Enebe et al. Biochar (2025) 7:107
https://doi.org/10.1007/s42773-025-00499-3

Biochar

REVIEW Open Access

The impacts of biochar on carbon sequestration, soil processes, and microbial communities: a review

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Abstract

Biochar application to the soil is an eco-friendly and sustainable nature-based solution for promoting soil carbon sequestration. It facilitates the reduction in the microbial carbon mineralization rate. Additionally, biochar enhances soil aggregate formation, neutralizes soil acidity, and increases microbial diversity, composition, and functions. The method adopted for this qualitative review entails a detailed examination of various research studies published on the contributions of biochar to soil carbon sequestration, its effect on the microbial community, and its contribution to greenhouse gas emission suppression, while also examining the various key factors that influence biochar's functional potential as well as biochar's contribution to environmental sustainability. We also put forward areas that needed further studies. Interestingly, this review emphasizes further the importance of exploring biochar in soil carbon emission control through a nature-based solution for climate change mitigation and management.

Highlights

- High temperature pyrolyzed biochar promotes soil carbon conservation via induction of a negative priming effects on microbes.
- It supports increase in microbial diversity for adequate soil ecological function.
- Biochar-organo-mineral interfaces aid the protection of labile carbon from microbial decomposition.

Keywords Carbon sequestration, Biochar, Environmental sustainability, Climate change, Soil microbial communities

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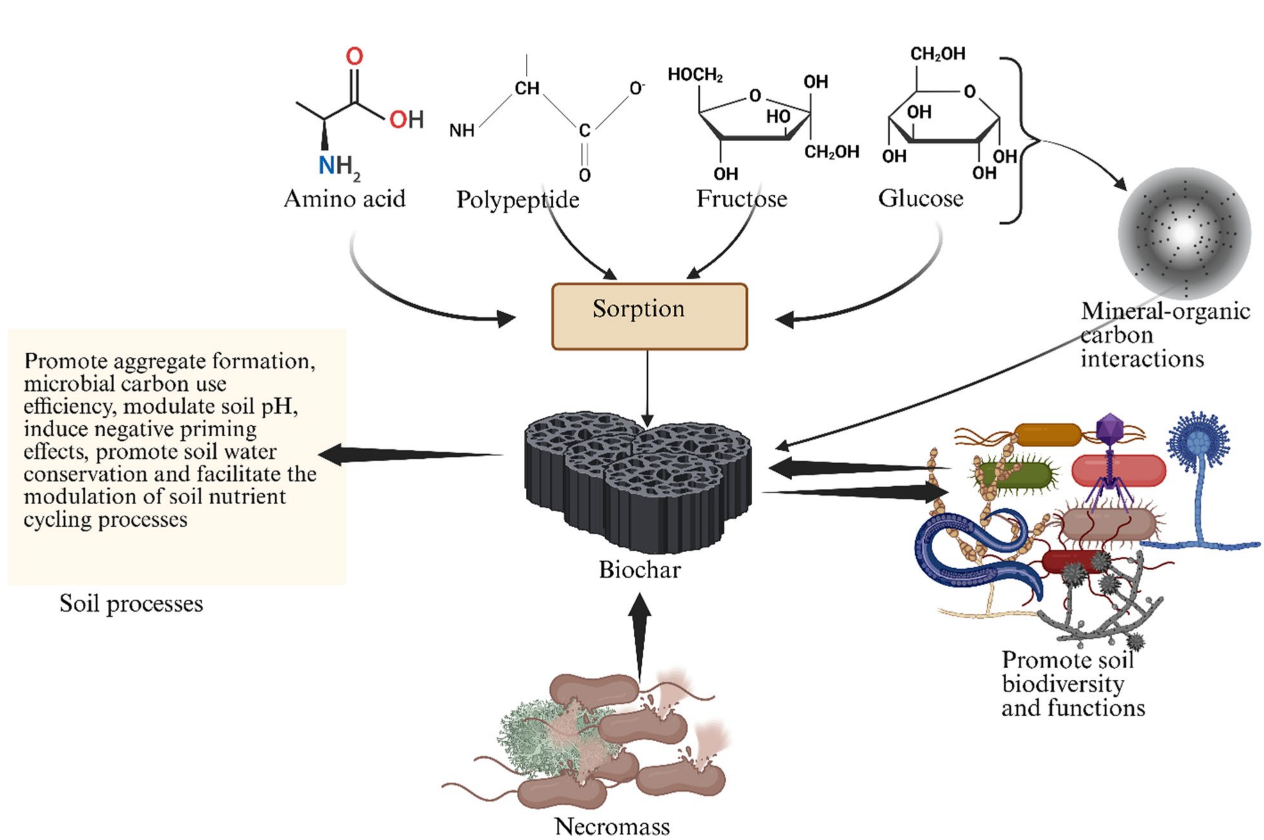
Graphical Abstract



1 Introduction

An increase in atmospheric temperature that results in climate warming and its corresponding effects on the ecosystem breeds the quest for environmental sustainability in controlling greenhouse gas emissions. Greenhouse gases, especially methane and carbon dioxide, originate majorly from microbial degradation of soil organic matter through carbon mineralization, respiration, and methanogenesis processes. Carbon mineralization occurs in the soil (Ray et al. 2020; Tikuye et al. 2025). The soil is perhaps considered the largest reservoir of carbon (organic and inorganic) in the biosphere. Most of these organic carbons originate from plants, which release approximately 50% of their fixed carbon (photosynthates) into the soil (Pausch and Kuzyakov 2018; Prescott 2022). The plant's root exudates (photosynthates and sloughed-off tissues) support microbial growth and metabolism, culminating in carbon dioxide production via respiration and methane production through methanogenesis. These microbial-mediated processes result in the loss of soil organic carbon (SOC) (Bossio et al. 2020; Ciais et al. 2013; Sae-Tun et al. 2022).

Although microbial metabolism leads to carbon loss, which negatively affects the climate, a nature-based approach is needed to solve or ameliorate the problem (Gurau et al. 2025). Nature-based solution approach entails any management practice that enhances ecosystem function and biodiversity, supports natural ecosystem processes and their adaptive capacity, and exerts little or no negative effects on the environment, animal and human lives, and with long-lasting benefits to the ecosystem (Sowińska-Świerkosz and García 2022). Based on the fundamental concepts proposed by the European Union (EU), a nature-based solution is defined as an approach that entails the use of a natural product or process. This approach must provide societal, environmental, and economic benefits while also supporting biodiversity (Policy 2021). For instance, biochar application to the soil fits well within the EU guidelines. It is a product of organic matter or biomass waste conversion into a stable organic carbon through pyrolysis. It has various attributes ranging from high porosity, stable carbon structure with high aromaticity, and low bulk density to high cation exchange capacity (Table 1) and through the

Table 1 Concise overview of the main properties of biochar

Biochar properties	General descriptions
Physical	1. High porosity
	2. Large surface area
	3. Low bulk density
	4. Stable dark organic carbon
	5. High CEC (cation exchange capacity)
	6. Moderate to high water retention capacity
Chemical	a. High aromaticity
	b. Posses neutral to alkaline pH
	c. Contain reactive functional groups such as carbonyl, oxonium, carbonate, carboxyl etc.
	d. Contain either recalcitrant or labile carbon composition that is determined by the pyrolysis temperature used for its production

modification of microhabitat and substrate availability, it controls the rate of microbial decomposition/degradation of organic matter, mitigates soil greenhouse gas emission and supports increase in soil organic carbon contents (Sapkota et al. 2024). Another key contribution of biochar towards soil carbon accumulation is its ability to enhance the carbon use efficiency of microbes, promote aggregate formation, and form biochar-organo-mineral interfaces for protecting labile carbon from microbial decomposition (Fig. 1).

Studies have shown that biochar application to the soil enhances soil properties, increases the accumulation of necromass carbon, and enhances the accumulation and stability of soil organic carbon (Aurangzeib et al. 2024; Bai et al. 2024). It is a good additive for increasing soil carbon sequestration. Biochar's contribution to soil carbon sequestration is attributed to its carbon content, which is rich in recalcitrant and aromatic carbon, and to its ability to induce negative priming effects on soil microbial metabolism. Negative priming is a phenomenon where biochar application reduces microbial mineralization of resident or native soil organic carbon by lowering microbial metabolic quotient, limiting microbial accessibility to soil organic carbon, and stimulating carbon use efficiency, thereby facilitating an increase in soil carbon storage and a decrease in soil respiration (Enebe et al. 2025). It also increases microbial biomass carbon through promoting carbon use efficiency and supports carbon assimilation into biomass as opposed to respiration. Biochar, also improves microbial habitat through enhanced soil cation exchange capacity, water holding capacity, aggregate formation, and aeration (Bai et al. 2024; Brown et al. 2024). Besides promoting soil carbon sequestration, biochar equally improves soil productivity while enhancing agricultural waste recycling to ensure environmental sustainability. Biochar is perhaps a suitable organic matter for promoting zero carbon emission from the soil (Dong et al. 2024). Additionally, it enhances soil processes, which is a series of actions involving biological and non-biological activities that bring about a result. For instance, nutrient biogeochemical cycling controls the movement and transformation of nutrients from one form to another. Another example is soil water content, which is determined by water percolation. In essence, soil processes are influenced by biochar, temperature, and precipitation (Duniway et al. 2010; Smercina et al. 2021; Yadav et al. 2023). In fact, microbes are the key drivers of the biogeochemical cycle, and their activities are influenced by soil conditions, soil management (biochar application), and abiotic conditions (precipitation, temperature, etc.) (Smercina et al. 2021).

To this end, a critical review of biochar's impact on carbon sequestration, soil processes, and microbial communities is required to understand biochar's contribution to environmental sustainability. To the best of our knowledge, no study has been done on evaluating the impact of biochar on soil carbon sequestration, soil processes, and microbial communities. This review seeks/aims to critically examine the impact of biochar on carbon sequestration, soil processes, carbon cycling, and microbial community dynamics. While examining the factors affecting biochar-mediated carbon sequestration, biochar influence on the microbial metabolic pathway and its impact on soil organic carbon sequestration, this review also suggests ways to maximize biochar's environmental, agricultural, and economic benefits in the attainment of a sustainable environment through minimizing greenhouse gas emission from soil.

2 Methodology

This comprehensive review was done using publicly available information contained in various databases such as Sciencedirect, Scopus, Web of Science and through Google search. It discusses the various efforts made by

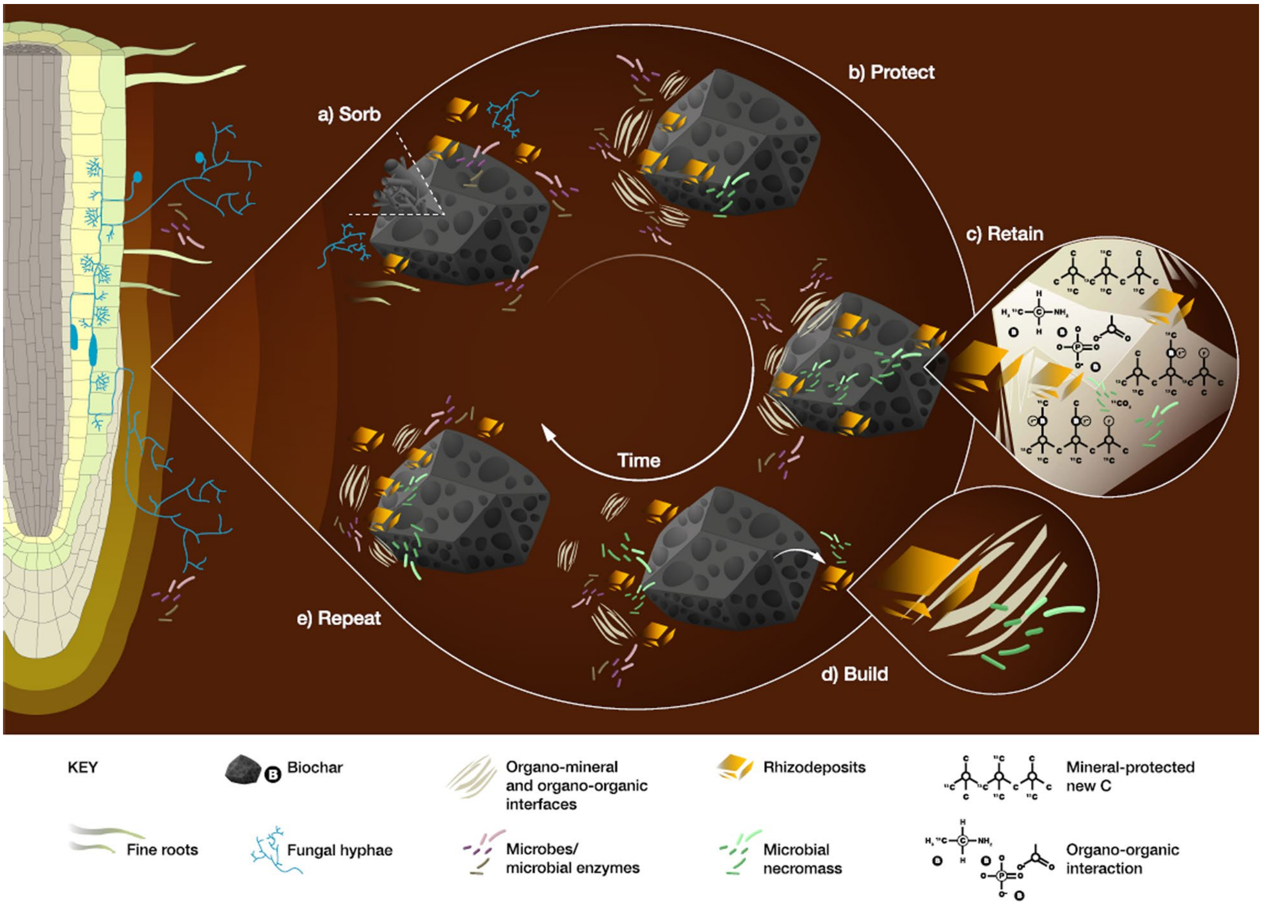


Fig. 1 A case study of the conceptual diagram of the formation of protected aggregates from catalytic biochar surfaces over time in a Rhodic Ferralsol. **a** Biochar sorbs root-derived carbon (rhizodeposits) onto its surface, protecting the rhizodeposits from immediate microbial consumption. **b**, **c** The rhizodeposits form organic interfaces with biochar, and organo-mineral interfaces with very fine layers of soil minerals that accumulate on the biochar that protect (**b**) and retain (**c**) rhizodeposits within the biochar coating. Over time, microbial necromass also adsorbs to biochar, which is retained in similar protective interfaces. **d** New organic and organo-mineral coatings can build on the biochar surface. **e** The process repeats to develop new, protected SOC over time. Adapted from Weng et al. (2022) published by Nature Communication with CC BY license permission

