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REVIEW ARTICLE

Carbon sequestration potential of biochar for sustainable agriculture

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Abstract

Biochar, a carbon-rich product from biomass pyrolysis, presents a promising solution for sustainable agriculture, particularly in long-term carbon sequestration and soil enhancement. Its durability enables it to persist in soils for extended periods, functioning as a permanent carbon sink and helping to reduce atmospheric CO_2 levels. The stability and carbon sequestration potential of biochar is influenced by factors such as the type of feedstock used, pyrolysis conditions, soil characteristics and environmental factors. Incorporating biochar into sustainable agricultural practices, such as conservation tillage, cover cropping and agroforestry, can significantly improve soil health and carbon storage. Additionally, biochar contributes to soil quality by minimizing nutrient leaching and runoff, controlling erosion and aiding in soil restoration efforts. While biochar provides a range of environmental and agricultural benefits, further research is necessary to optimize its production, application, integration and stability across diverse landscape conditions.

Keywords: biochar; soil carbon sequestration; pyrolysis; soil properties; sustainability

Introduction

Between 1959 and 2016, human activities led to 415 GT of CO2 emissions, with 45 % accumulating in the atmosphere (1). Rising CO2 levels have severe environmental consequences, including global warming, extreme weather and ecosystem disruptions. The 2021 IPCC report stresses the urgency of enhancing carbon sinks to mitigate climate change (2, 3).

Biochar, a carbon-rich byproduct of pyrolysis, offers a promising solution, capable of sequestering up to 12 % of anthropogenic greenhouse gas emissions sustainably (4). It also enhances soil fertility by increasing microbial activity, reducing bulk density, improving nutrient retention and stabilizing soil organic matter (5, 6). As a carbon-negative industry, biochar contains recalcitrant organic carbon and a condensed aromatic structure, enhancing enzymatic activity, soil micro-porosity and nutrient availability (7, 8). While its effectiveness varies by soil type, small-scale farmers benefit from locally produced biochar to boost crop yields (9).

Biochar properties depend on feedstock, pyrolysis temperature (300-600 °C) and manufacturing methods (10). Recognizing its potential, policymakers included biochar in the 2008 U.S. Farm Bill to support research and development. The 21st UNFCCC (COP21) emphasized nature-based solutions like carbon farming to achieve net-zero emissions by 2050 and limit warming to 2 °C (11). Biochar's increasing adoption stems from its dual role in long-term carbon sequestration and soil improvement (12). It also enhances soil through physical (micro-porosity, reduced bulk density, improved water retention), chemical (nutrient retention, stabilized organic matter) and biological (boosted microbial activity, enzymatic processes) benefits (13). These qualities support climate mitigation, soil health and sustainable agriculture. The graphical abstract (Fig. 1) provides a visual summary of the study's key findings and conceptual framework.

Despite its advantages, biochar initiatives must ensure long-term CO2 removal and minimize leakage risks (14). Addressing these challenges is crucial for maximizing biochar's role in sustainable climate mitigation.

Mechanisms of carbon sequestration by Biochar

Biochar plays a significant role in carbon sequestration through various mechanisms, offering both environmental and agricultural benefits.

Physical mechanism

Biochar enhances carbon sequestration through several physical mechanisms that limit organic carbon decomposition and promote long-term stabilization in soils. One key mechanism is soil aggregation and occlusion, where biochar facilitates the formation of macro- and micro-aggregates, physically trapping

