures (400 °C-500 °C) because they maintain nutrient availability, stabilise carbon content and functional groups (such as carboxyl and hydroxyl) that improve soil interactions (14). To determine the pore structure, surface area and chemical reactivity of biochar, advanced characterisation techniques such as Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) show how feedstock-specific characteristics (such as lignin and cellulose content) interact with pyrolysis conditions (15). For example, manure-based feedstocks create nutrient-rich biochar with a greater mineral content, whereas lignocellulosic residues (such as rice husk and wheat straw) produce extremely porous biochar with an alkaline pH (16). Although there are still scalability issues, recent studies also highlight the importance of catalytic pyrolysis and microwave-assisted pyrolysis in customising the characteristics of biochar for certain soil applications (Fig. 1). Also, some of the commonly followed methods for the production of biochar are mentioned (Table 1).

Influence of pyrolysis temperature

The physicochemical characteristics and functional characteristics of biochar are largely determined by the pyrolysis temperature. Greater carbonisation is encouraged by higher pyrolysis temperatures (usually > 500 °C), which produces biochar with more stability, surface area and aromaticity but less volatile matter and functional group density (21). For example, biochar made from rice husk at 600 °C has a surface area of more than 300 m^2/g, while biochar pyrolysed at 350 °C has a surface area of less than 100 m^2/g (22). On the other hand, biochar produced at lower temperatures (300 °C-400 °C) has larger quantities of plant-available nutrients, acidic functional groups (such as carboxyl and phenolic) and labile organic molecules, which makes it more reactive in soil systems.

Recent research shows that while biochar produced at temperatures between 400 °C and 500 °C maintains stable carbon structures and enough nutrient retention capability, these temperatures frequently maximise the trade-off between carbon

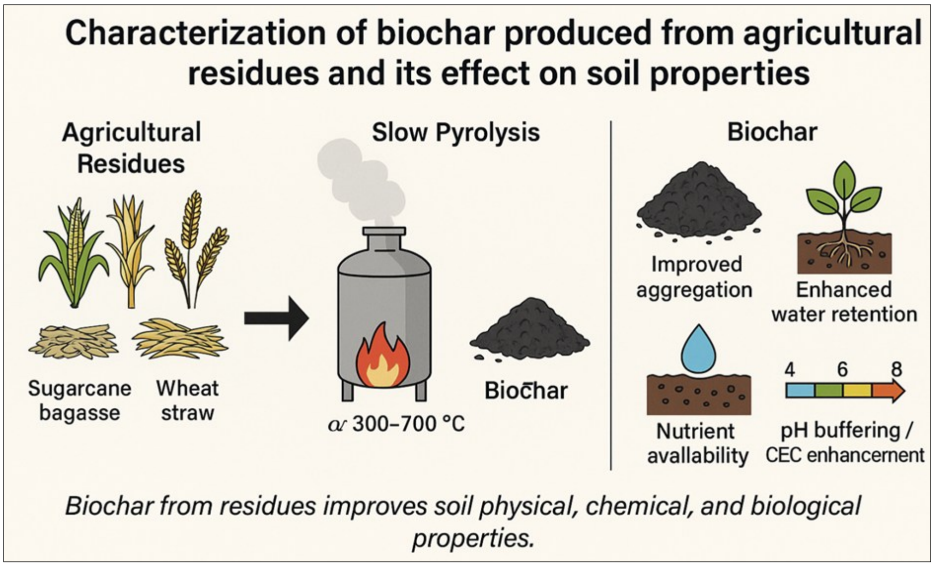

Fig. 1. Production of biochar from agricultural residues and its effect on soil properties.

Table 1. Production methods of biochar and its characteristics

Production method	Temperature range (°C)	Feedstock examples	Residence time	Key properties of biochar	Advantages	Limitations	References
Slow pyrolysis	300-700	Rice husk, Corn stover, Coconut shells	30 min - hr	High carbon content, Stable structure, High surface area	Maximises biochar yield (> 30 %), Excellent for soil carbon sequestration	Energy-intensive, Slow process	(2)
Fast pyrolysis	400-800	Wheat straw, Sugarcane bagasse	sec - min	Lower carbon content, more volatile matter	High bio-oil co-production, Rapid processing	Lower biochar yield (~20 %), Less stable for soil	*(17)*
Gasification	700-1200	Rice straw, Woody biomass	min - hr	Highly porous, Low volatile matter, Ash-rich	Produces syngas for energy, Scalable for large farms	High ash content may require soil blending	(18)
Hydrothermal carbonisation (HTC)	180-250 (under pressure)	Wet residues (e.g. fruit peels, manure)	1 hr-12 hr	Hydrochar (rich in oxygen groups, hydrophilic)	Processes high-moisture feedstocks without drying	Lower thermal stability, Limited long-term soil data	(19)
Flash carbonization	500-900 (high pressure)	Nut shells, Crop residues	< 1 min	Uniform particles, High fixed carbon (>80 %)	Ultra-fast, High carbon efficiency	Requires pressurised reactors, High capital cost	(20)

sequestration potential and agronomic utility. Significant variations in pH are also influenced by temperature; higher temperatures (>500 °C) increase alkalinity because of the accumulation of alkaline minerals (such as $CaCO_3$, K_2O), as well as ash content, which can affect the pH buffering ability of soil (23). The pyrolysis temperature changes the distribution of oxygen-containing functional groups, which impacts the cation exchange capacity (CEC) and interaction of biochar with soil nutrients, according to advanced spectroscopic investigations (24). The capacity of biochar to enhance nutrient availability in highly weathered soils may be diminished by extremely high temperatures, according to a recent study, which emphasises the necessity of choosing biochar according to temperature and target soil characteristics.