researchers to deepen our understanding of the contributions of biochar to soil processes, carbon sequestration, and microbial community dynamics. To carry out the study, we evaluated original articles describing biochar and the conditions affecting its potency in carbon sequestration and greenhouse gas emission control. We focused primarily on recent publications available in the public domain. Various biomass materials ranging from green waste, municipal solid waste, manure to industrial wastes converted to biochar were reviewed to ascertain how they contribute to soil carbon sequestration and greenhouse gas emission control. Therefore, although many articles were identified, only a limited number were included in this review. The selected articles were deemed relevant, provided quantitative data, and clearly demonstrated how biochar application contributes to soil carbon sequestration, microbial activity dynamics, and the modulation of processes within the biogeochemical cycle.

2.1 Biochar production process

Creating biochar involves sourcing biomass materials like plant materials, animal manure, agro-wastes, or municipality solid wastes and sludge. Biomass materials of large size will undergo mechanical breakdown into smaller pieces and then be pyrolyzed at very high temperatures without oxygen for a couple of hours. After conversion into biochar, the formed biochar is crushed into particles of different sizes (ranging from macro to nanoparticles). Biochar production could follow either the traditional method or the pyrolysis-condensation route. The traditional method involves loading the biomass material, optionally mixed with additives or enhancers such as calcium, iron salts, bentonite, ionic liquid (1-butyl-2,3-dimethylimidazolium triflate), etc., into a heating furnace and heating the biomass with or without these additives under a nitrogen atmosphere to limit oxidation. The heating is done at a particular high temperature for a certain residence time, as presented in Table 2. After heating the biomass, the kiln is cooled to room temperature, and the biochar content is extracted (Selvarajh et al. 2024; Yang et al. 2022). This method can generate biochar with high aromatic content and less aliphatic content. It does not require sophisticated systems for the thermal conversion of biomass into biochar. Additionally, blending biomass material with additives enhances the quality, porosity, yield, and chemical functional groups of the biochar particles. Another method and technology for biomass pyrolysis is termed pyro-condensation. In this process, the biomass is loaded in a furnace attached to a condensate chamber to typify pyrolysis coupled with in situ condensation. The principle behind the operation of this system is that as the biomass undergoes heating within the furnace, biomass contents with low heat of vaporization will form volatile organic carbon or substances, which will be released from the biomass and, upon passing through the condensation chamber, will condense and get recycled back into the heating chamber, leading to the repolymerization of the volatiles as well as facilitating their binding onto the biochar surfaces. After the pyrolysis-condensation cycle, the reaction system is cooled to about 100 °C and maintained for another 4 or 5 h to facilitate evaporation of the water molecules that might have adsorbed on the biochar surfaces. After this period, the dried biochar is extracted from the reactor and is ready for use (Sun et al. 2024). The major advantages of the pyro-condensation biochar production process are: (1) It leads to an increase in biochar yield compared to traditional methods, as the volatiles are recycled back onto the biochar surfaces and no organic matter is lost; (2) It produces high-quality biochar at low temperatures (such as at 450 °C) and consumes less energy during the pyrolysis process compared with the traditional method; (3) The biochar produced through this pyro-condensation process is rich in aliphatic hydrocarbons and could be applied in diverse uses (such as solid fuel, reductants, soil conditioners, adsorbents to remove pollutants, etc.); (4) It has low environmental impacts, as no volatile substances are allowed to escape from the system; (5) The biochar produced contains easily metabolizable carbon sources for microbial mineralization and is not recalcitrant compared with biochar produced via the traditional pyrolysis method described above (Sun et al. 2024).

2.2 Biochar contributions to carbon sequestration—a focus on the mechanism of action

The mechanisms through which biochar contributes to soil carbon sequestration are diverse and include stabilization of labile organic carbon through sorption, alterations in microbial community structure and composition, the accumulation of microbial necromass, changes in organic carbon degradation rates, and improvements in soil water retention, nutrient retention, and aggregate stability. Some of these categories may also overlap; for instance, the high aromaticity index of biochar that causes alteration in microbial community structure and composition may also play a role in altering microbial organic carbon degradation rates. Biochar's recalcitrant carbon composition has been implicated in an increase in the soil carbon sequestration capacity of urban greenspaces amended with biochar (Niu et al. 2024) (Table 3). The phenolic and aromatic carbon structures in biochar can induce a negative priming effect on soil microbes, promoting the selection of K-strategist microbial communities that are adapted to low-nutrient environments rather than r-strategists that thrive in nutrient-rich conditions (Bai et al. 2024; Yang et al. 2024b). This microbial shift is further influenced by the surface charge characteristics of biochar, which enable strong binding to O-alkyl and di-O-alkyl carbon groups found in hemicellulose and cellulose, as well as to carbonyl carbon in labile organic molecules such as amino acids and glucose—thereby reducing the availability of these substrates for microbial decomposition (Fig. 2). The binding of these carbon molecules to biochar aryl C or aromatic carbon as well as its interaction with soil minerals, helps stabilize these organic carbons and prevent them from being mineralized or degraded by microbes (Weng et al. 2022).

Additionally, biochar enhances carbon stabilization by promoting the accumulation of microbial necromass. About 27% to 80% of soil organic carbon pools originate from microbial necromass, which is stored in soil and persists for a very long time (Schmidt et al. 2011; Wang et al. 2021). Based on this significant contribution of necromass (dead microbes and their metabolites) to soil organic carbon, studies have shown that applying biochar to the soil increases microbial necromass accumulation (Niu et al. 2024). This study also shows that the aromatic content of organic matter applied to the soil determines the necromass carbon contributions from bacteria and fungi communities to the soil organic carbon. Organic amendments with high aromatic carbon contents like biochar enhanced the contribution of fungal necromass to soil organic carbon. While those containing very little

Table 2 Studies reflect state-of-the-art biochar production strategies for maximum carbon retention during pyrolysis and enhanced carbon sequestration

Biomass	Reaction conditions	Key findings	References
Cow manure	Incorporation of calcium into the biomass and pyrolyzed at 300, 400, 500 and 600 °C	It was observed that carbon retention of the pyrolyzed biomass was increased from 49.2 to 68.3% in the unamended-pristine biochars to 66.1–79.7% in the biochar amended with calcium (Ca-composite biochars) and at the temperature of 600 °C, a maximum carbon sequestration of 56.3% was achieved for calcium amended biochar	Nan et al. (2021a)
Wood chips	Wood chips were mixed with bentonite/kaolin in a ratio of 4:1 and pyrolyzed at 350 °C or 550 °C for 2 h	Co-pyrolysis of wood chip with the additives resulted in an increase in the biochar aromaticity—49.0% (Bentonite-Wood chip biochar), and 56.4% (Kaolin-Wood chip biochar) and a decrease in the biochar polarity by 69.9% for Bentonite-Wood chip biochar and 63.3% for Kaolin-Wood chip biochar	Wang et al. (2022)
Corn straw and wood	Treatment of corn straw and wood biochar with 7.3 g $FeSO_4 \cdot 7H_2O$ and 7.23 g $FeCl_3 \cdot 6H_2O$ and heated at 50 °C as well as the same biochars mixed with 100 mL of 1 M Fe $(NO_3)_3$ solution and heated at 60 °C for 60 h	It was observed that the biochars treated with $FeSO_4/FeCl_3$ reduced 28.5 and 6.9% of nitrous oxide emissions from the soil. Meanwhile, the biochars treated with Fe $(NO_3)_3$ recorded about 28.5% and 67.0% increase in nitrous oxide emission	Liao et al. (2024)
Corn stalk, rape straw, wheat stalk, and peanut shell	The agricultural residues were pyrolyzed at 300, 500, and 700 °C in a muffle furnace with a residence time of 1, 2, and 4 h	The result of the study clearly showed that the properties of the biochar (such as the ability to retain nutrients, pH, electrical conductivity, ash content, oxidation stability, and carbon sequestration potential) depend entirely on the pyrolysis temperature and increase with an increase in temperature	Wang et al. (2020)
Raw bamboo scraps	Bamboo particles were introduced into potassium phosphate solution and pyrolyzed at 350, 450, 550, 650, 750, 850, and 950 °C at a rate of 10 °C/min for 1 h	It was observed that the incorporation of K_3PO_4 into bamboo and pyrolyze at high temperature increased the stability and adsorption performance as well as the degree of aromaticity of the bamboo biochar	Zhang et al. (2022)
Rice husk	Rice husk was introduced into a kiln container and pyrolyzed at 300 to 400 °C	Application of the rice husk biochar significantly reduces ammonia loss and increases plant nutrient uptake and productivity of rice plants	Selvarajh et al. (2024)
Wastepaper	Blending of wastepaper with ionic liquid (1-butyl-2,3-dimethylimidazolium triflate) and pyrolyzing it at 350 °C	Introduction of ionic liquid blend into the paper waste resulted in the generation of biochar with high porous structure and more O-containing functional groups suitable for wide environmental applications	Yang et al. (2022)

Table 3 Contributions of biochar to soil carbon sequestration

Biochar materials	Biochar effects on soil carbon sequestration	References
Cotton straw, peanut shell, and sawdust	Biochar application to woodland, greenhouse soil and lawn increased the soil organic carbon by 207.2%, 22.3%, and 307.4%, as well as the soil humin content	Guo et al. (2024)
Waste dander	Soil treatment with biochar significantly increased soil carbon sequestration contents by 25.63% and reduced soil organic carbon mineralization rate by 0.48 mg CO_2/(g·d)	Ji et al. (2024)
Rice husk and cottonseed hulls	Biochar application to calcareous soil was found to increase significantly the soil organic carbon by 33%, humic substance by 24%, and 5% increase in the dissolved organic carbon content of the topsoil. It also increased the subsoil dissolved organic carbon contents by 162%	Wang et al. (2024b)
Pine wood and pine bark	Soil treatment with biochar pyrolyzed at 500 and 700 °C increased soil organic carbon content by 49.2% and 87.7%, corresponding to reduced carbon dioxide emissions of 66.9% and 72.4%	Sapkota et al. (2024)
Corn stover	Biochar treatment of soil with nitrogen fertilization significantly reduced carbon dioxide emission and increased soil organic carbon sequestration in the soil	Zhang et al. (2024)
Rice husk	Soil amendment with biochar under no-tillage and cover cropping systems showed that biochar significantly increased soil carbon sequestration by reducing soil respiration and carbon emission from the soil	Dewi et al. (2024)
Wheat straw	Introduction of biochar derived from pyrolysis of straw into the soil significantly decreased greenhouse gas emissions from the soil by 8.9%, while increasing soil organic carbon concentration	Lu et al. (2024)
Wheat straw	Biochar incorporation into the soil enhanced its organic carbon contents by an increase of 122% and enhanced the overall soil properties suitable for carbon sequestration	Mohan et al. (2024)
Waste leather dander	It was observed that biochar pyrolyzed at 400 °C gave the highest soil carbon sequestration level of 18.23% as well as a significant decrease of 0.499 mg CO_2/(g·d) in soil organic carbon mineralization rate	Tao et al. (2024)
Corn stalk	Application of modified biochar to the soil resulted in a decrease in greenhouse gas emissions from the soil as well as an increase in crop yield	Gong et al. (2024)
Corn straw	Biochar treatment of saline and alkaline soil exerted 16.7%, 13.1%, and 12.5% reduction in carbon dioxide emission at treatment doses of 30, 15, and 45 t/hm^{-2}. However, biochar efficiency in carbon fixation dosage input at 15 t/hm^{-2} were 72.8 and 64.1% greater than biochar treatment at 30 and 45 t/hm^{-2} doses	Yang et al. (2024c)

aromatic carbon support bacterial necromass, they make a significant contribution to soil organic carbon content (Niu et al. 2024).