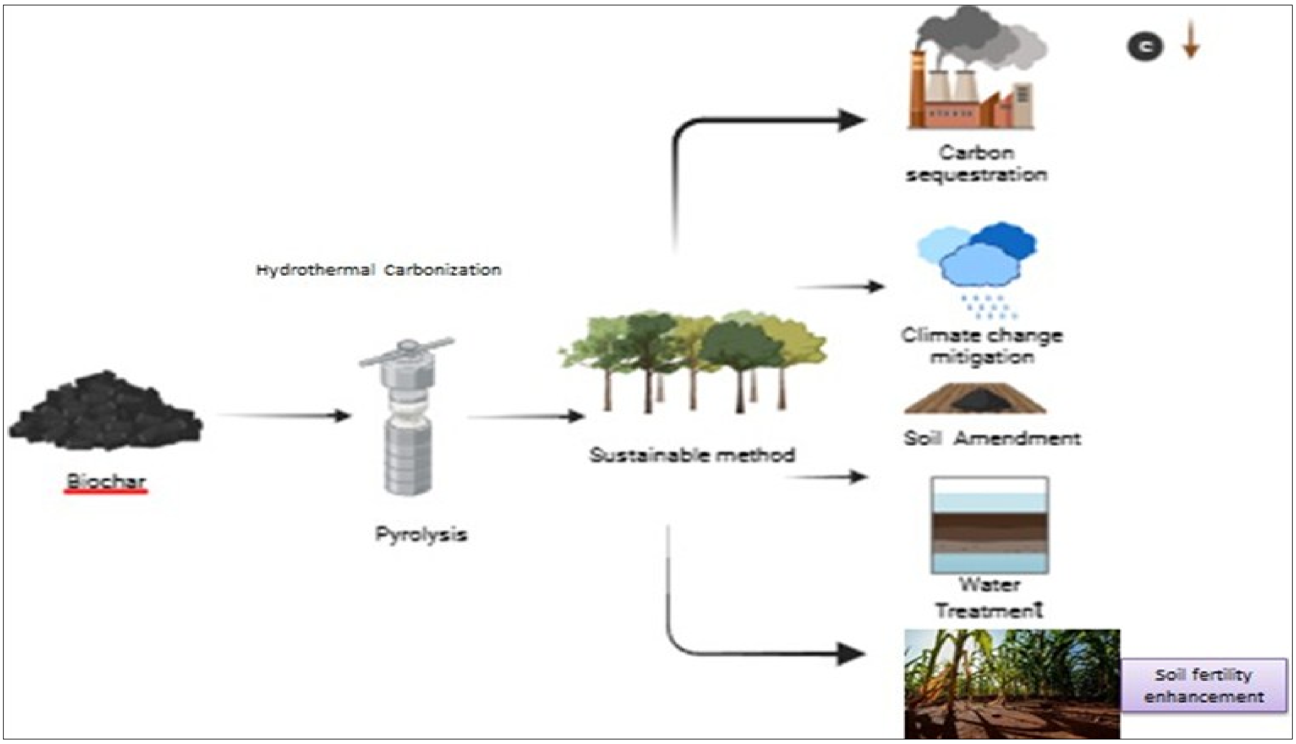

Fig. 1. Schematic diagram on biochar production and utilization of sustainable agriculture.

soil organic carbon (SOC) and restricting microbial access and enzymatic degradation. Additionally, biochar's high porosity and large specific surface area enable the encapsulation of organic carbon, further reducing its decomposition rate. Studies on century-old biochar demonstrate its ability to stabilize carbon in deeper soil layers, reinforcing its role in long-term carbon storage (15). Another crucial mechanism is adsorption on mineral surfaces, where clay and silt particles bind organic carbon through electrostatic and van der Waals forces. In tropical soils, iron and aluminum oxides form strong bonds with organic matter, further enhancing carbon stabilization. Biochar also improves soil structure and stability, increasing the proportion of macro-aggregates that shield SOC from microbial degradation (16). Moreover, its highly aromatic structure contributes to its slow turnover rates, making it resistant to microbial decomposition and extending its role in SOC sequestration (17).

Chemical mechanism

The chemical properties of biochar are crucial for its long-term carbon storage in soils, influenced by factors like feedstock composition, pyrolysis temperature and aging. Biochar stabilizes carbon through several mechanisms. It forms stable organo-mineral complexes with clay, iron (Fe) and aluminum (Al) oxides, limiting microbial access and decomposition (18). Cation bridges involving Ca^{2+}, Mg^{2+}, Fe^{3+} and Al^{3+} enhance stability by linking organic matter to mineral surfaces. Biochar also aids Humification, producing resistant humic substances. Organic molecules adsorb clay and metal oxides via ligand exchange, hydrogen bonding and hydrophobic interactions, further preventing degradation. Additionally, biochar promotes carbonate formation by facilitating CO_2 reactions with Ca^{2+} and Mg^{2+}, creating long-lasting carbonates (19). In anaerobic soils, biochar influences redox reactions, leading to stable carbon accumulation. Its surface functional groups form strong chemical bonds with minerals, while its aromatic and condensed carbon structures resist microbial breakdown, ensuring long-term carbon sequestration.

Biological mechanism

Biochar enhances soil organic carbon (SOC) stability through microbial priming effects, supporting long-term carbon sequestration (20). It promotes stable soil micro-aggregates that protect SOC and fosters microbial biofilms that immobilize organic matter, reducing decomposition (19). Biochar amendments alter microbial communities, increasing diversity and activity, especially at lower concentrations, improving soil health and nutrient cycling (21, 22). This enhances microbial carbon use efficiency (CUE), reducing SOC and organic matter mineralization for better carbon retention. While biochar generally aids carbon storage, it can also suppress SOC mineralization through a negative priming effect, further limiting decomposition and enhancing long-term sequestration (23).

Effectiveness of biochar for carbon sequestration

Biochar, a stable form of carbon produced through the pyrolysis of biomass, has garnered significant attention as a tool for carbon sequestration. This section explores the global sequestration potential of biochar, its carbon stability in soil, its efficiency in sequestration per hectare and its ability to reduce greenhouse gas emissions. The efficient utilization of the benefits of biochar application in sustainable agriculture is illustrated in Fig. 2.