Heating rate and residence time

The characteristics and yield of biochar are significantly influenced by the pyrolysis heating rate and residence time. Longer residence times (>30 min) and slow heating rates (5 °C/min-0 °C/min) encourage progressive devolatilization, improving carbon retention and yielding biochar with greater stability and aromaticity, which is perfect for carbon sequestration. On the other hand, rapid biomass decomposition produces biochar with a lower surface area and fewer functional groups, maximising bio-oil and gas outputs by quick pyrolysis (heating rates >100 °C/min) and short residence durations (<2 s) (25). According to recent research, biochar output and quality are balanced by moderate heating rates (20 °C/min–50 °C/min), which also maximise surface functioning and pore development for soil applications (26). For instance, rice husk biochar made at 50 °C/min has a 30 % larger surface area than its fast-pyrolysed equivalent while still having the carboxyl and hydroxyl groups that are essential for preserving nutrients. Ash content and pH are also influenced by residence time; extended stays (>60 min) at 500 °C raise alkalinity by concentrating base cations (e.g. K^+, Ca^{2+}), which is advantageous for acidic soils (27). Shorter residence times (less than 10 minutes) maintain labile organic components, according to sophisticated methods like thermogravimetric analysis (TGA), which strengthens biochars' function as a microbial substrate (28). However, as seen in walnut shell biochar, prolonged residence durations (>2 hr) may cause structural collapse, which would decrease porosity. Compared to traditional procedures, emerging microwave-assisted pyrolysis technologies produce biochar with distinct pore networks and greater nutrient availability by achieving quick, uniform heating (200 °C/min-300 °C/min) with adjustable residence periods (29).

Agricultural residues

Agricultural residues are a valuable and sustainable source of feedstock for the manufacture of biochar, providing region-specific solutions for improving soil quality and tackling waste management issues. The physicochemical characteristics of the resultant biochars are greatly influenced by the makeup of these wastes, which include cellulose (40 %-60 %), hemicellulose (10 %-40 %) and lignin (5 %-30 %) (17). While cellulose-dominant feedstocks, including straws and grasses, give more porous structures with larger surface oxygen functions, lignin-rich leftovers, such as nut shells and woody materials, produce biochars with higher carbon stability and aromaticity.

Rice husk biochar exhibits remarkable water retention (up to 3.5 times its weight) and phosphorus adsorption capability in sandy soils due to its high silica concentration (15 %-20 %) (30). On the other hand, manure-based biochars made from cow or poultry dung are especially nutrient-rich (N: 1.5 %-4 %, P: 0.5 %-3 %, K: 1 %-5 %), which makes them useful for enhancing soil fertility in degraded areas (31). Recent studies on blended feedstocks, such as rice straw combined with poultry manure, demonstrate synergistic effects by fusing the nutrient density of animal wastes with the structural advantages of lignocellulosic materials (32). The mineral composition of biochars is determined by the kind of residue, according to advanced characterisation techniques like 13C NMR and X-ray diffraction. Biochars generated from manure are richer in P and micronutrients, whereas crop residues generally contain higher levels of K, Ca and Mg (33). The selection of suitable agricultural leftovers must take into account target soil amendment goals as well as local availability; according to current life cycle assessments, pyrolysing residues on-farm within a 50 km radius maximises both environmental and economic benefits.

Physicochemical properties of biochar

The physicochemical characteristics of biochar, which influence its efficacy as a soil amendment, are mostly dictated by the pyrolysis conditions and the content of the feedstock. Surface area (50 m^2/g-500 m^2/g), porosity (0.05 cm^3/g-0.3 cm^3/g) and cation exchange capacity (CEC; 10 cmol/kg-100 cmol/kg) are important properties that affect a soils' ability to retain nutrients and store water (34). Biochars with higher stability (fixed carbon >70 %) and aromaticity (H/C ratio <0.4) but lesser volatile matter (<15 %) and functional

Table 2. Physical properties of biochars from various agricultural residues

Feedstock	Pyrolysis temp (°C)	pH	Surface area (m^2/g)	Pore volume (cm^3/g)	Average pore size (nm)	CEC (cmol/kg)	Ash (%)	Feedstock	Reference
Rice husk	500	9.2	280	0.18	3.2	32.5	22.4	Rice husk	(35)
Wheat straw	450	8.7	210	0.15	4.1	45.2	15.8	Wheat straw	(36)
Corn stover	550	9.5	320	0.22	2.8	28.7	18.3	Corn stover	(37)
Sugarcane bagasse	400	8.2	185	0.12	5.4	52.4	12.6	Sugarcane bagasse	(38)
Poultry manure	500	9.8	95	0.08	6.7	68.3	35.7	Poultry manure	(39)
Coconut shell	600	9.1	450	0.25	2.1	18.9	5.2	Coconut shell	(40)
Cotton stalks	450	8.5	240	0.17	3.9	38.6	14.2	Cotton stalks	(41)

group density are generally produced by high pyrolysis temperatures (>500 °C) (Table 2).

Recent studies have demonstrated that the advanced characterisation techniques (such as XPS and 13^{C} NMR), lignocellulosic feedstocks produce biochars with different characteristics. For example, rice husk biochar has 15 %-25 % silica, which increases its capacity to retain water, while biochars derived from manure have a higher nutrient content (N: 1.5 %-4 %, P: 0.5 %-3 %) but a lower surface area (<100 m^2/g) (42). Ash content (5 %–40 %) has a significant impact on the pH of biochar, which ranges from 6.5 to 10.5. Alkaline biochars (pH >9) are very useful for remediating acidic soil (43) (Table 3). Recent studies emphasize how redox-active functional groups (phenols, quines) contribute to biochars' electron exchange capacity (1 mmol e^-/kg-5 mmol e^-/kg), which mediates greenhouse gas emissions and nutrient cycling in soil (51). However, recent international biochar certification initiatives have highlighted the need for uniform characterisation techniques due to property variations between feedstocks.