Strikingly, another mechanism through which biochar contributes to soil carbon sequestration is by regulating the activities of microbial carbon cycling enzymes. Enzymes, as biocatalysts, are responsible for the breakdown of macromolecules into their monomeric units, which can easily be assimilated or metabolized by microbes. They are an integral component in the functionality of the ecosystem and catalyze the breakdown of organic biomass from fauna, animals, microbes, and plants. Through its ability to adsorb enzymes, biochar contributes to a decrease in carbon cycling enzyme activities and carbon mineralization in a soil amended with biochar (Cheng et al. 2024). Biochar application has been shown to promote the accumulation of fungal necromass, particulate organic carbon, and easily oxidizable carbon, which contributes to soil carbon sequestration. In another study, it was uncovered that microbial enzyme activities promoted by biochar treated soil were those (β-N-acetyl-glucosaminidase, β-1, 4-Glucosidase, β-D-cellobiosidase) responsible for promoting the accumulation of soil mineral associated organic carbon and equally contribute to biochar enhanced soil carbon sequestration (Yang et al. 2024a). The mechanism involves the decomposition of soil organic carbon into smaller units that are assimilated into microbial biomass carbon or adsorbed to the mineral surfaces, forming mineral associated organic carbon. Both the carbon absorbed by microbes that eventually yield necromass and the unabsorbed ones will eventually bind to the soil minerals and get stabilized (Yang et al. 2024a). In another study, the synthetic enzymatic index, enzyme activities (β-glucosidase and butyrate esterase), and microbial community structure were significantly improved in a biochar-treated soil, which contributed to a decrease in ecoenzymatic C:N ratio, qCO_2 (carbon dioxide emission quotient), and an increase in microbial immobilized carbon quotient (qMIC) (Massaccesi et al. 2024). All in all, biochar application to the soil has been proven effective in soil carbon sequestration as well as in inducing carbon immobilization by microbes.

Furthermore, biochar application to the soil also contributes to an increase in crop and biomass yield of plants, as presented in studies by Massaccesi et al. (2024)

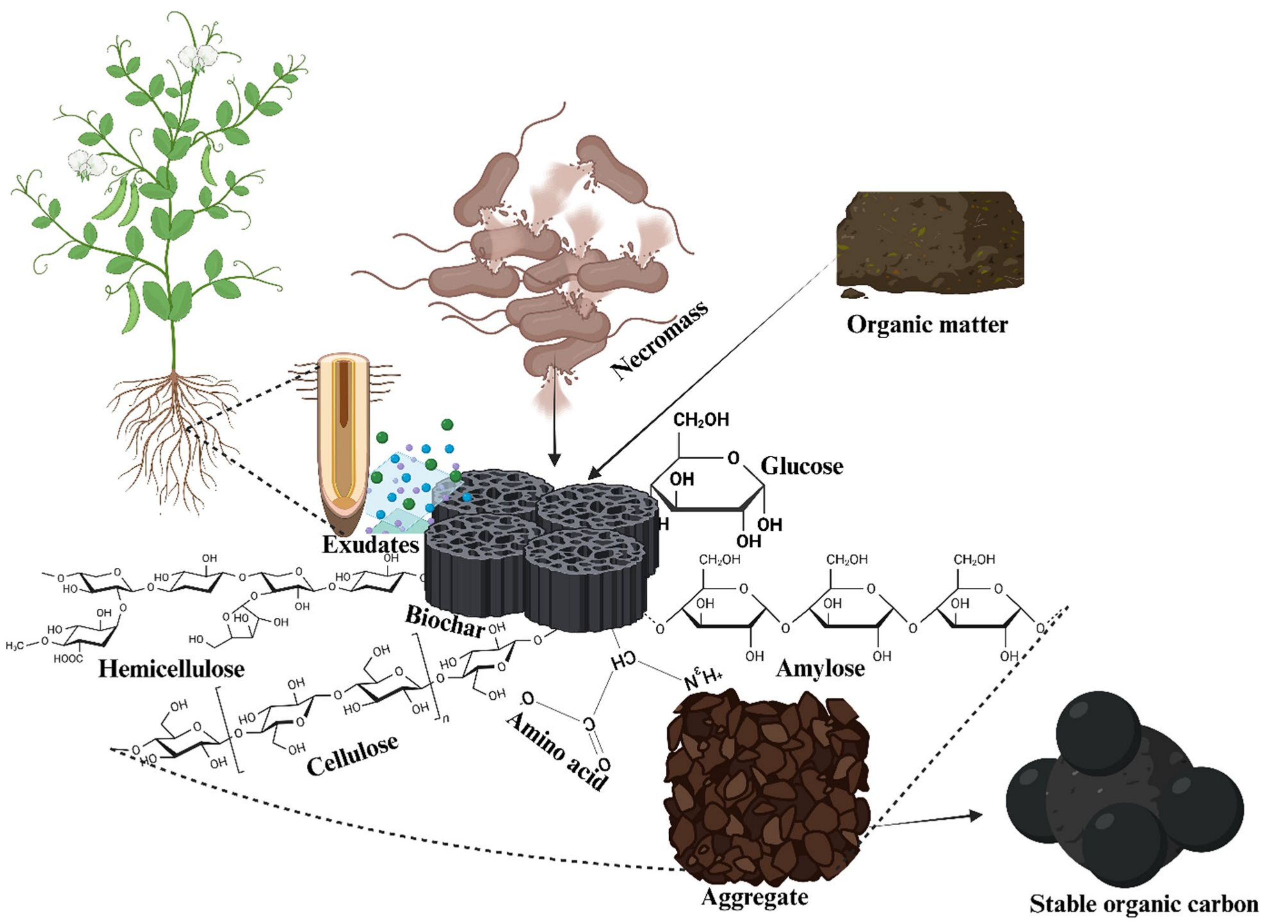


Fig. 2 Chemical mechanisms of biochar contribution to soil carbon sequestration. The exudate carbon released by plants gets adsorbed on the surface of the biochar as well as decomposed organic carbon from organic matter to form biochar-organo interface and organo-mineral interface with soil minerals. Biochar also adsorbs and retains microbial necromass, protecting it from decomposition to form an aggregate and stable organic carbon pool in the soil

and Xing et al. (2024). In these studies, it was found that soil amended with biochar significantly increased yield and promoted the overall performance of the plants. It is important to note that an increase in plant growth, performance, and yield correlates positively with an increase in carbon influx into the soil via plant enhanced photosynthetic process. An increase in photosynthetic carbon input in the soil, facilitated by biochar treatment, indirectly contributes to soil carbon sequestration and reduction of atmospheric carbon dioxide concentrations. Biochar performs this function by increasing soil water and nutrient retention capacity, which supports the growth and productivity of plants (Khadem et al. 2021; Li and Tasnady 2023). It also promotes soil carbon sequestration by promoting stable soil aggregate formation. Readers interested in understanding the mechanisms through which biochar contributes to soil aggregate formation and stabilization should refer to a recent review by Li and Tasnady (2023).

Table 3 clearly shows biochar's various mechanisms and contributions in carbon sequestration, ranging from increased soil humic acid and humin content to reduced soil respiration and soil organic carbon mineralization rate. It is evident from the data presented in the table that biomass pyrolysis at 700 °C resulted in the most significant increase in soil organic carbon (87.7%) and reduction in carbon dioxide emission by 72.4% (Sapkota et al. 2024). Therefore, the ideal biochar for enhancing soil carbon sequestration should be biomass pyrolyzed at 600 to 700 °C. However, it is worth noting that the choice of the feedstock to be pyrolyzed at such a high temperature is a critical consideration since studies have shown that biochar's morphology and physiochemical properties are affected by pyrolysis temperature and feedstock type (Antonangelo et al. 2019).

2.3 Carbon sequestration and microbial responses to biochar

Majority of research on the impact and/or effects of biochar on soil carbon sequestration focused mainly on the topsoil (0–25 cm depth), ignoring the subsoil (30–100 cm depth) as a potential reservoir of carbon and how biochar influences carbon storage in this area. Due to its inherent slow carbon turnover rate, subsoil has the potential to store organic carbon in the soil. This tendency of subsoil to accumulate stable soil organic carbon is influenced by slow microbial processes, rate of supply of fresh carbon, and soil mineral compositions (Button et al. 2022).

A study by Wang et al. (2018) showed that biochar soil amendment with straw at both high and small quantities decreased by 33.26% to 52.61% of the relative abundance of *Methylocaldum*. At high straw amendment with biochar, *Methylosarcina* abundance increased by 14.03%. In contrast, biochar and low straw amendment decreased the type II methanotrophs population by 14.7% to 40.12% and increased the *Methylobacter* population by 21.30% to 53.13% with high straw input. This *Methylobacter* increase was also observed in all straw and biochar treatments in the BH (Binhai) soil (S1, S2, BS1, BS2) (Fig. 3).

Methylosarcina increased in biochar with high straw-amended soil is facilitated by the biochar's capacity to adsorb methane and/or oxygen, thereby increasing the methane concentration, which favors *Methylosarcina* metabolism. The original soils from Taoyuan and Binhai have different dominant methanotrophs before receiving straw and biochar treatments. *Methylocystis* and *Methylosinus* (type II methanotrophs) dominated TY (Taoyuan paddy soil), while *Methylosarcina*, *Methylocaldum,* and *Methylobacter* (type I methanotrophs) dominated BH (Binhai paddy soil) (Fig. 3) (Wang et al. 2018). The functional role of biochar in regulating the activities and abundance of methanotrophs and methanogens in the soil centers on its influence in modulating soil physiochemical properties such as aggregate, water holding capacity, pH, and soil porosity. These biochar-enhanced soil properties aid the proliferation of methanogens and, in some cases, could either enhance or inhibit the abundance and activities of methanotrophs (Razzaghi et al. 2020; Si et al. 2018; Zhao et al. 2021).

Nevertheless, methanogenesis is often reduced in biochar-amended soil due to the biochar's sorption of dissolved organic carbon (Nan et al. 2021b). Therefore, biochar application reduces methane emissions due to its influence on the bioavailability of dissolved organic carbon. Han et al. (2016) noticed that methane emission suppression of 39.5% was achieved when the soil was

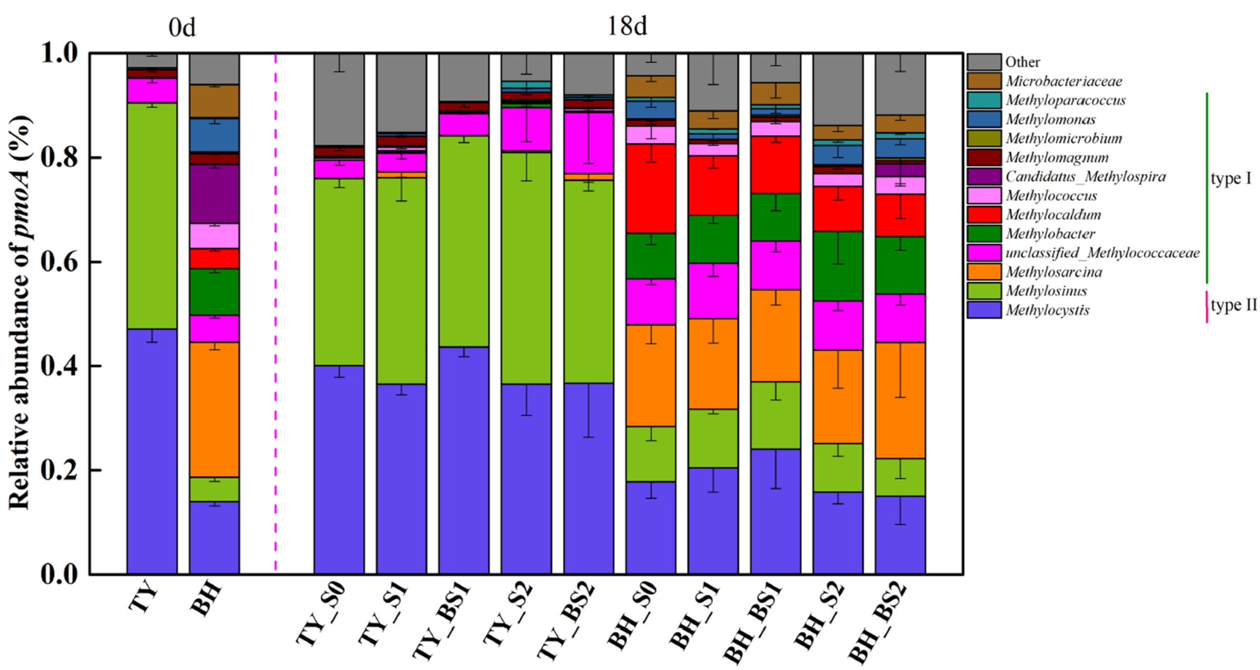


Fig. 3 Taxonomic distributions of *pmoA*-based methanotrophs at the genus level at day 18 during the seedling stage. Other include the sequences with a relative abundance of less than 0.9% and the unclassified sequences at the genus level. Mean ± SD, n = 3.0 d represents the original soil used in this experiment. (1) S0, no addition of rice straw (control); (2) S1, 0.33% (w:w) rice straw addition (equal to all aboveground biomass return); (3) S2, 0.66% (w:w) rice straw addition; (4) BS1, 0.33% (w:w) rice straw addition plus 2.0% (w:w) biochar (equal to 45 t ha^{-1}); and (5) BS2, 0.66% (w:w) rice straw addition plus 2.0% (w:w) biochar. TY, paddy soil from Taoyuan, and BH, paddy soil from Binhai Southeast China. Adapted from Wang et al. (2018), published by Frontiers in Microbiology in 2018 with CC BY license permission

treated with biochar at high CO_2 and temperatures, due to its reductive effect on the bioavailability of dissolved organic carbon.