Global sequestration potential

Biochar has a substantial potential for carbon sequestration, with estimates ranging from 0.3 to 2.2 gigatons (Gt) of CO_2 per year, contingent on factors such as feedstock availability, production scale and application methods. If adopted globally, the theoretical maximum sequestration potential of biochar could reach up to 130 Gt CO_2 over the course of the century, offering a significant contribution to climate change mitigation efforts (24).

Carbon stability in soil

One of the main benefits of biochar lies in its carbon stability. Research shows that 50-80 % of biochar carbon remains stable for periods ranging from 100 to 1000 years, which is notably

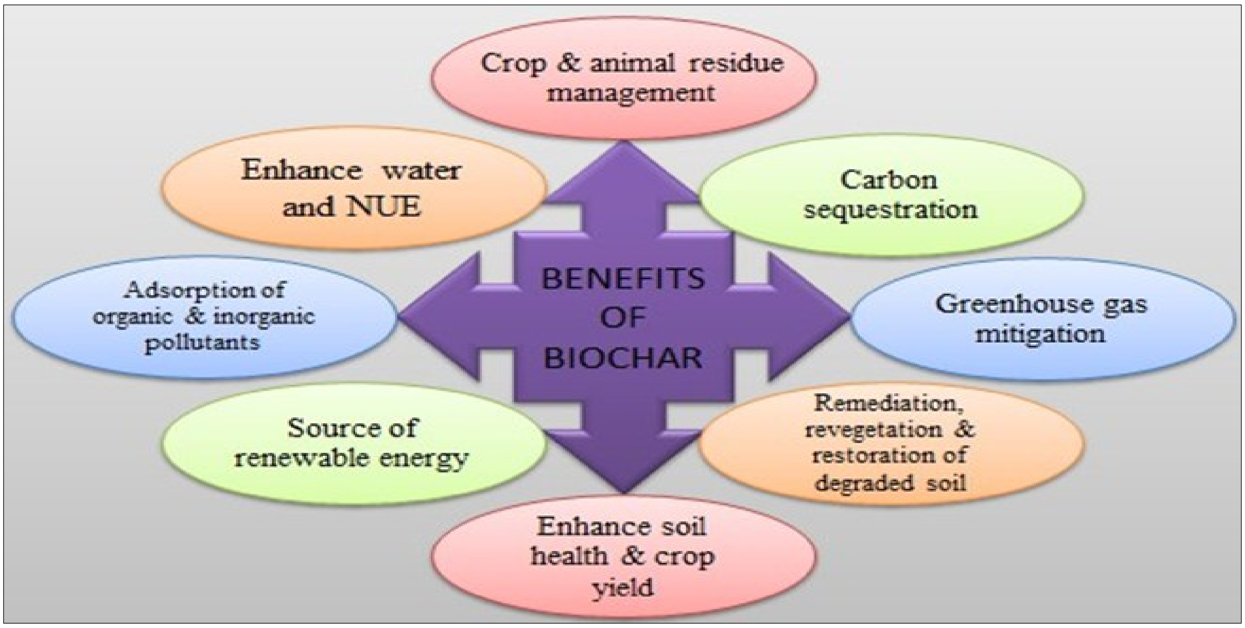

Fig. 2. Schematic representation of the benefits of biochar application in sustainable agriculture.

longer than most other organic amendments. The mean residence time (MRT) of biochar carbon in soil varies, generally ranging between 100 to 5000 years, depending on soil type, microbial activity and local climatic conditions. This stability ensures that biochar can serve as a long-term carbon sink, contributing to sustained carbon storage over extended periods (25).

Per hectare sequestration

The application of biochar to agricultural soils has proven effective in sequestering carbon at a per-hectare scale. Specifically, applying 10-20 tons of biochar per hectare can sequester between 3 and 6 tons of CO_2 per ha in a single application. Over time, this can result in an increase in soil organic carbon (SOC) by 10-30 %, particularly in degraded soils, thus enhancing soil quality and carbon storage capacity. This capacity for long-term carbon sequestration makes biochar an essential tool for improving soil health and addressing climate change (26).

Conversion efficiency

Biochar's conversion efficiency is another key factor in its effectiveness as a carbon sequestration strategy. During the pyrolysis process, approximately 40-60 % of the carbon in the biomass is converted into a stable form as biochar, a significant improvement compared to other organic waste management methods. For example, in composting or direct decomposition, only 3-10 % of biomass carbon is stabilized. This high conversion efficiency allows biochar to serve as a more reliable means of capturing and storing carbon compared to other carbon management practices (27).

Emission reduction impact

In addition to its carbon sequestration capabilities, biochar also provides substantial greenhouse gas (GHG) emission reductions (28). Studies have shown that biochar application can reduce CH_4 emissions by up to 50 % in paddy fields and N_2O emissions by 10–70 %, making it an effective strategy for mitigating the emissions of potent greenhouse gases. These reductions further enhance the climate mitigation potential of biochar, making it a multifaceted tool in global carbon management strategies (29).