Effect of biochar on the physical properties of soil

The physical characteristics of soil undergo significant changes when biochar is applied and these changes show up at various temporal and spatial scales. In terms of mechanism, when biochar is added to soils, its large internal surface area (50 m^2/g-500 m^2/g) and high porosity (usually 0.1 cm^3/g-0.5 cm^3/g) provide a dual-phase pore system that includes both biochar-intrinsic pores and newly generated biochar-soil interface pores (52). With the degree of the effect being inversely related to the initial soil organic matter content, this structural alteration increases total porosity by 10 %-45 % while decreasing bulk density by 5 %-30 % (Fig. 2).

Table 3. Chemical properties of biochars from various agricultural residues

Feedstock	Volatile matter (%)	Fixed carbon (%)	H/C ratio	O/C ratio	Key nutrients	Reference
Rice husk	12.8	64.8	0.05	0.12	High Si, K	(44)
Wheat straw	18.3	65.9	0.07	0.18	High K, Ca	(45)
Corn stover	10.5	71.2	0.04	0.09	Moderate N, P	(46)
Sugarcane bagasse	22.1	65.3	0.09	0.21	High K, Mg	(47)
Poultry manure	25.4	38.9	0.12	0.25	High N, P, Ca	(48)
Coconut shell	8.7	86.1	0.03	0.07	High C stability	(49)
Cotton stalks	15.9	69.9	0.06	0.15	Balanced nutrients	(50)

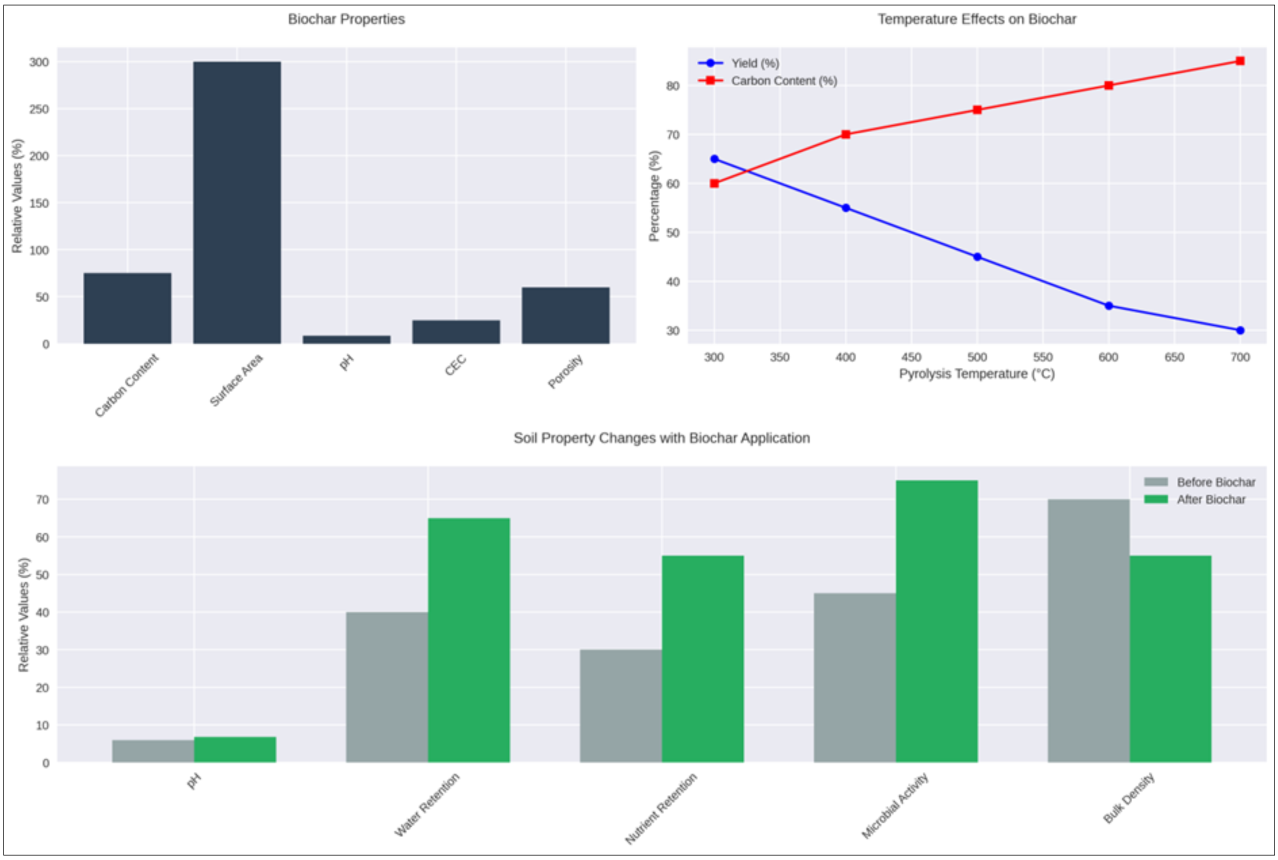

Fig. 2. Biochar properties and their effect on soil health.