2.4 Carbon sequestration and soil responses to biochar application

In this section, we will discuss in detail the influence of biochar application on soil pH modulation, ecological processes, physical properties, microbial metabolic pathways, and nutrient cycling in the soil.

2.5 Biochar and soil pH

Biochar surfaces are composed of functional groups such as carbonyls, phosphates, carbonates, carboxyl, carboxylate, and oxonium ion groups that participate in soil pH adjustment and neutralization of the acidic content of the soil (Dai et al. 2017; Das et al. 2021). Soil pH affects microbial growth and metabolism. Acidic soil induces stress on non-acidophilic microbes and suppresses their growth. However, adding biochar to the acidic soil will facilitate the neutralization of the soil acidity, thereby enhancing the proliferation of neutrophilic and alkaliphilic microbes. In essence, biochar's acidic pH neutralization is based on its intrinsic alkaline or liming nature. Thus, it has liming properties and can sorb ions like aluminium ions, amongst others (Dai et al. 2017; Qian and Chen 2013). In addition to neutralizing soil pH, it enhances soil water retention, cation exchange capacity of the soil, dissolved organic carbon, and reduced soil bulk density. Biochar can efficiently sorb and immobilize aluminium ions, thereby reducing its toxicity on plants and soil microbes (Das et al. 2021; Zhang et al. 2019). It is noteworthy to say that the application of biochar is indeed a suitable means for neutralizing acidic soil, as evidenced in the study conducted by (Geng et al. 2022). This study observed that soil treatment with biochar made from peanut shells, fruit tree branches, and cow dung, which were pyrolyzed at different temperatures—300, 450, and 600 °C significantly increased soil pH by 8.48–79.25%. It equally reduced the exchangeable acidity by 56.94–94.95%, exchangeable aluminum by 34.38–95.66%, and exchangeable hydrogen by 58.72–93.27%. These soil conditions improved by biochar resulted in oxidative stress reduction, plant growth enhancement, leaf glutathione and malondialdehyde reduction, as well as increased diversity of the soil microbial communities. This study demonstrates that applying biochar to acidic soil is an efficient strategy for reducing soil acidity, increasing crop yield, and sequestering carbon (Geng et al. 2022).

To reiterate, with its liming effect, biochar contributes to the reduction of soil acidity and an increase in soil alkalinity level. Acidic soil inhibits the activities of methanotrophs, and a pH reduction of as little as 0.2 to 0.3 will significantly negatively impact the metabolic activities of methanotrophs and inhibit methane oxidation (Hütsch 1998; Nwokolo and Enebe 2024). Nevertheless, biochar addition ameliorates it by increasing soil pH. It indirectly controls soil methane emission by promoting the availability of potassium ions. An increase in the concentration and availability of soil potassium ions will lead to a corresponding decrease in soil redox potential and a resultant inhibition of the activities of methanogenic bacteria while promoting the proliferation of methanotrophs (Bi et al. 2019). Biochar application to the soil correlated positively with soil potassium ion availability, whereas methane emission equally correlated negatively with available soil potassium contents (Bi et al. 2019). Therefore, the application of biochar is a sustainable approach to environmental conservation, mitigation of greenhouse gas emissions, and modulation of soil pH.

2.6 Biochar and soil ecological environment

The interaction of biochar with soil biological and non-biological components affecting hydrological, biological, chemical, and physical characteristics is a necessary research focus for improving our knowledge of biochar's contribution to soil health, plant productivity, and climate change mitigation. Evidence of biochar's contribution to soil ecological environment enhancement, at present, is attracting significant attention. As a soil ameliorant and stress alleviator, biochar is efficient in soil carbon sequestration, soil structure or aggregate enhancement, and climate change mitigation. Due to the intrinsic nature of biochar, especially its recalcitrant carbon content, its application to soil has been reported to decrease soil respiration and carbon dioxide emissions, as the carbon composition of the char is not an easy-to-use carbon source by microbes (Fan et al. 2021; Grutzmacher et al. 2018; Lefebvre et al. 2021). However, although we stated that biochar decreases soil respiration and reduces carbon emission, the overall reduction of carbon emission by biochar occurs with a progressive increase in time. But at the initial or onset of the application, biochar exerts a positive effect in increasing soil respiration and carbon emissions, which gradually decrease with time and with a corresponding increase in soil organic carbon content (Geng et al. 2022). In light of the foregoing, Horel et al. (2019) observed that biochar application to soil planted with pepper plants at varying biochar concentrations exhibited an increase in water-holding capacity. It also recorded increased carbon dioxide emissions during the initial few days of the study and decreased with time. This observation is at par with the one reported by Liu et al. (2019) (Fig. 4). According to Horel et al.

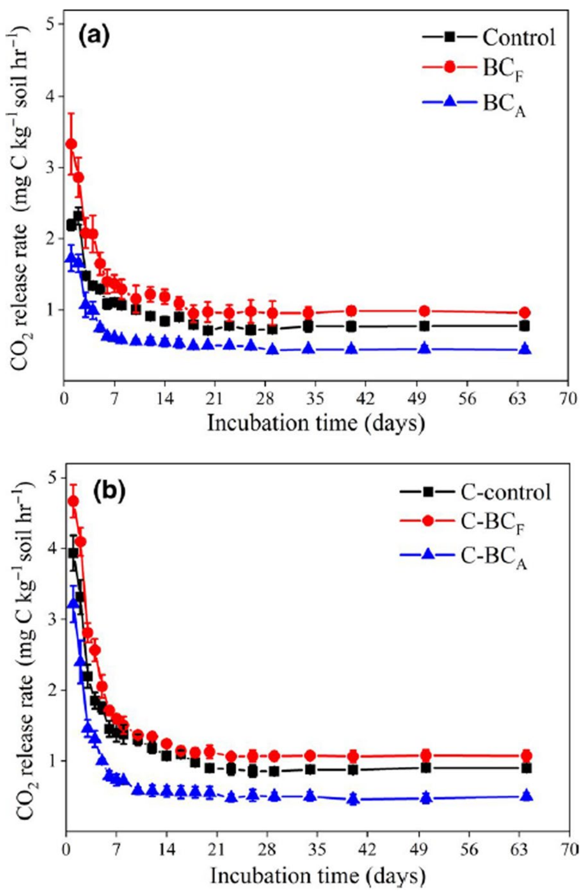


Fig. 4 The total C mineralization rate (**a**, **b**) during the 64-day incubation under different treatments. Control, soil without biochar; BC_F, Control with fresh biochar addition; BC_A, the soil with biochar applied in the field (**a**); C-control, Control with CRM addition; C-BC_F, BC_F with CRM addition, C-BC_A, BC_A with CRM addition (**b**). Error bars show the standard deviation (n = 3). F and A stand for fresh and aged biochar. CRM means crop residue-derived dissolved organic matter. Adapted from Liu et al. (2019) published by Global Change Biology Bioenergy with CC BY license permission

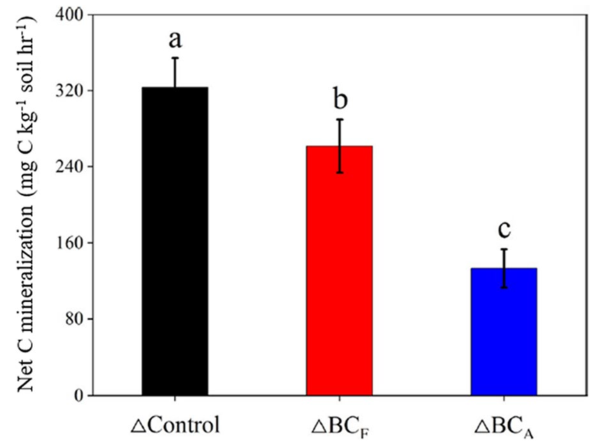


Fig. 5 The net C mineralization at 64 days of incubation under different treatments. ΔBCA, C-BCA minus BCA; ΔBCF, C-BCF minus BCF; ΔControl, C-control minus Control. Error bars show the standard deviation (n = 3). *Different letters* indicate significant differences between the treatments at $p < 0.05$. Adapted from Liu et al. (2019) published by Global Change Biology Bioenergy with CC BY license permission

(2019), the effect of biochar is concentration-dependent. The higher the quantity of biochar applied to the soil, the more the observed effects on the soil's ecological environment.

Figure 4 shows that adding freshly produced biochar to the soil significantly increased carbon dioxide evolution on the initial days of soil incubation. In Fig. 4a, it can be seen that soil amended with fresh biochar without crop residue-derived dissolved organic matter increased total organic carbon mineralization by 28.9%, whereas soil treated with aged biochar showed a 38.8% decrease in total organic carbon mineralization (Liu et al. 2019). Consequently, in Fig. 4b, fresh biochar amendment with crop residue-derived dissolved organic matter exhibited equally high carbon mineralization and increased CO_2 evolution, followed by the control, and the least was that of the aged biochar with crop residue-derived dissolved organic matter. Cumulatively and surprisingly, biochar amendment in the study by Liu et al. (2019) resulted in lower net carbon mineralization (Fig. 5). Specifically, the subtraction of the carbon emission value of BC_F from C-BC_F and BC_A from C-BC_A gave a low value for net carbon mineralization. All in all, biochar application decreases carbon mineralization rates in the soil. This biochar effect on carbon cycling could be attributed to its large surface area to volume ratio, porosity, and sorption capacity, which binds to organic carbon compounds and prevents microbial decomposition of the sorbed organic matter (Liu et al. 2019; Smebye et al. 2016; Zimmerman et al. 2011). As another example, three years after biochar addition to the soil, Chen et al. (2018) observed that a 12% and 20% reduction in soil basal respiration was recorded for 20 and 40 t/ha biochar treatments.

Comparing soil amendment with straw and biochar, the former contains easily degradable or labile carbon and will be quickly decomposed by microbes, leading to an increased carbon mineralization rate. The latter, on the other hand, especially fresh biochar with easily decomposable organic matter, will preferentially undergo decomposition while the remaining carbon present in the biochar that is recalcitrant will remain as a stable carbon pool in the soil (Ameloot et al. 2014; Yi et al. 2020). Therefore, biochar reduces the mineralization of labile organic matter and stimulates negative priming effects regardless of the amount of labile organic matter addition to the amended soil. Methane emissions from soil, on the other hand, were found to significantly decrease in a biochar-amended soil even under a high straw amendment rate (Wang et al. 2018). Through an increase in pH by 0.5 units, biochar amendment facilitated a decrease in methane emissions despite the presence of high concentrations of added straw in acidic soil (Wang et al. 2018). One may ask why biochar has this negative priming effect on methane emissions. The answer lies in the intrinsic properties of biochar, especially those containing electroactive functional groups (quinone and hydroquinone, amongst others), which actively participate in redox reactions in the soil by either accepting or donating electrons. It is believed that these functional groups present in biochar particles could compete favorably for electrons with carbon dioxide molecules and interfere with the methanogenesis process, thereby resulting in decreased methane emission from biochar-amended soil (Klüpfel et al. 2014; Wang et al. 2018). In addition to the competitive interference of biochar on the substrate for methanogen metabolism, it also reduces methanogenic archaea abundance as well as the methane emissions from biochar-amended paddy soil, as reported by Qi et al. (2021). According to the authors' report, this methane emissions reduction following biochar application was within the ranges of 22.2% to 95.7%. Recall that biochar intrinsic properties—such as microporosity, high specific surface area, ability to alter soil bulk density, and its influence on microbial community— are the main rationale behind it negative priming effect as well as reduction effects on methane emissions (Mukherjee and Lal 2013; Wang et al. 2018, 2019). Another explanation for the observed decrease in methane emissions following biochar application to the soil as reported by Qin et al. (2016) is biochar-induced increase in the diversity and abundance of methanotrophs which metabolise methane in the soil. In another study, changes in methanogenic archaeal genes (*mcrA*) rather than methanotrophic bacterial genes (*pmoA*) were found to be the rationale behind changes in methane emissions (Cai et al. 2018). Further research is needed in this area to fully ascertain the reason behind biochar's negative priming effect on methane emissions while considering variable that may exert spaciotemporal variations in the soil ecological environment.