Factors influencing biochar efficiency

Soil type dependency

Some studies reported that the addition of biochar to calcareous soils may increase or decrease P availability (30). For instance, its ability to boost SOC levels tends to be more pronounced in sandy soils with low organic matter than in clayey soils with higher organic matter content (31). Its application has shown greater SOC sequestration in loamy and acidic soils compared to sandy and alkaline soils, with a meta-analysis revealing an increase in SOC stock. Higher C/N ratio biochar in acidic soils resulted in more significant SOC increases, emphasizing the importance of soil pH in biochar effectiveness (32). The biochar response varies by soil type; for instance, Andisols may not exhibit the same yield improvements as other soils (33) (Table 1).

Climate influence

Environmental parameters such as temperature, precipitation and seasonality interact with biochar characteristics to influence soil carbon dynamics (34). However, in tropical conditions with strong microbial activity and fast organic matter turnover, biochar's performance in carbon sequestration may be less predictable (35). Its stability is affected by soil temperature, with empirical data suggesting that lower temperatures (0-10 °C) may lead to overestimated stability predictions, while higher temperatures (>10 °C) may yield underestimations. Regions with higher precipitation and temperature like British Columbia show greater potential for carbon sequestration through biochar, mitigating between 3 to 5 t CO2 ha^{-1} over 20 years (36).

Agricultural system complexity

The effectiveness of biochar for carbon sequestration is shaped by agronomic practices and environmental conditions, with its impact on soil organic carbon (SOC) influenced by factors such as tillage, fertilizer management and crop systems (37). Reduced or no-till practices generally enhance biochar's carbon retention by preserving soil structure, while conventional tillage can disrupt this benefit. Fertilizer type and timing-especially organic or nitrogen-based-interact with biochar, affecting its stability and soil microbial activity. Crop diversity further enhances biochar's efficacy, as diverse rotations support microbial communities that promote carbon sequestration, whereas monocultures may

Table 1. Potential feedstock

Residual biomass	
Agriculture	Rice straw, wheat straw, cotton stalks, corn stalks, pearl millet stalks
Livestock	Cattle manure, chicken litter, dairy manure
Agro-industrial	Bagasse, empty fruit bunch, coconut shells, rice husk, corn cobs, olive cake, palm kernel shells, peanut hull
Municipal	Sewage sludge, municipal tree prunings
Forestry	Logs, chips and bark from tree thinning activities
Industrial	Sawdust, slab timber, sawmill wood chips and of cuts, distillers' grains
Dedicated biomass	
Herbaceous	Switchgrass, bamboo, elephant grass
Woody	Short rotation coppice, e.g. poplar, willow, eucalyptus, casuarina
Aquatic	Micro algae and macro algae

diminish these effects. Integrating biochar into agriculture also improves soil health, productivity and sustainability. Agronomic strategies like reduced tillage, appropriate fertilization, moisture management and targeted soil amendments significantly influence biochar performance. It enhances nutrient use efficiency, particularly with nitrogen fertilizers, by reducing leaching and improving retention, although outcomes vary by soil type and application rate. Biochar also improves soil moisture retention in sandy soils, reduces bulk density, increases porosity and supports beneficial microorganisms that enhance nutrient cycling and disease suppression. Maximizing biochar's potential thus requires tailored, integrated management practices that align with specific soil and crop conditions (38).

Factors influencing biochar quality

Production method

Pyrolysis temperatures deeply influence biochar traits and the effect on the nutrient availability and biological traits may vary in soils treated with biochar made at different pyrolysis temperatures (39). Higher pyrolysis temperatures increase biochar's aromaticity and recalcitrance, increasing its potential for carbon sequestration (40). Slow pyrolysis biochar is often characterized by its stability and resistance to decomposition, with relatively low temperatures (300-500 °C) in an oxygen-limited environment making them suitable for long-term carbon sequestration in soils (41). Fast pyrolysis involves pyrolysis at higher temperatures which yields biochar with a smaller surface area and porosity, enhancing pH, nutrient availability, soil fertility and carbon storage (42). The hydrothermal process enhances carbonization efficiency and allows for the utilization of diverse feedstock materials, including organic wastes and agricultural residues (43). Key parameters like temperature and biomass-to-water ratio significantly influence the quality of the hydrochar, with optimal conditions enhancing energy content by up to 20 % (44). The hydrochar produced has a higher surface area, enhancing its potential for applications such as soil amendment and carbon sequestration. HTC can process high-moisture biomass without the need for pre-drying, making it suitable for diverse organic wastes (45). HTC biochar typically exhibits carbon content ranging from 55 % to 63 %, surpassing that of conventional pyrolysis biochar (46). HTC processes can produce biochar with ash content below 2 %, which is beneficial for energy applications (47).