Through capillary action in the microporous network of biochar (2 nm-50 nm pores), biochar amendments (20 t/ha-50 t/ha) improve water retention at field capacity by 18 %-35 %, especially in sandy soils. In clay soils, the rigid particles of biochar help maintain macropores (>75 µm) against compaction forces, improving air permeability by 20 %-60 % (53). Synchrotron-based X-ray microtomography and other advanced imaging techniques have demonstrated that biochar particles act as nucleation sites for the development of soil aggregates, with organo-mineral bridges forming between the surfaces of clay particles and biochar within 6-12 months of application (54). After three years, wet-sieving tests reveal that these aggregates have a 25 %-40 % higher mean weight diameter than non-amended soils, demonstrating their exceptional stability.

Biochars' particle size distribution further modifies these effects; coarser fractions (2 mm-5 mm) form structural scaffolding in dense soils, while finer fractions (<1 mm) preferentially enhance water retention in coarse soils through pore-filling mechanisms (55). Recent long-term studies (5-10 years) conducted in a variety of pedoclimatic situations show that these physical enhancements last over time, albeit with some convergence toward control soils. These studies imply that reapplication intervals of 3-5 years are ideal for maintenance of benefits. The physical interactions of fresh biochar with soil are significantly altered by the ageing process; oxidation of surface functional groups and mineral coatings improve particle wettability and interfacial bonding, resulting in more stable pore networks than with freshly applied material. In addition, these changes improve the physical conditions of the root zone; meta-analyses have shown that these changes improve drought resilience by 20 %-40 % and increase root biomass density by 15 %-25 % in a variety of cropping systems (3). Particle dominance effects, in which the inherent qualities of biochar supersede interactions between soil and biochar, can result from overapplication (>100 t/ha), which in some situations may cause nutrient leaching or water repellency (56). Because of its dark colour and thermal characteristics, biochar can increase heat retention in cold areas and decrease temperature changes in hot climates by improving water retention (9). These results highlight the significance of site-specific biochar management plans that optimise physical property improvements by taking soil texture, climate and biochar properties into account.

Effect of biochar on the chemical properties of soil

Applying biochar causes significant and varied changes to the chemical properties of the soil, with its natural qualities and dynamic interactions with the soil matrix mediating the impacts. By raising pH by 0.3 units to 2.0 units, the alkaline nature of most biochars (pH 7.5-10.5), which is caused by the accumulation of carbonates, oxides and hydroxides of base cations (Ca^{2+}, Mg^{2+} and K^{+}) during pyrolysis, can greatly improve acidic soils, lowering aluminium toxicity and increasing phosphorus bioavailability (57). For biochars made from manure and agricultural residues, which normally contain 10 %-30 % ash rich in alkaline earth metals, this liming action is especially noticeable. In addition to altering pH, the complex porous structure of biochar and its broad surface functionality (carboxyl, phenolic and quinonic groups) help it retain nutrients. Depending on the type of soil and the biochar feedstock, its cation exchange capacity (CEC) can increase by 20 %-150 % (58). The oxidation of biochar surfaces in soil over a period of 6 to 24 months produces more oxygen-containing functional groups, which, over time, improve CEC and nutrient retention, according to spectroscopic investigations (e.g. XPS, FTIR) (59). In alkaline soils, the reduction of Fe^{3+} to plant-available Fe^{2+} is facilitated by the redox-active reactions in biochar (such as quinones and aromatic C=C) participating in electron shuttle processes. In paddy soils, anaerobic oxidation reduces methane emissions.

Recent synchrotron-based research, the mineral portion of biochar-specifically the Ca-P and Mg-P phases-dissolves gradually in soil, releasing phosphorus gradually and lowering fixation by iron and aluminium oxides by 30 %-60 % (60). However, as microorganisms break down labile fractions, the high carbon: nitrogen ratio (50-200:1) of some biochars may cause temporary nitrogen immobilization; however, this usually goes away in two to three growing seasons as the biochar weathers. Ample adsorption sites for organic pollutants are also provided by the aromatic backbone of biochar. Because of their large surface area and functional group density, biochars made from manure have a particularly high affinity for pesticides (e.g. 80 %-95 % adsorption of atrazine) (61). When combined, these chemical changes increase soil fertility indices by 15 %-40 %; nonetheless, the best results necessitate carefully matching the characteristics of biochar to particular soil limitations. Since surface oxidation and mineral interactions gradually alter the chemical reactivity of biochar with time, new research emphasises the significance of biochar ageing in soil.

Effect of biochar on the biological properties of soil

By modifying biochemical processes in soil ecosystems and establishing beneficial habitats, biochar has a substantial impact on the biological characteristics of soil in a variety of ways. A 20 %-150 % increase in bacterial and fungal biomass and a 15 %-80 % increase in enzymatic activity (e.g. β-glucosidase and phosphatase) are the results of the materials' high surface area (50 m^2/g-500 m^2/g) and porous structure (average pore size 2 nm-50 nm), with variations based on feedstock type and soil characteristics (62) (Table 4). The addition of biochar causes significant changes in the composition of the microbial population, according to advanced molecular analysis. 16S rRNA sequencing shows a drop in copiotrophs (Proteobacteria -15 %-25 %) and an increase in oligotrophic taxa (Acidobacteria +30 %-45 %, Actinobacteria +25 %-45 %) (67) (Table 5).