Considering recent discussions regarding climate change, the three top GHG emissions, CO_2, CH_4, and N_2O, are the most important factors to consider for agricultural production. Climate change mitigation depends on actions available to reduce GHGs. The contributions of biochar to CO_2 and CH_4 emission control from the soil have been described above. Hence, it is necessary to clarify biochar-mediated control of N_2O emissions. In a study conducted by Case et al. (2012), the application of biochar to soil followed by wetting at a uniform water holding capacity of 87% resulted in about 49% suppression in nitrous oxide emissions from the soil. This nitrous oxide suppression effects of biochar could be attributed to its influence on decreasing soil bulk density, increasing soil aeration, microbial activity and physical immobilization of nitrate ions in the soil. Nitrification and denitrification are both soil moisture sensitive. An increase in soil moisture content results in a decrease in soil aeration and oxygen availability to microbes. Nitrifiers are very sensitive to the oxygen content of the soil and tend to be more active at soil water holding capacity (WHC) of 60% or less but beyond the 60% WHC, their activities decrease. Denitrifiers, on the other hand, thrive well at WHC above 70%, resulting in an increase in N_2O emissions from the soil (Bateman and Baggs 2005; Gillam et al. 2008). Therefore, soil moisture, temperature, microbial activity, pH, aeration, and organic matter content strongly affect nitrous oxide emissions via the denitrification process (Hofstra and Bouwman 2005). For instance, a study has shown that the conversion of nitrous oxide to nitrogen is facilitated by an increase in soil pH following biochar application (Taghizadeh-Toosi et al. 2011), and biochar possesses the inherent property of increasing soil pH. Additionally, a meta-analysis study conducted by Cayuela et al. (2014) shows that biochar decreased nitrous oxide emission by 54% across multiple studies. This effect of biochar on nitrous oxide emission was found to be influenced by soil water content, soil pH, organic carbon content, etc. Additionally, it has been shown in a study performed by Mechler et al. (2018) that in biochar treated soils, seasons affect soil $NH4^+$-N, with spring having the highest amount, followed by summer and autumn. This is also true for NO_3^- N. The authors observed that nitrous oxide emission was significantly and negatively correlated to soil moisture and significantly and positively correlated to soil temperature. The concentration of NH_4^+ in the soil also affects nitrous oxide emissions. Therefore, soil characteristics influenced by biochar control nitrous oxide emission from the soil. With respect to temperature, Mechler et al. (2018) reported that biochar application contributed to a reduction in soil temperature. This could be attributed to changes in soil texture, lower bulk density and reduction in the absorption of infrared radiation from the sun which causes insulation effects in the soil during changes in atmospheric temperature (Zhang et al. 2013). Interestingly, soil tillage and crop canopy development influence soil surface albedo (i.e. the proportion of the incident light and/or radiation that is reflected by soil or earth surface) variations in a biochar-treated soil. Therefore, in the absence or reduced tillage and no canopy development under 30 to

60 t ha^{-1} biochar application, soil temperature increases due to a decrease in about 80% of soil surface albedo. But with tillage and crop canopy development comes a lower surface albedo and decreased soil temperature under biochar treatment (Genesio et al. 2012). All in all, soil temperature may affect soil organic matter decomposition, soil respiration, and greenhouse gas generation (N_2O, CO_2) since it affects microbial activities and soil water availability (Fang and Moncrieff 2001). Indeed, further research is needed to fully understand the influence of biochar on soil temperature and heat fluxes.

Interestingly, biochar application, in addition to significantly affecting the abundance, diversity, and distribution of soil microbial communities, also exerts a similar influence on soil processes involved with biogeochemical cycling and the emission of both carbon and nitrogen greenhouse gases from the soil. Application of straw biochar in a successive approach to the agricultural soil was found to increase soil carbon sequestration and decrease nitrous oxide and methane emissions from the soil. Biochar application also decreased the net global warming potential by 0.6–19 folds (Bi et al. 2019). Evidently, biochar's impact in reducing carbon dioxide emissions could be attributed to its adsorption of dissolved organic carbon in its pores, binding with other ions needed for microbial growth and metabolism, as well as inducing negative priming effects on microbes. This will decrease soil carbon mineralization, basal soil respiration, and selection of dominant microbial taxa. Other non-carbon dioxide greenhouse gases, such as nitrous oxide and methane, are controlled by soil biochar. The rationale behind biochar mitigation of nitrous oxide emissions from soil could be attributed to its ability to bind or adsorb nitrous oxide gas due to its high surface charge and specific surface area. It can also indirectly control nitrous oxide emission by decreasing soil bulk density and promoting soil aeration. An increase in soil aeration will inadvertently retard the activities of denitrifying bacteria and their reductase enzymes that catalyze the conversion of nitrite and nitrates into nitrous oxide in the soil. Thus, it significantly halts the denitrification processes involved in nitrous oxide formation while promoting the denitrification process and facilitating the conversion of nitrous oxide to nitrogen molecules. It equally increases microbial nitrogen use efficiency as well as the activities of nitrogen fixing bacteria. In an agricultural soil, the increase in plants uptake of inorganic nitrogen (NH_4^+/NO_3^-) will result in a significant decrease in soil inorganic nitrogen pool that will be available for the production of nitrous oxides by denitrifying bacteria (Cornelissen et al. 2013; Jiang et al. 2023; Khan et al. 2014; Mooshammer et al. 2014; Van Zwieten et al. 2010, 2014). Another study supporting the contributions of biochar in enhancing plant uptake of nitrogen from the soil was reported by Saarnio et al. (2013) and, as a consequence, decreased nitrous oxide flux from the soil (Fig. 6). It is imperative to note that biochar can perform a dual role in inhibiting the activity of nitrogen fixing bacteria through the processes described below. It equally could contribute to an increase in plant nitrogen uptake by improving soil nitrogen retention, enhancing ammonium retention, promoting the proliferation of beneficial nitrogen cycling microbes as well as enhancing plant root growth and assimilation of nitrogen. Therefore, biochar might suppress the proliferation and activities of nitrogen fixing bacteria yet promote the uptake of nitrogen from the soil.

It is imperative to note that the methane emission from the soil is equally circumvented or mitigated by biochar. Biochar performs this function through the adsorption of methane molecules on its surfaces, promoting the abundance of methanotrophs by increasing soil aeration and decreasing soil bulk density. The presence of oxygen in the soil inhibits the activities of methanogens and retard the process of methanogenesis. This biochar-modulated soil processes result in decreased methane emission from the soil (Bi et al. 2019; Lehmann and Joseph 2024; Nwokolo and Enebe 2024; Sadasivam and Reddy 2015).

Nevertheless, it is noteworthy to mention that the potential of biochar to influence or mitigate the emission of greenhouse gases from soil entirely depends on the biochar pyrolysis temperature, which determines the chemical composition of the biochar particles. Recall that biomass pyrolyzed at low temperatures will generate a biochar characterized by a high percentage of aliphatic carbon content and the presence of high oxygen-carbon functional groups, which increases the solubility of the biochar. Aliphatic carbons enhance microbial mineralization of soil organic carbon and degradation of biochar particles through inducing positive priming effects on the microbes. But biomass pyrolyzed at very high temperatures, on the other hand, generates biochar rich in aromatic carbon with high hydrogen-carbon functional groups that are inert and resistant to microbial oxidation or mineralization and, as a consequence, induce negative priming effects on soil microbes (Bi et al. 2019; Xiao et al. 2014). It is therefore recommended that the application of biochar pyrolyzed at high temperatures is needed to achieve maximum impact in the control of greenhouse gas emissions from soil.

2.7 Biochar influence on metabolic pathway and their impact on soil organic carbon stabilization

Biochemically, biochars are notorious for affecting the metabolic activities of microbes as well as impacting soil organic carbon stabilization. Despite biochars' positive contribution to improving soil fertility, metal chelation,

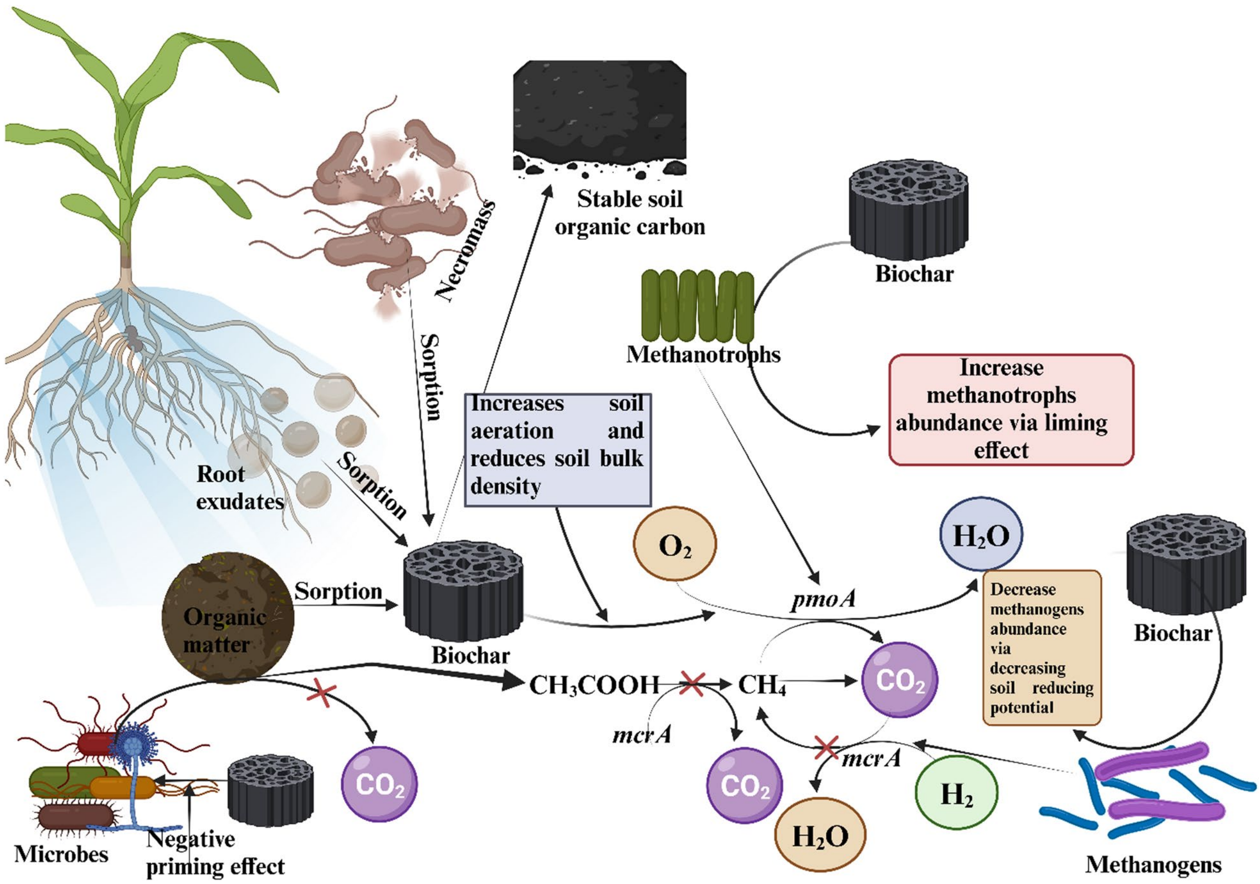


Fig. 6 Diagrammatic illustration of the impact of biochar in the modulation and regulation of soil processes and metabolic pathways involved in the carbon cycle. Genes abbreviation and meaning: *mcrA* (Methyl-coenzyme M reductase), *pmoA* (particulate methane monooxygenase). Biochar, through sorption of soil organic carbon, reducing soil bulk density, increasing soil aeration, decreasing soil basal respiration, inducing negative priming effect on microbial metabolism, decreasing soil redox potential, and soil liming effect facilitates the modulation and control of carbon, and methane cycles

and promoting microbial activities, they also negatively affect the metabolic activities of microbes in the soil. For instance, the application of biochar leachate into a BD-11 medium containing N_2-fixing cyanobacterium—*Nostoc* sp. inhibited the photosynthesis, nitrate assimilation, and nitrogen fixation of the organism. Through biotoxicity and impairment of the cyanobacterial membrane and photosystems functions especially through damaging the D1 protein of the oxygen evolution complex, and a decrease in the electron transfer activities of the photosystem II, biochar leachate was able to inhibit the metabolic functions of the organisms. This inhibition in the metabolic functions of the cyanobacteria negatively and significantly affected nitrogen fixation, nitrate assimilation, and photosynthesis (Jiang et al. 2024). Similarly, biochar equally induces a decrease in microbial absorption of irons, resulting in a decrease in the nitrogen fixation efficiency, as iron (a cofactor) needed for efficient enzyme activities was adsorbed by biochar. The rationale behind biochar leachate-induced toxicity on nitrogen fixing cyanobacteria isolated from paddy soil as described above could be attributed to the presence of toxic polyaromatic hydrocarbon and long chain saturated fatty acids (such as 4-Methylquinazoline, Methanesulfonamide, 4-Hydroxyquinazoline, 2-phenylquinoxaline, 1,2,3-Propanetriol,1-acetate, 1,3-Dichloro-2-propanol, 2,3-Dichloro-1-propanol, a-Hydroxycyclohexylphenylketone, bis(2-ethylhexyl) cyclohexane-1,2-dicarboxylate, Ethyl 2-hydroxyacetate, 5-Methyl furfural, 4-Acetamidobenzaldehyde, succinic acid, and 2-ring naphthalene) present in the leachate. These toxic organic molecules present in biochar leachate possess the tendency to impair the activities of photosystem II by disturbing its electron transport chain, decreasing cytochrome *b6f* concentration and ATP production as well as altering the reaction units in the photosystem II. This negative effect on the microbes resulted in decreased growth, nitrogenase activity, and photosynthetic efficiency. This drawback corresponds with the adsorption of signaling molecules (flavonoids, nod facts), decreased nitrate assimilation, and nitrogen fixation (Buss et al. 2015; Jiang et al. 2024; Tomar et al. 2022).