Influence of feedstock sources

Wood-based Biochar

Wood-based biochar often exhibits high porosity, high carbon content, structural stability and large surface area, making them effective sorbents for organic compounds and nutrients in soils (94). Feedstock like corn stalks and Acacia nilotica yield biochar with high carbon content and surface area, essential for soil amendment (48).

Agricultural residues

Biochar produced out of agricultural residues has different characteristics depending on the feedstock composition and processing conditions. It can provide additional benefits, such as nutrient recycling, waste valorization and soil amendment (49). Rice husk and sugarcane bagasse biochar have different impacts on nutrient availability, emphasizing the necessity for customized biochar composition (48) (Table 2).

Implications for soil characteristics

Biochar is positively influencing the physical, chemical and biological properties of soil and are elaborated here under (Fig. 3).

Impacts on soil physical properties

The addition of biochar significantly affects soil physical properties, including bulk density, porosity and aggregation. Due to its lower intrinsic density (1.3-1.8 g/cm^3) compared to mineral soils (2.6-2.7 g/cm^3) and high porosity (70-90 %), biochar reduces bulk density by diluting the soil matrix and introducing pore spaces. This improves soil structure, enhances water retention and reduces erosion (50). Increased porosity enhances aggregation, interactions with mineral particles and reduces compaction, particularly benefiting degraded or compacted soils (51). Biochar's impact on water retention varies with soil type and properties (52, 53). By modifying the soil matrix and improving aggregation (54), biochar application at 10-50 t/ha increases field capacity, promoting plant growth and water efficiency. In sandy soils, it boosts water holding capacity (WHC) by 20-50% at 10-30 t/ha, while clayey and loamy soils see increases of 10-30 % and 5-20 % respectively, at similar rates. Small-scale studies show WHC improvements of 10-60 % at 1-5 % biochar incorporation by weight. Repeated annual applications of 1-5 t/ha provide long-term benefits for structure and retention. Biochar also binds clay

Table 2. The effect of varied rates and sources of biochar application on soil properties across various soil textures

Biochar source and application rate	Soil texture	Soil response details
Prosopis biochar at 5 t ha^{-1}	Sandy loam (Red acidic soil)	Increased the soil pH (0.5 to 0.6), reduced the soil bulk density (3 to 5 %) and increased water content (11.2 %)
Palm kernel shell biochar at 20 t ha^{-1}	Loamy soil	Increased total carbon content of 9.41 g kg^{-1}
Biochar, compost or biochar blended crop residue at 10.9 t ha^{-1}	Clay soil	Improved SOC by 0.17, 0.11 and 0.17 %
Rice husk Biochar at 10 t ha^{-1}	Clay soil	Increased available soil nitrogen (243 kg ha^{-1}
Rice husk biochar at 12 t ha^{-1}	Sandy soil	Increased organic matter content by 26 g kg^{-1}
Maize stover biochar at 15 t ha^{-1}	Clay soil	Increased plant N, P and K absorption by