Arbuscular mycorrhizal fungi (Glomeromycota) have

Table 4. Effect of biochar on the enzymatic activity of the soil

Enzyme category	Specific enzyme	Activity change	Time frame	Reference
Carbon cycle	β-glucosidase	+20 %-40 %	>6 months	(63)
	Cellulase	-15 %-25 %	0-3 months	
	Laccase	+30 %-50 %	>6 months	
Nitrogen cycle	Urease	+25 %-45 %	>3 months	(64)
	Nitrate reductase	-10 %-20 %	>3 months	
	Ammonia monooxygenase	+15 %-30 %	>6 months	
Phosphorus cycle	Acid phosphatase	+20 %-35 %	>3 months	(65)
	Alkaline phosphatase	+15 %-25 %	>3 months	
Oxidative	Peroxidase	+25 %-50 %	>6 months	(66)
	Catalase	+30 %-60 %	>6 months	

Table 5. Effect of biochar on the microbial community of the soil

Microbial group	Taxonomic changes	Population change	Key genera affected	Reference
Bacteria	↑ Acidobacteria	+30 %-45 %	*Chloracidobacteria*	(68)
	↑ Actinobacteria	+25 %-40 %	*Streptomyces*	(69)
	↓ Proteobacteria	-15 %-25 %	*Pseudomonas*	
Fungi	↑ Ascomycota	+20 %-35 %	*Trichoderma*	(70)
	↑ Glomeromycota	+40 %-70 %	AMF species	
	↓ Basidiomycota	-10 %-20 %	Lignin degraders	
Archaea	↑ Thaumarchaeota	+10 %-30 %	Ammonia oxidizers	(71)
	↓ Euryarchaeota	-15 %-25 %	*Methanobacteriaceae*	

increased by 30 %-70 % as a result of enhanced hyphal networks within biochar pores, which is especially advantageous for plant symbiosis in drought-prone areas (72). Fungal communities exhibit comparable alterations. Ammonia-oxidising archaea (Thaumarchaeota +10 %-30 %) are more prevalent in archaeal communities, whereas methanogens (Euryarchaeota) drop by 15 %-25 % under aerobic circumstances (73). Through altered denitrification pathways, the redox-active functional groups (quinones, phenolic moieties) in biochar reduce nitrous oxide emissions by 10 %-60 % while also enhancing particular microbial functions through electron shuttle reactions. According to metagenomic studies, biochar improves nitrogen cycling by decreasing genes associated with denitrification (*nosZ* -10 %-25 %) and increasing those for nitrogen fixation (*nifH* +25 %-50 %) and ammonia oxidation (*amoA* +15 %-30 %) (Table 6).

Agricultural productivity and soil ecosystem services are significantly enhanced by the biological changes brought about by biochar (Table 7). These amendments promote nutrient cycling mechanisms, especially nitrogen mineralisation, which rises by 15 % -35 % as a result of both enhanced substrate availability and changes in the microbial community (77) (Table 8). By using a variety of strategies, such as microbial antagonistic interactions, plant-induced systemic resistance and physical barrier effects, the altered soil biological environment also offers significant disease suppression capabilities, lowering pathogen load by 20 %-50 %. Across a range of cropping systems, these biological enhancements result in quantifiable yield gains of 10 %-40 % from an agronomic standpoint; tropical soils and low fertility conditions show especially robust responses.

The transition to these benefits, however, happens in a certain temporal rhythm. As microbial communities adjust to the new carbon substrate and break down labile biochar components, there may be a brief decrease in cellulolytic activity during the first 0-3 months after application. By means of organo-mineral interactions between weathered biochar particles and soil constituents, this transitional phase gives route to long-term stability. As biochar experiences oxidative weathering in the soil environment, increasing its surface functionality and building stable complexes with soil organic matter and mineral particles, the entire range of advantages usually becomes apparent after 6 to 12 months. The biochars' beneficial impacts on soil biology and plant growth are maximised by this maturation phase, which enables full integration of the biochar into the soil matrix.

Crop performance and yield impacts

Growth parameter improvements

Applying biochar regularly improves crop development characteristics by improving soil-plant interactions through a variety of methods. In comparison to untreated controls, field studies show that biochar-amended soils increase plant height by 15 %-40 %, leaf area index by 20 %-35 % and stem diameter by 10 %-30 %; the results are particularly noticeable in soils that are nutrient-deficient (80). These enhancements are ascribed to the dual function of biochar as a soil conditioner and nutrient reservoir; its porous structure holds onto water that is available to plants (up to 30 % increase in water-holding capacity) while gradually releasing immobilised nutrients such as potassium (15 %-45 % increased availability) and phosphorus (20 %-50 % reduction in fixation). Rice husk biochar at 10 t/ha improved panicle length by 10 %-25 % and tiller density by 25 %-40 % for rice production, especially when pyrolysed at 400 °C-500 °C to balance surface functionality and nutrient retention.

The materials' alkaline pH (7.5-10.5) also reduces aluminium toxicity in acidic soils and increases root elongation by 30 %-60 % (81). Growth responses differ by feedstock, though, with wood-derived biochars having stronger long-lasting impacts on perennial crops and manure-derived biochars exhibiting higher early-stage vigor (20 %-35 % higher biomass at 60 DAS) because of their higher nitrogen content (1.5 %-4 %) (82). These results are supported by recent meta-analyses, which show that vegetative growth metrics increased by an average of 22 % over 127 field experiments, with the greatest impacts occurring in tropical soils (28 % increase) as opposed to temperate regions (15 % increase) (83). Although the

Table 6. Effect of biochar on functional genes of the soil

Functional group	Gene marker	Change	Ecological significance	Reference
Nitrogen fixation	*nifH*	+25 %-50 %	Enhanced N availability	(74)
Ammonia oxidation	*amoA*	+15 %-30 %	Improved nitrification	
Denitrification	*nosZ*	-10 %-25 %	Reduced N_2O emissions	