In fact, studies have also shown that applying biochar to the soil inhibited the growth potential of *Rhizobium* and decreased the soil's nitrogen content. A decrease in the activities and metabolic functions of nitrogen fixing bacteria inevitably leads to a proportionate decrease in crop nitrogen content, especially when there is no external nitrogen supply. Nitrogen fixing microbes are perhaps among the key contributors to replenishing soil nitrogen and could contribute within a single crop growing season as high as 60 kg N ha^{-1} (Jiang et al. 2023; Khan et al. 2014).

In a study that examined the impact of biochar on soil microbial metabolic potential in a saline, alkaline soil planted with cotton and supplemented with biochar, Wang et al. (2024a) noticed that the application of biochar to the soil influenced the up-regulation in the metabolism and biosynthesis of multiple compounds, including 2-hydroxyphenylacetic acid, phenylacetic Acid, norephedrine, guanosine 3′-monophosphate, 2,3,4,5-tetrahydro-2-pyridinecarboxylic acid, calystegin A3, 3-dehydroshikimate, allysine, 3-hydroxybenzoic acid, L-Glutamic gamma-semialdehyde, L-asparagine, O-acetyl serine, 3-dehydroshikimate, and allysine. Metabolites such as lipids, organic acids, organic heterocyclic compounds, and derivatives of organic acids act as indicators or signal molecules with benefits in facilitating plant–microbe interactions. These interactions enable plants to tolerate saline or abiotic stress under biochar application (Abedini et al. 2021; Banerjee et al. 2019; Stringlis et al. 2018). Microbes adapt to abiotic stress by modulating the metabolic pathways involved with pyrimidine and purine metabolism and other important biomarkers, as presented above (Li et al. 2023; Wang et al. 2024a; Xu et al. 2020).

2.8 Effects of biochar on soil physical properties

Soil physical properties such as porosity, water retention capacity, and bulk density affect biochar potential in soil carbon sequestration and vice versa. Site-specific soil properties, for instance, have proven to be key determinants of long-term soil organic carbon sequestration following biochar application. This was observed in a comparative study examining the influence of biochar application on two different paddy soils (Yellow River alluvium and a quaternary red clay paddy soils). The results showed that biochar application increased the soil organic carbon content in the Yellow River alluvium paddy soil by 57.6 and 64.5 Mg C ha^{-1} in the quaternary red clay paddy soil despite receiving the same amount of biochar treatment (of 11.3 Mg ha^{-1} per cropping season) applied for a period of 4 years. Chemically, the quaternary red clay paddy soil has high amorphous iron and clay compositions, protecting soil organic carbon from mineralization by soil microbes after biochar application. This paddy soil decreased the abundance of fungi, Gram-positive bacteria and actinomycetes community due to a decrease in the anomeric carbon-hydrogen contents (C–H content) after biochar application compared with the former, which supports the proliferation of these microbes due to an increase in the concentrations of O-alkyl Carbon contents (Bi et al. 2020). Soil properties that negatively inhibit the proliferation of soil microbial community, like the presence of aluminum ions in acidic soil, influence the decrease in microbial biochar mineralization compared with the alkaline soil. Clay particles also contribute to stabilizing biochar and soil organic carbon (Fang et al. 2015; Luo et al. 2011). Therefore, regardless of biochar application, forming iron-organo complexes in the soil will surely reduce the microbial degradation of labile organic carbon. Iron-organo complexes often are formed in soil with high clay contents (Jones and Edwards 1998). Put another way, regardless of biochar application, forming iron-organo complexes in the soil will surely reduce the microbial degradation of labile organic carbon. Contextually, this highlights the importance of iron-organo interactions as an independent mechanism of carbon preservation and protection and perhaps as a counterpoint or complement to biochar-related mechanisms. Soil carbon sequestration behavior of biochar clearly shows that biochar accumulates mainly in the zones of soil organic matter pools that are not protected by the soil mineral matrix. By forming organo-mineral complexes (i.e. through binding with mineral particles and organic matter), biochar contributes to soil carbon sequestration and stabilization (Plaza et al. 2016). In another study involving biochar recovery from a laboratory soil incubation experiment, it was noticed that high concentrations of recovered biochar were mostly from areas containing free organic matter fraction, showing the interactions and/or affinity of biochar with organic matter. Thus, biochar protects exogenous and endogenous organic carbon against biological degradation and chemical oxidation (Fernández et al. 2014; Ngo et al. 2013).

In another study, the application of biochar (made from corn residues) that was produced at 350 °C enhanced a significant increase in the structural stability and aggregation of the soil compared to the biochars pyrolyzed at higher temperatures. In fact, an increase in pyrolysis temperature for biochar production has been shown to decrease basal soil respiration, soil organic carbon, soil structural stability indices, and the percent water soluble aggregate regardless of the type and rate of feedstock used (Saffari et al. 2020). A soil is considered structurally stable when it can retain its arrangement against any stresses. Structural stability of the soil is a good indicator of aggregate stability (Mamedov and Levy 2013; Six et al. 2002). The contribution of biochar to enhancing or not soil aggregate stability depends on its solubility and aromaticity. Biochar with less available oxygen containing functional groups and high aromatic content has no significant effect on soil aggregate stability compared to biochar with low aromaticity and high oxygen functional groups. For instance, organic substances containing carbohydrate molecules (with high oxygen functional groups) significantly correlated with soil aggregate stability. The amount of oxygen bearing functional groups present in an organic molecule will determine the solubility of the organic substance in the soil (Kavdır et al. 2005), and high pyrolysis temperature converts the carbohydrate molecules into aromatic compounds with decreased solubility and increased stable carbon content.

In other soils, for instance, Madari et al. (2017) observed that biochar application to sandy clay loam Haplic Ferralsol soil increased soil pH, and plant-available water but decreased soil bulk density and Al^{3+} concentrations linearly with biochar application rates. Similarly, increased biochar application in clay Rhodic Ferralsol soil was found to increase soil organic carbon (Carvalho et al. 2016). Other types of soil, such as Ferralsol in north Queensland, Australia, that received biochar amendment yielded a significant nitrous oxide emission reduction, an increase in soil water contents, soil organic carbon, and crop yield (Agegnehu et al. 2015). In a Xerofluvent clay loam soil, Plaza et al. (2016) observed that the application of 20 t ha^{-1} biochar, both alone and with organic fertilizer, significantly increased soil organic carbon contents. In Acrisol soil, a mixture of biochar with organic fertilizer reduced soil carbon loss (Ngo et al. 2016). Biochar, therefore, exerts varying effects on soil, carbon sequestration, and greenhouse gas emission across different soil types. This is largely due to differences in organic matter contents, pH, microbial community compositions, and mineral compositions of the soil. In oxisols and ultisols (acidic soils), biochar liming effects contribute towards soil pH neutralization, increase base cation and phosphorus availability, and decrease aluminum solubility. In vertisols (a type of clay soil), biochar enhances soil structure, aeration, and cation exchange capacity of the soil. In calcareous soils such as alkaline soils, biochar exerts weaker liming effects and may contribute towards iron, zinc, and manganese chelation while maintaining soil moisture. In other soils, such as saline or sodic soils, biochar application could reduce sodium ion activities through binding to the ions. In sandy soils, it also helps increase soil water holding capacity, cation exchange capacity, and nutrient retention. Therefore, soil type strongly influences biochar's effectiveness, with the most pronounced in acidic, sandy, and degraded soils. For instance, in an experiment investigating the influence of biochar supplemented with ammonium sulfate on CO_2 and N_2O emissions from acidic sandy and alkaline clay soils, Wu et al. (2018) observed that corn biochar addition had no significant effects on CO_2 and N_2O emissions in the alkaline soil, whereas in acidic soil, it significantly decreased CO_2 emissions by 11.8% and N_2O emissions by 26.9%. Therefore, biochar's effects on mitigation of these greenhouse gas emissions are more pronounced in acidic than alkaline soils. Additionally, olive biochar applied to alkaline clay soil was also observed to have no significant effects on CO_2 emissions, but it decreased significantly N_2O emissions by 34.3%. Whereas, in acidic soil, it increased CO_2 emission and decreased about 68.4% of N_2O emissions (Wu et al. 2018).

2.9 Factors affecting biochar-mediated carbon sequestration and stability

With an increase in the need for controlling the emission of greenhouse gases and conserving the environment through promoting the build-up of soil organic carbon, scientists and environmentalists have proposed that biochar application to the soil is a definite and sustainable avenue for achieving this objective. However, the carbon sequestration efficiency of biochar may be affected by several factors such as soil type, wilting point, soil organic carbon content, rainfall, ambient temperature, atmospheric carbon level, pyrolysis technologies, pyrolysis temperature, feedstocks, experimental durations, and soil pH (Rosinger et al. 2023; Wang et al. 2016). Some of these factors have been described in the previous sections. Here, we will examine the major factors affecting biochar-mediated soil carbon sequestration.

2.10 Pyrolysis temperature

The temperature at which a feedstock material is subjected to pyrolysis will determine the conversion of labile or easily degradable carbon into aromatic carbon that is recalcitrant and stable. The pyrolysis temperature will often determine the degree of destruction or transformation of biomass structure and the development of macropores (Geng et al. 2022), as presented in Fig. 7. Pyrolysis temperature increase results in a corresponding increase in biochar's aromatic carbon content. A temperature within 300 degrees will achieve a partial denaturation of biomass material into biochar with high degradable carbon and low porosity, as shown in Fig. 7 (Geng et al. 2022). But as the pyrolysis temperature increases, the biomass material undergoes further

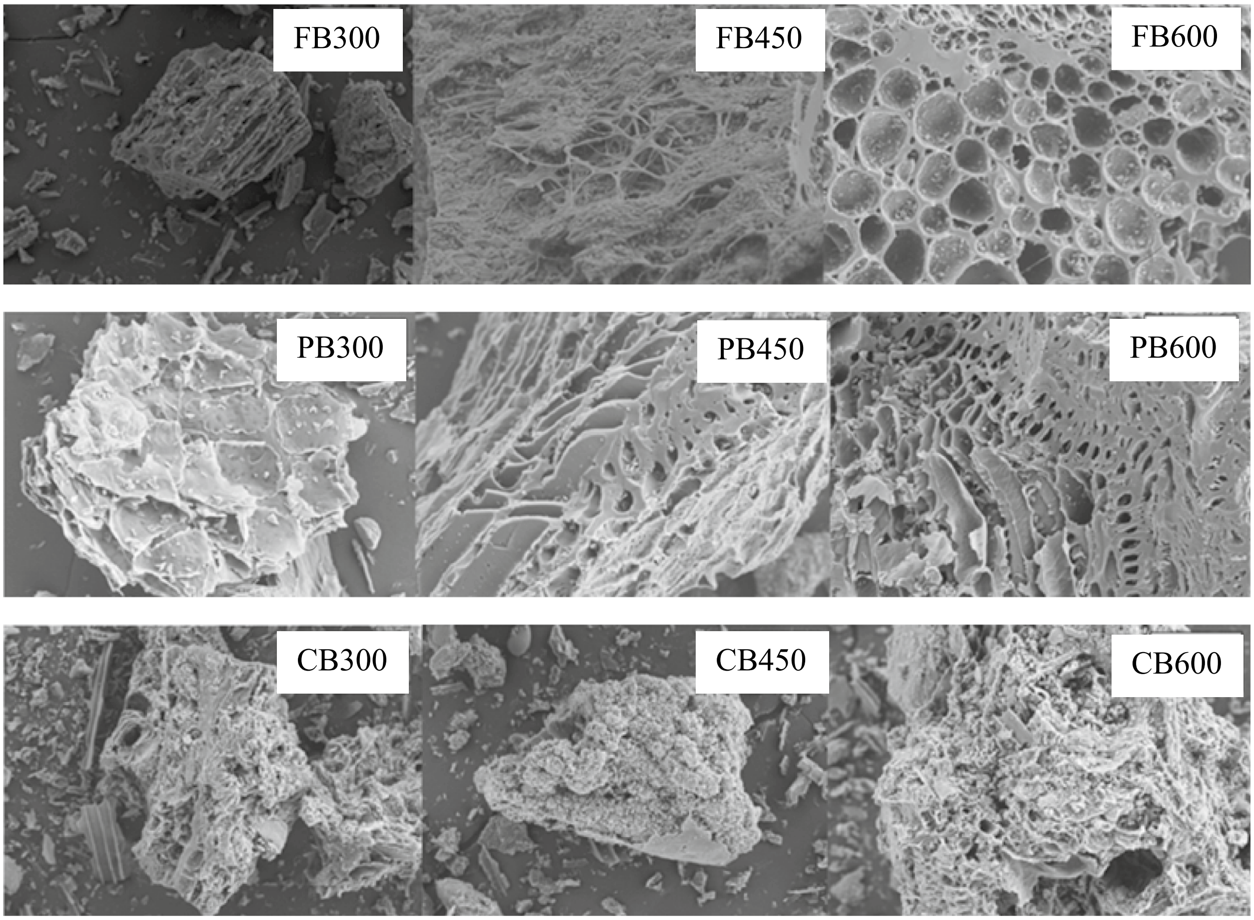


Fig. 7 Scanning electron microscopic images of different biochar types made from a fruit tree branch (FB), peanut shell (PB), and cow dung (CB) pyrolyzed at 300, 450, and 600 °C. Adapted from Geng et al. (2022) with minor modification, published by Ecotoxicology and Environmental Safety with CC BY-NC-ND license permission. The small and unreadable scanning electron microscope dimension contained at the bottom of each panel is removed to increase the figure's clarity and quality