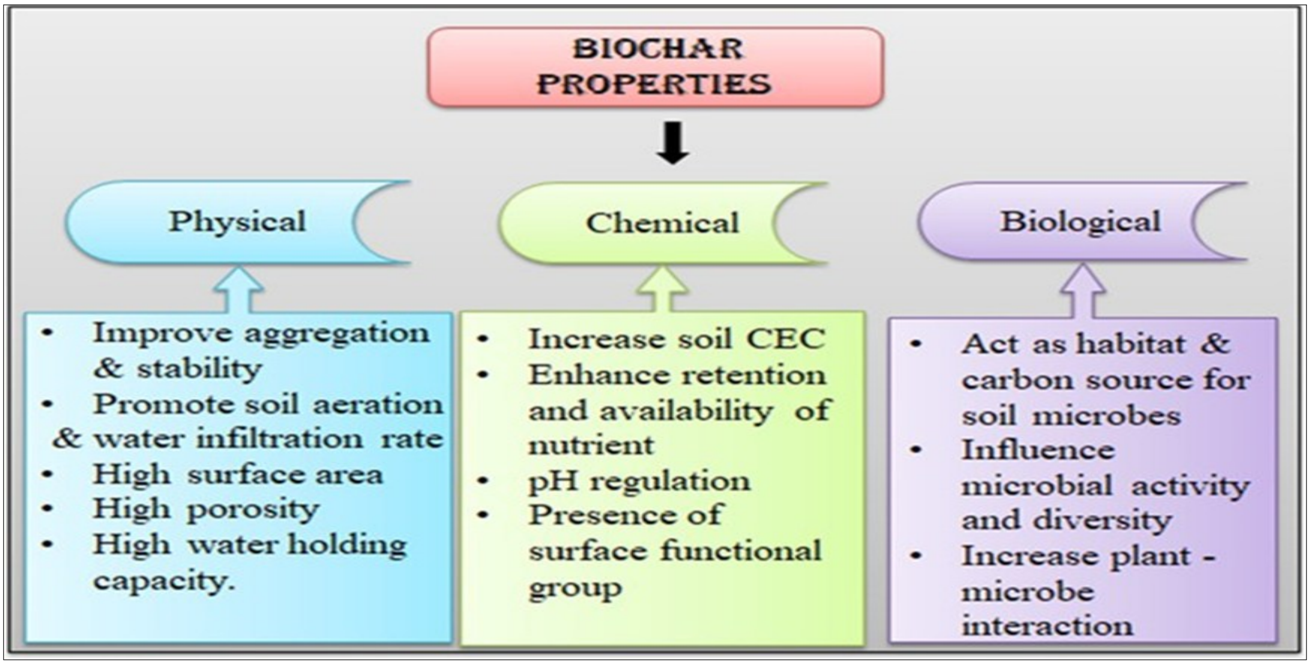

Fig. 3. Role of biochar in soil properties.

particles, enhancing aggregation, porosity, infiltration and erosion resistance. Its effectiveness depends on factors like porosity, particle size (<2 mm preferred) and soil conditions (55). Additionally, biochar darkens soil, improving heat absorption and indicating increased organic carbon. It enhances aeration, promoting oxygen availability, root growth and microbial activity. In clayey soils, biochar reduces bulk density by 5-15 % at 20-50 t/ha, further aiding root and microbial development (56).

Impacts on soil chemical properties

Biochar influences soil pH, electrical conductivity (EC), cation exchange capacity (CEC) and nutrient availability. Its alkaline nature raises soil pH, particularly in acidic soils, enhancing phosphorus availability (57). Biochar can slightly increase EC due to soluble salts, especially at high pyrolysis temperatures (42). It significantly boosts CEC, improving nutrient retention and supply, particularly for calcium, magnesium and potassium (58). Its effect on nitrogen (N) is complex; while it enhances availability through microbial activity and mineralization, it may also cause nitrogen immobilization due to adsorption (57). Biochar increases phosphorus (P) availability in acidic soils by raising pH, reducing fixation by iron and aluminum oxides and adsorbing phosphorus to prevent leaching (41, 59). It also improves potassium (K) availability by supplying K from its composition and enhancing retention via increased CEC, reducing leaching and promoting plant uptake (57). By enhancing CEC in clay-rich soils, biochar improves nutrient retention for K^+, Ca^{2+} and Mg^{2+}, minimizing losses and increasing plant accessibility (60). Clay minerals further stabilize phosphorus by preventing fixation. Additionally, biochar's alkalinity neutralizes acidic clay minerals like kaolinite in highly weathered soils, improving pH and nutrient availability. Additional information can be found in Table 3.

Effects on soil biological properties

Biochar's impact on soil biodiversity depends on its characteristics, application rates and management practices (20). It provides a stable habitat and carbon source for soil microbes, promoting beneficial shifts in microbial communities and supporting nutrient cycling (21). Studies show biochar can significantly increase microbial populations; for example, it was reported bacterial abundance rising by 200 % and fungal populations by 50-100 % with biochar application (35). It also enhances organic matter decomposition and carbon stability, aiding sequestration (61). It also boosts microbial diversity, especially in degraded soils. A study found a 50 % increase in microbial species richness (62), particularly bacterial diversity, while a 35-40 % rise in species diversity compared to control soils was reported (63). These benefits stem from improved soil structure and nutrient availability. However, effects vary by application rate and soil type, meaning benefits are not universal (45).

Long-term stability and persistence of biochar carbon

Biochar is highly valued for its carbon sequestration potential due to its exceptional stability and resistance to degradation compared to other organic compounds. While its long-term effectiveness may be influenced by factors like microbial acclimation, feedstock type, pyrolysis conditions, soil characteristics and climate (64), biochar typically persists in soil for hundreds to thousands of years. Studies estimate that 60-80 % of biochar can remain stable for over 100 years, with some fractions lasting 1000 years or longer (65). This long-term persistence is one of the key advantages of biochar as a soil amendment for sustained carbon storage and climate change mitigation.

Table 3. The effect of varied rates and sources of biochar application on soil properties across various soil textures

Biochar feedstock	Pyrolysis temp. (^{0}C)	pH	C %	N %	C/N	P %	K %
Corn cob	600	10.1	79.1	4.25	19	-	-
Corn stover	300	7.33	59.5	1.16	51	0.14	1.71
Peanut hull	400	10.0	65.5	2.0	33	0.01	0.01
Pearl millet	400	10.6	64	1.10	58	106	2.52
Dairy manure	700	9.9	56.7	1.51	38	1.69	2.31
Poultry litter	350	8.7	51.1	4.45	12	2.08	4.58
Cow manure	500	9.20	33.6	0.15	22	0.81	0.01

Factors affecting long-term stability

Feedstock kind

A study inferred that biochar with lower H: C (< 0.4) is associated with higher, carbon stability, while those with higher lignin content demonstrate better resistance to oxidation and longer carbon half-lives (66). It was stated that lignin-rich biomass, such as wood, leads to biochar with a lower H:C ratio, indicating higher aromaticity and greater stability (67).