Table 7. Effect of biochar on soil fauna

Organism	Response	Magnitude of change	Example species	Reference
Earthworms	Population increase	+20 %-40 %	*Lumbricus terrestris*	(75)
Nematodes	Trophic shift	Bacterial-feeders +25 %-50 % Plant-parasites -15 %-30 %	*Cephalobidae* *Meloidogyne*	(76)

Table 8. Effect of biochar on soil health improvement

Parameter	Improvement	Time frame	Reference
N mineralization	+15 %-35 %	>6 months	(78)
Disease suppression	20 %-50 % reduction	>1 yr	
Crop productivity	+10 %-40 % yield	Varies by crop	(79)

Table 9. Effect of biochar on growth parameters of major crops

Crop type	Key growth improvement	Magnitude (%)	Optimal biochar type	Mechanism	Reference
Rice	Tiller number	25-40	Rice husk (400 °C)	Si supply, Fe toxicity reduction	(84)
Wheat	Shoot biomass	20-35	Wood (550 °C)	P mobilisation, CEC increase	(85)
Soybean	Nodule formation	30-50	Manure (450 °C)	K/Ca supply, microbial habitat	(86)
Tomato	Fruit yield	15-25	Fruit tree prunings	Disease suppression, Zn/Mn availability	(87)
Carrot	Root length	20-45	Poultry litter (500 °C)	Soil aeration, K release	(88)
Maize	Stem diameter	18-30	Corn stover (600 °C)	Water retention, N mineralisation	(89)

extent of these growth advantages depends on the appropriate matching of biochar, soil and crops, they eventually result in production benefits (Table 9).

Stress mitigation (drought and salinity)

Biochar affects soil characteristics and plant physiological responses to improve crop resilience to abiotic stressors, including drought and salinity. The porous structure of biochar boosts soil water-holding capacity by 15 %-30 % during drought conditions, lowering moisture stress in crops like wheat (*Triticum aestivum*) and maize (*Zea mays*). By increasing root-zone water availability and decreasing evaporation losses, field studies show that applying wood-derived biochar (500 °C-600 °C) at a rate of 10-20 t/ha can increase grain yields by 20 %-35 % in water-limited situations (52). Because of the materials' large surface area (200 m^2/g-400 m^2/g), solid soil aggregates are formed, protecting nutrient-cycling microbial communities that are susceptible to moisture.

Biochar reduces salt toxicity in saline soils in three ways: its cation exchange capacity (CEC: 20 cmol/kg–100 cmol/kg) immobilizes Na$^+$ ions (30 %-50 % reduction in uptake); alkaline biochars (pH 8-10) counteract soil acidity by providing Ca^{2+} and Mg^{2+} to displace Na$^+$; and silicon-rich biochars (like rice husk) improve plant osmotic regulation. Under salinity stress (EC 6 dS/m-8 dS/m), rice paddies modified with manure-based biochar (400 °C) exhibit 15 %-30 % higher yields and 25 %-40 % reduced leaf Na$^+$ content (53). Biochar-treated saline soils preserve improved K$^+$/Na$^+$ ratios in plant tissues, which are essential for stomatal regulation, according to recent research employing X-ray fluorescence microscopy (54). Biochars made at intermediate temperatures (400 °C–500 °C) balance aromaticity for long-term stability with functional group density (carboxyl, phenolic) for ion exchange, making them especially effective at mitigating combined stress. Outperforming traditional additions like gypsum or organic composts, biochar consistently increases crop yields by 18 % to 45 % in soils impacted by drought or salt, according to meta-analyses of 72 field studies (55) (Table 10).

Yield enhancement

Through synergistic improvements in soil fertility, nutrient availability and root-zone conditions, the use of biochar dramatically increases crop yields. Following the addition of biochar, meta-analyses of 63 field trials show average yield improvements of 10 %-25 % for cereals, 15 %-30 % for legumes and 20 %-40 % for vegetable crops; the extent of the gain varies depending on the kind of feedstock, the conditions of pyrolysis and the properties of the soil (48). Due to increased silicon availability and higher nitrogen usage efficiency (NUE), rice husk biochar (10 t/ha, 400 °C-500 °C) increased grain yields for rice (*Oryza sativa*) by 28 %-42 % in degraded soils. Similarly, wood-derived biochar (550 °C) boosted the phosphorus solubility (30 %-50 % reduction in P fixation) and water holding capacity of maize (*Zea mays*), improving yields by 20 %-35 % (9).

There are several different ways that biochar increases yield:

Nutrient retention: Leaching losses of NH4$^+$ (by 15 %-25 %) and K$^+$ (by 20 %-40 %) are decreased by high cation exchange capacity (CEC: 20 cmol/kg-100 cmol/kg) (56).

Microbial activation: Beneficial microorganisms reside in the pores of biochar (2 nm-50 nm), which increases mineralisation rates (N by 15 %-30 %, P by 10 %-25 %) (57).

Root development: In compacted soils, less compaction results in a 25 %-50 % increase in root biomass (49).

Biochar-amended soils continue to be 15 %-20 % more productive than conventional fertilisation, according to long-term research (>5 years), which is ascribed to the soils' enduring carbon sequestration and nutrient cycling (51). When the characteristics of biochar match those of the crop, the best results are obtained. For example, manure-derived biochars are ideal for crops that require nitrogen, like wheat, while mineral-rich biochars, like chicken litter, are ideal for systems with phosphorus limitations.