structural modification with a reduction in the amount of easy-to-use carbon (labile carbon) and an increase in micro-, meso-, and macropores in the biochar (Fig. 7). Geng et al. (2022) reported that biochar generated from fruit tree branches, peanut shells, and cow dung pyrolyzed at 300, 450, and 600 °C exhibited varying effects on carbon mineralization and carbon dioxide evolution. Fruit tree branch biochar pyrolyzed at 300 °C (FB300) induced the highest cumulative carbon dioxide emissions from the soil, while the least was observed for cow dung pyrolyzed at 600 °C (CB600). They further that pyrolysis of biomass material at a lower temperature, such as 300 °C, similar to those used in the torrefaction of biomass material (Nwabunwanne et al. 2021), will result in higher cumulative carbon dioxide emissions from amended soil compared to the same biomass material pyrolyzed at a higher temperature like 450 and 600 °C (Geng et al. 2022). High-temperature pyrolysis yields biochar with stable carbon molecules that have about 25–50% carbon sequestration potential per feedstock carbon pyrolyzed. Therefore, it is essential to achieve biochar hydrogen to organic carbon ratio of 0.38 to 0.44 at high pyrolysis temperatures (500 to 550 °C, for instance), which will have an efficient soil carbon sequestration potential (Rodrigues et al. 2023). Although this evidence of high pyrolysis temperature in biochar's carbon sequestration efficiency has been put forward, a comprehensive understanding of the mechanism and influence of high pyrolysis temperature on soil carbon sequestration at varying environmental conditions is not yet fully understood and requires further investigation.

However, we will discuss here the correlation between pyrolysis temperature and carbon sequestration efficiency and biochar stability. The temperature of pyrolysis affects the properties of biochar. It equally influences the efficiency and stability of its carbon sequestration potential. In a study examining the effect of biochar pyrolysis temperature on soil microbial nutrient use efficiency and soil enzymes, Guo et al. (2020) reported that pyrolysis temperatures of 500 and 700 °C produced biochar that resulted in a decrease in soil carbon-to-nitrogen ratio due to a corresponding decrease in dissolved organic carbon, increase in pH and increase in the activities of carbon-to-nitrogen acquiring soil enzymes. This led to an increase in microbial biomass nitrogen content and a decrease in microbial biomass carbon. To illustrate, for instance, a decreased dissolved carbon-to-nitrogen ratio implies a carbon deficiency condition with increased nitrogen availability. At this point, microbes will adjust their nutrient use efficiency by lowering their nitrogen use efficiency and increasing their carbon use efficiency, which will result in a corresponding increase in the activities of carbon-to-nitrogen acquiring enzymes (α-glucosidase, β-glucosidase, β-D-cellobiosidase and β-xylosidase) activities. But at high substrate carbon-to-nitrogen ratio implying a condition of nitrogen deficiency, microbes will lower their carbon use efficiency and increase the nitrogen use efficiency as well as the activities of nitrogen acquiring enzymes (such as N-acetyl-β-glucosaminidase and leucine aminopeptidase) (Guo et al. 2020; Mooshammer et al. 2014). In essence, microbial carbon use efficiency was increased by the increased pyrolysis temperature of the applied biochar and a corresponding decrease in nitrogen use efficiency. Carbon use efficiency measures the partitioning or allocation of carbon assimilated by microbes that are incorporated into microbial biomass, and the one respired into carbon dioxide. An increase in carbon use efficiency will increase microbial incorporation of substrate carbon into biomass and less into carbon dioxide production. Thus, enhancing soil carbon sequestration. The same applies to nitrogen use efficiency, which measures the difference in the microbial incorporation of nitrogen into its biomass versus conversion into inorganic nitrogen. An increase in nitrogen use efficiency will result in an increased incorporation of nitrogen substrate into the microbial biomass and a decrease in denitrification or nitrogen mineralization rate (Mooshammer et al. 2014). Biochar's effect on soil carbon sequestration correlated positively with pyrolysis temperature. An increase in pyrolysis temperature causes an imbalance in the carbon-to-nitrogen ratio, affecting microbial carbon use efficiency. Lower pyrolysis temperature (350 °C), on the other hand, increases soil nitrogen availability, soil pH, and dissolved nitrogen concentrations.

Similarly, another explanation for the increase in biochar's carbon sequestration with increased pyrolysis temperature for biochar production could be attributed to the structural modification of the biochar particles under increased pyrolysis temperatures. Biochar produced at a higher temperature, for instance, at 500, 600, and 700 °C, bears high porous spaces within its structure (see Fig. 7). These pore spaces serve as sites for the adsorption of soluble or dissolved carbon, water, and nutrients. The immobilization of labile carbon within the biochar pore spaces limits its accessibility to microbes and microbial enzymes and consequently decreases microbial carbon turnover in the soil (Luo et al. 2013; Singh and Cowie 2014). Labile carbon immobilization is not only the mechanism by which biochar controls microbial processes in the soil; another approach is soil humification. Biochar enhances soil humification by promoting the transformation of protein-like substances present in the soil organic matter into humus or humic like components. Ordinarily, the fate of dissolved organic matter in the soil is either to undergo decomposition or to be transformed into humus, a process mediated by microbes. Still, the presence of biochar facilitates this bioconversion process of soil organic matter into humus and limits its accessibility to microbes, thereby affecting their activities, processes, and proliferation (Cotrufo et al. 2013; Huang et al. 2023; Lipczynska-Kochany 2018).

Additionally, the influence of biochar pyrolysis temperature on the carbon sequestration potential of biochar cannot be overemphasized. Following a comparative study on the effect of pine wood biochars pyrolyzed at different temperatures (460, 500, 700, and 760 °C), Sapkota et al. (2024) reported that soil amended with biochars produced at 500, and 700 °C contributed to an improved soil organic carbon content by 49.2% and 87.7%, and a cumulative reduction in nitrous oxide emission by 68.5 and 73.9% as well as a carbon dioxide emission reduction of 66.9 and 72.4% respectively. This observation could be explained by the loss of water, tar, oxygen, and hydrogen functional groups during the high temperature pyrolysis of the biomass, resulting in the concentration and conversion of the biomass carbon into its aromatic forms. With greater aromaticity comes an increase in the carbon sequestration potential of the biochar compared with that of low temperature pyrolyzed biochar, which has easily accessible carbon and low aromatic carbon that enhance the metabolic activities of microbes as well as carbon mineralization (Ippolito et al. 2020).

It is noteworthy to mention that, considering the high energy consumption involved in high-temperature pyrolysis, one may wonder whether this technology can be practically promoted and widely accepted by farmers, despite the aforementioned biochar's good sorption, protective properties, and effectiveness in greenhouse gas emission reduction? Arguably, based on the cost of the huge amount of energy used in this case (i.e., biomass pyrolysis at 500 to 700 °C), biochar production and its application may not necessarily be economically reasonable. However, the use of heat recovery systems has shown to be effective in reducing the energy cost of biochar production. For instance, a study by Nwokolo et al. (2020) has shown that a significant amount of heat can be recovered from a biomass gasifier using a heat exchanger system installed on the gasifier. This heat exchanger system uses water as a heat carrier for trapping waste heat energy generated during pyrolysis at high temperatures. It has also been proven that biomass pyrolysis, as well as the syngas produced at high temperature, can generate as much as 665893.07 kcal quantity of energy. This energy ordinarily could be recovered, but it often gets lost through the surfaces of the cyclone or from the heating chamber. Hence, recovering this energy with heat exchanger units could allow it to be further used in electricity generation, biomass drying, and steaming (Nwokolo et al. 2016). In light of this, it is plausible to argue that the economic cost of biochar production at high temperatures is not high and may be well accounted for. Therefore, it would be appropriate to evaluate the amount of recoverable energy and consider using it to prepare organic waste (biomass) for the pyrolysis process. If these conditions are met, this technology could potentially be a viable technique in the transition toward sustainability.

2.11 pH

Soil pH is an essential determinant of soil redox potential. Carbon sequestration, which involves a certain level of chemical reactions in the soil, is indeed affected by soil pH. After applying biochar to acidic soil, it was found that the carbon dioxide released through microbial respiration was about 1.5 to 3.5 times higher than that of the control compared with neutral and alkaline soils (Sheng et al. 2016). In this acidic soil, indigenous organic carbon and biochar carbon were degraded easily to produce carbon dioxide, and the generated carbon dioxide aided the progressive degradation of the biochar. Prevalent in acidic soil were gram-positive bacteria responsible for biochar breakdown and soil organic carbon mineralization (Sheng et al. 2016). The rationale behind acidic soil promotion of biochar degradation lies in the acid–base neutralization reaction between the biochar functional groups and the hydrogen ions present in the soil. The affinity of carbon dioxide with an alkaline medium facilitates its adsorption in alkaline or neutral soil (Blagodatskaya and Kuzyakov 2008). Acidic soil induced a positive priming effect on microbial mineralization of soil organic carbon as well as an increase in microbial biomass carbon in the presence of biochar. However, this positive priming effect was inhibited in soil with increased pH (alkalinity) (Liu et al. 2016).

Biochar application to soil indeed significantly affects the soil microbiota by decreasing their activities through negative priming, as discussed earlier, or via biotoxicity effects. However, recall that this effect is often dependent on the pH of the soil. For instance, biochar application to soil with slightly acidic pH conditions (pH 5.19) has been found to induce higher carbon dioxide emission compared with soil at neutral or slightly alkaline pH (7.81). The slightly acidic pH soil contributed to an increase in biochar carbon degradation and a positive priming effect on the microbes, while the slightly alkaline soil showed a negative priming effect on microbes in soil organic carbon mineralization and decreased carbon dioxide emission (Sheng and Zhu 2018). Acidic soil, with its associated positive priming effect, promotes the dominance of copiotrophic bacterial taxa (*Bacteroidetes*, *Gemmatimonadetes*, and *Actinobacteria*) and a decreased abundance of oligotrophic groups (*Acidobacteria*, *Chloroflexi*). Other bacterial taxa that are abundant in both acidic and alkaline soils and are independent of pH and soil organic carbon priming effects associated with biochar application are *Actinobacteria*, and *Anaerolineae*. These bacterial taxa are efficient in the degradation of aromatic compounds present in biochar and are not likely affected by the toxicity of biochar's aromatic compounds. In alkaline soil, biochar enhances the stability of soil organic carbon through sorption, preventing microbes from accessing it, thus resulting in an increase in oligotrophic bacteria and a decrease in carbon dioxide emission (Sheng and Zhu 2018) (Fig. 8).

However, it would be exaggerated to attribute biochar mineralization solely to soil pH, as microbial mineralization may affect biochar degradation to a greater extent than soil pH. This obscurity requires further studies to ascertain the complete impact of biotic processes (microbial metabolism) and soil physiochemical properties on the degradation of biochar in acidic, neutral, and alkaline soils.