Pyrolysis conditions

Higher pyrolysis temperatures enhance the stability of biochar, as observed in biochar produced from forest biomass at 500 °C, which showed superior stability compared to lower temperatures. Biochar stability largely depends on the temperature at which it's produced. At lower temperatures (300-400 °C), biochar tends to be less stable due to its higher oxygen content and the presence of easily degradable carbon. This makes it more susceptible to microbial breakdown, making it useful for short-term soil improvement but not for long-term carbon storage. When produced at moderate temperatures (400-600 °C), biochar becomes more stable, with increased aromaticity and lower volatile matter, making it a great option for soil enrichment and carbon sequestration. At high temperatures (600-1000 °C), biochar reaches its highest stability, with a highly condensed carbon structure that resists decomposition, making it ideal for long-term carbon storage. In general, the higher the pyrolysis temperature, the more stable the biochar. Lower temperatures create more reactive carbon that breaks down faster, while medium temperatures offer a good balance between stability and soil benefits (12). Increased pyrolysis temperatures also improve pH and electrical conductivity, contributing to biochar's overall effectiveness in soil applications (63).

Particle size

The effectiveness of biochar in agriculture is significantly influenced by its particle size, which impacts soil structure, water retention and nutrient availability. Fine biochar (≤1 mm) is particularly effective in compacted or clayey soils, improving aeration and enhancing microbial activity. However, its high surface area can lead to nutrient immobilization and faster decomposition (35). Medium-sized biochar (1-5 mm) is most commonly recommended for general agricultural use, particularly in loamy and sandy soils. It offers a good balance of water retention, nutrient storage and microbial support (68). Coarse biochar (5-10 mm) is suited for sandy soils and well-drained soils, improving soil structure and preventing nutrient leaching, though it integrates more slowly into the soil. Very coarse biochar (>10 mm) is typically used for erosion control, composting and long-term carbon sequestration, but it has limited immediate benefits for soil fertility unless pre-treated (12). In general, biochar with a particle size of 1-5 mm is ideal for most agricultural applications, offering optimal benefits for soil health and stability.

Surface functional groups

The surface functional groups on biochar, such as hydroxyl, phenolic, carboxyl and aromatic structures, play a key role in its carbon sequestration potential by influencing its stability and decomposition rates. Hydroxyl and phenolic groups enhance water retention, fostering microbial colonization while contributing to the slow breakdown of biochar in soil. Carboxyl groups increase biochar's hydrophilicity but may slightly reduce its stability by interfering with microbial processes involved in carbon turnover (69). Aromatic structures enhance biochar's resistance to microbial degradation, facilitating its long-term persistence in soils and contributing to carbon sequestration. Together, these functional groups help biochar resist decomposition, ensuring that a significant portion of the carbon remains sequestered in soil for hundreds to thousands of years (69).

Interactions with soil minerals

Biochar, a carbon-rich substance created through pyrolysis, interacts extensively with clay minerals, which are layered alumino - silicates known for their high surface area, cation exchange capacity (CEC) and reactivity. One primary interaction involves surface adsorption, where biochar's porous structure and functional groups (e.g. carboxyl, hydroxyl) bond with clay surfaces, forming organo-mineral complexes that enhance stability. Electrostatic interactions also play a role, as biochar's negative charge interacts with the charged surfaces of clay minerals like montmorillonite and kaolinite, fostering the formation of stable aggregates and improving soil structure. Beyond clay minerals, biochar interacts with other soil minerals, including iron (Fe) and aluminum (Al) oxides, calcium carbonate (calcite) and silicate minerals. For example, biochar can adsorb onto Fe and Al oxides, reducing the bioavailability of toxic Al^{3+} in acidic soils and influencing phosphorus solubility. In calcareous soils, biochar interacts with calcium carbonate ($CaCO_3$) to boost the release of calcium ions (Ca^{2+}), enhancing soil structure and nutrient availability, while its alkaline nature complements the soil's buffering capacity (70). Furthermore, biochar interacts with silicate minerals like quartz and feldspar, releasing silicon (Si), which supports plant growth and stress resistance and promoting the weathering of these minerals to release nutrients such as potassium (K) and magnesium (Mg) (71). These diverse interactions between biochar and soil minerals collectively contribute to improved soil fertility, structure and nutrient dynamics (72).