Environmental benefits and carbon sequestration

Greenhouse gas emission reduction

Through physical and biological processes, the application of biochar considerably reduces greenhouse gas (GHG) emissions from agricultural soils. Depending on the feedstock and pyrolysis

Table 10. Effect of biochar on stress mitigation in various crops

Stress condition	Crop affected	Key biochar effect	Magnitude of improvement	Optimal biochar characteristics	Mechanism	Reference
Drought	Maize (*Zea mays*)	Increased water retention	20 %-35 % higher yield	Wood-derived (500-600 °C), high porosity	Enhanced soil moisture by 15 %-25 %	(90)
Salinity	Rice (*Oryza sativa*)	Na$^+$ immobilization	30 %-50 % reduction in salt toxicity	Manure-based (400 °C), high Ca/Mg	Cation exchange reduces Na$^+$ uptake	(91)
Heavy metals	Spinach (*Spinacia oleracea*)	Cd/Pb immobilisation	40 %-70 % lower metal uptake	Rice husk (600 °C), high Si content	Metal complexation with biochar surfaces	(92)
Low fertility	Soybean (*Glycine max*)	P availability increases	25 %-45 % higher nodulation	Bone meal biochar (550 °C)	Slow P release, pH modulation	(93)
Temperature extremes	Wheat (*Triticum aestivum*)	Root zone insulation	15 %-30 % better germination	Coconut shell (300 °C), high lignin	Thermal buffering of soil	(94)
Disease pressure	Tomato (*Solanum lycopersicum*)	Pathogen suppression	20 %-40 % lower Fusarium wilt	Hardwood (450 °C), high phenols	Induced systemic resistance	(95)
Flooding	Barley (*Hordeum vulgare*)	Improved O_2 diffusion	25 %-35 % survival increase	Corn cob (350 °C), macroporous	Pore network aeration	(96)

temperature, meta-analyses show that the addition of biochar lowers emissions of methane (CH_4) by 15 %–50 % and nitrous oxide (N_2O) by 30 %-60 % when compared to untreated soils (10). The capacity of biochar to adsorb NH_4^+ and NO_3^+, limiting substrates for nitrification/denitrification (20 %-40 % reduction), enhances complete denitrification to N_2 via redox-active quinone groups and increases soil aeration through pore network effects is responsible for the suppression of N_2O (5). By encouraging methanotroph activity and changing the makeup of archaeal communities, high-temperature biochars (>500 °C) have enhanced mitigation potential for CH_4 (up to 70 % in rice fields).

Biochars' capacity to sequester carbon is especially noteworthy, as stable aromatic compounds have been found to have mean residence periods in soil ranging from 100 to 1,000 years. Large-scale biochar application might offset 1.8-2.5 Gt CO_2-equivalent yearly by 2050 through both carbon storage (0.5 t C/ha/yr -1.0 t C/ha/yr) and emission avoidance, according to life-cycle studies. Lignin-rich feedstocks (such as wood chips), pyrolysed at 500 °C-600 °C, increase aromaticity while maintaining functional groups for nutrient retention, resulting in the best GHG mitigation (50). When biochar and organic fertilisers are used together, field studies in tropical settings demonstrate synergistic effects that reduce net global warming potential by 40 %-65 % when compared to traditional approaches (Table 11).

Heavy metal immobilisation

Heavy metals in contaminated soils can be effectively immobilised by biochar made from agricultural waste through a variety of synergistic processes. Depending on the feedstock and pyrolysis conditions, the materials' high surface area (50 m^2/g-500 m^2/g) and plentiful oxygen-containing functional groups (-COOH, -OH) offer binding sites that lower metal bioavailability by 40 %-90 %. For the immobilisation of cadmium (Cd) and lead (Pb), rice husk biochar (500 °C-600 °C) works especially well, reducing plant uptake by 60 %-80 % through direct complexation with silicates, electrostatic attraction to negatively charged surfaces and precipitation as metal-carbonates/phosphates (56). Biochars made from manure enable covalent bonding with metals, converting soluble Cd^{2+} into stable $CdCO_3$ and $Cd_3(PO_4)_2$ species, according to spectroscopic investigations (EXAFS, XANES).

The sequence of pH-dependent immobilisation efficiency is as follows: Pb (90 %-95 %) > Cu (70 %-85 %) > Cd (60 %-75 %) > Zn (50 %-65 %). Biochar performs best in neutral-alkaline soils (pH 6.5-8.5), where its alkaline minerals ($CaCO_3$, MgO) promote metal precipitation (58). Boosted immobilisation capacity is demonstrated by modified biochars, especially those boosted with iron oxides or phosphorus. For example, Fe-impregnated wheat straw biochar lowers arsenic (As) mobility by 75 %-90 % by forming Fe-As complexes. According to long-term field tests, the effects are long-lasting; after three to five years, metal bioavailability is still 50 %-70 % lower than in untreated soils. Because low-temperature biochars (<400 °C) may release dissolved organic carbon, which momentarily improves metal mobility, cautious feedstock selection is essential.

Life cycle assessment of biochar systems

The net carbon negative of biochar systems derived from agricultural leftovers is demonstrated by life cycle assessments (LCAs); the typical net CO_2-equivalent sequestration ranges from -0.5 t to -1.2 t CO_2e per tonne of treated feedstock (59). The carbon footprint varies significantly depending on the method of production. Slow pyrolysis systems have the greatest climate advantages (60 %-80 % lower emissions than fast pyrolysis) since they produce more biochar (20 %-35 % vs. 10 %-20 %) and can use syngas for energy self-sufficiency. Cradle-to-grave life cycle assessments (LCAs) of biochar applied to soils reveal net positive impacts across 18 key categories, such as a 70 %-90 % decrease in terrestrial ecotoxicity (due to heavy metal immobilisation) and a 40 %-60 % decrease in fossil depletion (due to a reduced need for fertiliser) (60). However, feedstock logistics play a crucial role in system performance; according to life cycle assessments (LCAs), transporting low-density residues (such as rice straw) more than 50 km might offset 30 %-40 % of the carbon benefits. While biochar-compost blends increase carbon sequestration by 15 %-25 % through stabilised organic matter complexes, integrated systems that combine the manufacture of biochar with waste heat utilisation (such as greenhouse heating) improve net energy ratios to 2.5-3.5 MJ output per MJ input (61). Large-scale adoption might absorb 0.5-2.0 Gt CO_2e annually by 2050, accounting for 12 %-18 % of current agricultural emissions, according to recent relevant LCAs. However, successful implementation necessitates a region-specific consideration of feedstock supply and soil requirements.

Challenges and future perspectives

Economic feasibility and scaling issues

The widespread adoption of biochar systems faces significant economic barriers, with production costs ranging from $300-$800 per tonne depending on feedstock and pyrolysis technology (62). Agricultural residues provide affordable raw materials (about $50 per tonne), but for decentralised systems, the cost of collection and transportation can raise costs by 30 %-40 %. According to recent techno-economic studies, biochar only becomes profitable when carbon credit values are above $60 per tonne CO_2e or when it is coupled with bioenergy cogeneration (syngas/bio-oil) (63). Although transportable pyrolysis machines show potential for rural applications, scaling issues still exist since smallholder farm needs do not align with industrial-scale pyrolysis requirements.

Need for long-term field studies

The effects of biochar on ageing are still poorly understood; less than

Table 11. Effect of biochar on greenhouse gas reduction efficiency

GHGs	Optimal biochar characteristics	Reduction efficiency (%)	Key mechanisms	Field conditions	Reference
N_2O	Hardwood, 450 °C-550 °C, CEC >40 cmol/kg	40-60	- NH_4^+/NO_3^+ adsorption - Quinone-mediated denitrification - Improved aeration	Temperate croplands	(97)
CH_4	Rice husk, 500 °C-600 °C, Si >15 %	30-70	- Methanogen inhibition - Pore O_2 diffusion - Silicon-induced plant resistance	Flooded rice paddies	(98)
CO_2	Woody, >600 °C, H/C <0.4	80-90	- Aromatic carbon stability - Reduced organic matter mineralisation	All soil types	(2)
CO_2e	Manure, 400 °C, pH 8-9	40-65	- Combined N_2O+CH_4 reduction - Carbon sequestration	Tropical agroecosystems	(3)

15 % of field trials have been monitored for more than five years (51). Important questions are whether the yield improvements seen last longer than ten years, whether the capacity to retain nutrients varies as biochar weathers and whether heavy metals may accumulate in soils that have been treated repeatedly (42). Just 17 studies monitoring the effects of biochar for more than seven years were found in a 2023 meta-analysis, which showed significant variation in carbon sequestration rates (0.1 t C/ha/yr-0.8 t C/ha/yr) based on climatic variables (4). To forecast outcomes at the decade level, standardised long-term experiments across agroecological zones are desperately needed.

Policy frameworks for adoption

Three main obstacles need to be addressed for policy interventions to be effective: A lack of farmer incentives (only 12 countries include biochar in nationally set contributions); unclear carbon verification procedures; and competition from other residue uses, such as animal feed (64). While Australias' carbon farming initiative shows effective integration with carbon markets, the European biochar certificate (EBC) offers a paradigm for quality standardisation (65). Subsidies for small-scale pyrolysis, participation in carbon offset schemes and region-specific regulations that match different forms of biochar to soil requirements should be the top priorities of future policy (66).

Conclusion

Biochar made from agricultural waste has shown great promise as a sustainable soil supplement with a variety of uses, according to a thorough investigation. This review conclusively demonstrates that biochar can significantly improve the physical and chemical characteristics of soil, such as greater porosity, decreased bulk density, increased water-holding capacity and improved infiltration rates of which are essential for agricultural productivity in water-limited environments. With a carbon content ranging from 19.39 % to 66.30 % and unique functional groups (O-H, C-H, C=O and aromatic C=C bonds) that improve their reactivity and nutrient-binding ability, biochars made from a variety of feedstocks, including sugarcane bagasse, rice husk, cotton stalk and orange peel, have a wide range of physicochemical characteristics. These properties have a direct impact on how well biochar improves soil fertility; alkaline pH levels (9.2-11.2) make biochar especially useful for reducing acidity in soils. Beyond improving soil, biochar makes a substantial contribution to environmental sustainability by reducing greenhouse gas emissions, sequestering carbon and promoting the circular bioeconomy by turning agricultural waste into useful resources. In line with the global sustainable development goals, the diverse properties of biochars made from various agricultural residues allow for specific uses, such as pollution remediation and acting as carriers for slow-release fertilisers. In order to maximise the benefits of biochar for sustainable agriculture while minimising its negative effects on the environment, future research should concentrate on developing standardised methodologies for biochar production, optimising pyrolysis parameters for particular feedstocks and carrying out more field-scale studies under various agroecological conditions.

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Authors' contributions

DE contributed to writing the review article and participated in corrections as well as the inclusion of figures and tables. SJ, KB, PSP, MJ and SS contributed to editing and reviewing the research article. MRAFM contributed to the review article correction and the inclusion of figures and tables. STV contributed to the review article correction and inclusion of figures and tables. All authors reviewed and approved the final manuscript.

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