Microbial decomposition

Biochar's long-term stability in soil is due to its condensed aromatic carbon structure, which resists microbial degradation. Its high-temperature pyrolysis formation makes it less accessible to microbial enzymes, further protected by low bioavailability and a porous structure (12). However, specialized microbes like white-rot fungi and Actinobacteria can slowly degrade biochar through surface oxidation, co-metabolism and the priming effect (32). Degradation rates depend on pyrolysis temperature, feedstock type, soil conditions and aging (73). Higher pyrolysis temperatures increase stability, with wood-based biochar lasting longer than grass-based. Soil factors like pH, moisture and temperature, along with natural oxidation and fragmentation, also influence breakdown (6). Despite slow degradation, biochar remains stable for centuries to millennia, making it a valuable tool for long-term carbon sequestration (41). Its persistence enhances nutrient retention, soil structure and microbial habitats, supporting sustainable soil management and climate change mitigation (73).

Environmental conditions

Biochar degradation is influenced by moisture, temperature, tillage and soil management. High moisture increases microbial activity, accelerating degradation, though biochar's resistance slows this process (41). Low moisture preserves stability, benefiting drought-prone areas. Temperature also plays a role; high temperatures promote microbial breakdown, while low temperatures help maintain carbon sequestration potential. Tillage impacts stability, with conventional tillage accelerating degradation and reduced or no-till methods preserving biochar's structure (35). Fertilization enhances nutrient retention but may temporarily immobilize nitrogen, while soil pH and type affect microbial communities and biochar stability. Microbial inoculation can aid biochar degradation, improving nutrient cycling. Effective moisture, temperature, tillage and soil management are essential for maximizing biochar's long-term benefits in sustainable agriculture and carbon sequestration (73).

Integration Strategies of Biochar

Integrating biochar into agriculture enhances soil health, boosts crop productivity and supports environmental conservation through carbon sequestration and reduced nutrient pollution. In conservation tillage, biochar improves nutrient availability, increasing crop yields (74), while promoting carbon storage and reducing soil disturbance (37). It also enhances soil structure by improving water retention, root penetration and nutrient retention, making farms more resilient to droughts and heavy rainfall (13). In cover cropping, biochar supports microbial activity and nutrient availability, improving soil fertility, water retention and microbial health (75). However, its stability and compatibility with different cover crop species require further study (21). In agroforestry, biochar improves soil health, boosts crop production and enhances climate resilience by supporting carbon storage, nutrient cycling and biodiversity conservation, though more research is needed (49). Combining biochar with organic sources like biogas slurry can increase soil carbon, improve soil health and mitigate the short-term downsides of relying solely on biogas slurry for agriculture (76).

Limitation of biochar

Biochar effectiveness varies with feedstock type, production techniques and soil conditions, leading to inconsistent results. Its production can be costly, especially at high temperatures requiring specialized equipment, limiting large-scale adoption. Long-term impacts on soil fertility and plant growth remain uncertain, as benefits may decline over time due to environmental factors and soil differences. Heavy metal contamination is another concern, as certain feedstocks may introduce harmful metals, posing risks to plants and human health. The lack of standardized application guidelines complicates its use, leading to varied effectiveness across regions and soil types. Optimal application rates are still under study and improper use may result in poor outcomes, including reduced crop yields in unsuitable conditions.

Future prospects for biochar in soil carbon sequestration

Future research on biochar will focus on optimizing feedstock selection, improving production methods and reducing costs to maximize its benefits for carbon storage and soil health. Long-term studies are needed to assess its impact on soil carbon retention, microbial ecosystems and agricultural productivity. Understanding biochar's carbon sequestration mechanisms will enhance its effectiveness in soil improvement. Investigating biochar's combination with organic materials like compost may further boost soil fertility and carbon capture. Research will also examine its interactions with various soil types and climates to refine application strategies. Policies and financial incentives, such as carbon credits, can facilitate adoption by making biochar more affordable for farmers. Raising awareness among farmers, policymakers and the public will promote biochar's role in sustainable agriculture. Lastly, sustainability assessments will ensure environmentally responsible biochar production while supporting long-term carbon sequestration.

Conclusion

Biochar stands as a vital tool in advancing sustainable agriculture and enhancing climate resilience. Its remarkable capacity to sequester carbon, improve soil health and increase agricultural productivity makes it a multifaceted solution to pressing environmental challenges. By integrating biochar into various agricultural practices, we can move toward a more sustainable, carbon-conscious future. Embracing biochar presents a valuable opportunity to mitigate climate change while promoting resilient ecosystems and sustainable food production. However, despite its promising potential, the full-scale integration of biochar into climate strategies remains an area of ongoing research. A significant limitation in current studies is the lack of standardized methodologies for evaluating the long-term impacts of biochar in ecosystem management. Addressing these gaps through more comprehensive and systematic research will allow us to maximize biochar's effectiveness in environmental restoration and sustainable agriculture.

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Authors' contributions

YR and BK conceived the concept and wrote the manuscript. YR designed the diagrams and tables. MK and JS reviewed and revised the manuscript. BK, JPB, MK, AM, JS and AR finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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