2.12 Feedstock material used

The type of feedstock material used in biochar production has a significant effect on its carbon sequestration potential and its microbial mineralization rate. When subjected to pyrolysis, agricultural waste such as manure tends to generate carbonates and high ash contents (Murray et al. 2015). Like crop residues, herbaceous feedstock material tends to have a surface area of around 2 to 70 $m^2\ g^{-1}$. Meanwhile, woody feedstock material will have a higher surface area in the range of 200 to 380 $m^2\ g^{-1}$ (Liao et al. 2018). The surface area of biochar is an essential determinant of its sorption capacity in the soil as well as its charge distributions. Herbaceous biomass yields biochar with lower carbon contents and

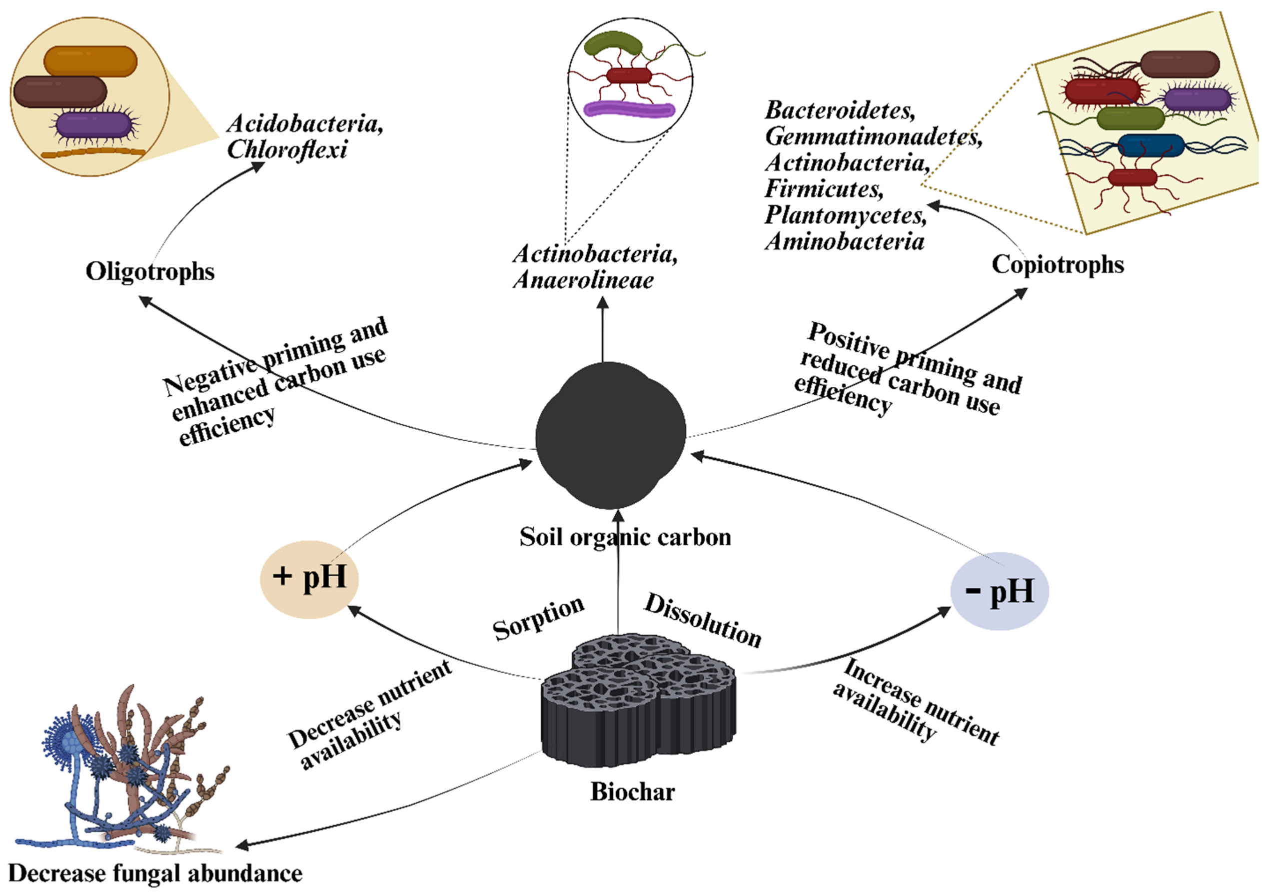


Fig. 8 Impacts of biochar on soil microbial biodiversity under the influence of soil pH

lower yield per feedstock material pyrolyzed at high temperature (Liao et al. 2018). In another study, it was found that pyrolysis of coffee hulls, palm oil fiber, and pineapple stubble at 600 °C yielded biochar with surface area and pH of 60 $m^2\ g^{-1}$ and 9 for biochar from coffee hull and pineapple stubble feedstocks. Meanwhile, palm oil fiber yields biochar with a 29 $m^2\ g^{-1}$ surface area. These biomass materials have varying levels of fixed carbon, with palm oil fiber and coffee hull derived biochar having about 80% fixed carbon. Biochar derived from these two feedstocks with 80% fixed carbon content is perhaps the best material with high carbon sequestration potentials, as evidenced in the study (Chin-Pampillo et al. 2021).

Suffice it to say that feedstock material can be grouped as woody and non-woody or herbaceous biomass. Forest biomass, especially wood and other forest residues, is regarded as woody biomass. These biomass materials usually have very low water contents, low ash contents, high bulk density as well as high calorific values, and their biochar generally has high fixed carbon contents. Non-woody biomass (agricultural residues, municipal solid wastes, sewage sludge, animal dung, etc.), on the other hand, has high water contents, high ash contents, low bulk density, and low calorific values. They equally have low fixed carbon (Jafri et al. 2018; Tomczyk et al. 2020). The composition of woody biomass that contributes to a high yield of biochar with high fixed carbon is the presence of lignin, cellulose, and hemicellulose contents compared with non-woody biomass, which has low fixed carbon and high ash content as a result of low or moderate levels of lignin composition, cellulose and/or hemicellulose (Wang et al. 2015).

In a study comparing the carbon sequestration capacity of biochar derived from pigeon pea and maize stalk biomass, Kumar et al. (2024) reported that biochar derived from pigeon pea has a carbon sequestration potential of 84 CO_2 eq kg^{-1}, while maize-derived biochar has 55 CO_2 eq kg^{-1}. This difference in carbon sequestration potential between these agricultural crop residues could be attributed to the higher lignin content in pigeon peas — about 18%, 33% cellulose, and 24% hemicellulose (Sahoo et al. 2021; Sathish et al. 2024) — as well as a corresponding higher hydrogen content than that of maize-derived biochar (whose biomass has lignin composition in the range of 10–15%, cellulose in the range of 40–50% and hemicellulose 20–30%) (Liang et al. 2023; Mori et al. 2015). Also, the oxygen content of pigeon peas was found to be higher than that of maize, as maize stalks contain fewer oxygen-rich compounds relative to pigeon peas with high oxygen-rich compounds. The oxygen content of biochar particles (oxygen-containing functional groups) influences their carbon sequestration potential, stability, and reactivity (Yang et al. 2016). It is evidenced that biochar carbon sequestration capacity is influenced by the feedstock material pyrolyzed; however, further studies should focus on understanding the surface chemistry of biochar and its overall properties, as well as how these properties enhance or affect carbon sequestration across diverse environmental conditions and locations.

To reiterate, it is expected that different feedstock materials will exert different effects in carbon sequestration; however, this is not always the case, as what determines the contributions and influences of different feedstock materials on carbon sequestration potentials of biochar is pyrolysis temperature, rather than the type of biomass feedstock materials types used. Evidently, while examining the carbon layer planes of biochar produced from the coniferous tree, broadleaf, and herbs plants, Lu et al. (2016) observed that the size distribution of carbon layer planes in the produced biochar indicated that the composition and content of the carbon layer plane are similar among the different plant feedstock materials but differed with an increase in pyrolysis temperature, which resulted in a 2- and 3-times increase in the carbon layer plane at pyrolysis temperatures of 600 and 800 °C compared with biochar produced from feedstock materials pyrolyzed at 400 °C. That's to say, an increase in pyrolysis temperature significantly increases the development of pore sizes within the biochar material and would result in increased carbon sequestration regardless of the feedstock material pyrolyzed. The fibrous nature and the chemical composition of the feedstock material subjected to heat treatment (pyrolysis) will determine the amount of aromatic organic matter present in the resulting biochar. The pyrolysis temperature equally influences it. An examination of the biochar aromatic compositions derived from the pyrolysis of rice straw, pine wood, pig manure and sewage sludge at 300, 400, 500, 600 and 700 °C, shows that at temperature above 500 °C, pine wood biochar with the highest stable aromatic carbon will be the best agent for maximum carbon sequestration followed by rice straw and pig manure. At high pyrolysis temperatures, these organic biomasses tend to generate biochar with low oxygen to carbon and hydrogen to carbon ratios. However, at pyrolysis temperatures below 500 °C, the produced biochar has high dissolved organic carbon, unstable organic-carbon and yield (Wei et al. 2019). Biochar with stable organic carbon contents is a good agent for soil carbon sequestration, while biochar with high labile or dissolved organic carbon contributes to soil respiration and soil processes and supports microbial carbon needs (Beesley et al. 2010; Tang et al. 2016). In essence, the stability of biochar carbon will influence its durability in the soil and its overall contribution to soil carbon sequestration. Pyrolysis temperature influences the extent of carbonization of the biomass material undergoing pyrolysis, and feedstock material equally contributes to the carbon concentration level of the biochar produced. The more cellulose, lignocellulose and fiber present in the feedstock material, the higher the carbon content of the biochar produced. An increase in pyrolysis temperature will increase the carbon content of the plant-derived biochar (Al-Wabel et al. 2013; Deng et al. 2021; Wei et al. 2019).

Additionally, the biomass material type and temperature determine the properties of different feedstock materials undergoing pyrolysis (Murtaza et al. 2022). Pyrolysis of different feedstock materials at different temperatures shows that BET (Brunauer–Emmett–Teller) surface area (a measure of the physical adsorption of gas molecules on solid surfaces) increased from 3.39–443.79 and 11.61–280.97 $m^2 g^{-1}$ for sawdust and rice husk biochar. An increase in pyrolysis temperature resulted in a decrease in the biochar values for cation exchange capacity. An increase of 57.20 ± 0.02 and 44.10 ± 0.02 ash content was observed for paper sludge and poultry litter biochar. Whereas the biomass with the highest fixed carbon content of 55.31 ± 0.15, 48.47 ± 0.31, and 58.85 ± 0.22 was reported for sawdust, rice husk, and food waste biochar at 650 °C (Pariyar et al. 2020). With an increase in pyrolysis temperature comes a corresponding decrease in biochar polarity and an increase in the aromaticity of the biochar formed, irrespective of the feedstock material used (Ambaye et al. 2021; Ippolito et al. 2020; Murtaza et al. 2022). Therefore, rice husk and sawdust biochar pyrolyzed at high temperature is superior to other biomass feedstocks in carbon sequestration, carbon pool, and recalcitrant carbon content (Pariyar et al. 2020). Having considered the overall benefits, properties, and major factors influencing biochar's contribution to soil carbon sequestration, it will be appropriate to evaluate the economic merit of large-scale biochar application.

Pyrolysis temperature used during biochar generation has been found to influence the surface chemistry and biochar pore structure. Regardless of the biomass feedstock material pyrolyzed, higher temperatures like 650 °C significantly increased biochar net negative charge and surface area, whereas the 250 °C pyrolyzed biochar has the greatest cation exchange capacity due to its richness in volatile organic matter content.

Increasing the pyrolysis temperature from 250 °C to 400 °C and above for the same biomass material has been implicated with being negatively correlated with biochars' microporous surface area and the percentage of volatile organic matter. Therefore, the alteration in biochar surface functional groups and structure is the key determinants of their carbon sequestration potential (Mukherjee et al. 2011; Reeves et al. 2007).

3 Conclusion

Biochar is indeed an effective soil additive for increasing carbon sequestration and reducing agricultural-associated greenhouse gas emissions. This high-carbon substance also contributes to increased microbial diversity, soil health, soil pH modulation, and crop yields. Moreover, further studies are required in the area of biochar's impact on microbial enzymes as well as the physiological properties of the soil microbes especially through the use of nano-biochar. Additionally, the influence of mineral ions-supplemented biochar on carbon sequestration and microbial processes requires further investigation. The effect of biochar on autotrophic or photosynthetic bacteria also requires extensive study to promote soil carbon dioxide sink. It is, therefore, imperative to explore ways to improve the economic potential of biochar production and utilization and to promote its carbon sequestration potential through biochar modifications in soil nutrients enhancement, crop yield, and regulating soil carbon emissions.

Nevertheless, the application of biochar to the soil stimulates an increase in carbon sequestration through the promotion of soil organic carbon content, reduction in carbon mineralization rates, and promotion of microbial richness and diversity. It also protects soil organic carbon by decreasing microbial diversity and microbial biomass carbon and reducing catabolic enzyme activities involved in carbon degradation. Finally, to mitigate climate change through controlling greenhouse gas emissions, applying biochar with high aromaticity and carbon content on a long-term basis is recommended.

Author contributions

All authors researched data for the article and contributed substantially to the discussion of the content as well as wrote the article. R.G and R.R. reviewed and edited the manuscript before submission.

Funding

This project was funded by the Evans-Allen project of the United States Department of Agriculture (USDA) and the National Institute of Food and Agriculture (NIFA).

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

Received: 24 February 2025 Revised: 10 July 2025 Accepted: 21 July 2025
Published online: 09 September 2025

References

Abedini D, Jaupitre S, Bouwmeester H, Dong L (2021) Metabolic interactions in beneficial microbe recruitment by plants. Curr Opin Biotechnol 70:241–247

Agegnehu G, Bass AM, Nelson PN, Muirhead B, Wright G, Bird MI (2015) Biochar and biochar-compost as soil amendments: effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. Agric Ecosyst Environ 213:72–85

Al-Wabel MI, Al-Omran A, El-Naggar AH, Nadeem M, Usman AR (2013) Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresour Technol 131:374–379

Ambaye TG, Vaccari M, van Hullebusch ED, Amrane A, Rtimi S (2021) Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. Int J Environ Sci Technol 18(10):3273–3294

Ameloot N, Sleutel S, Case SD, Alberti G, McNamara NP, Zavalloni C, Vervisch B, delleVedove G, DeNeve S (2014) C mineralization and microbial activity in four biochar field experiments several years after incorporation. Soil Biol Biochem 78:195–203

Antonangelo JA, Zhang H, Sun X, Kumar A (2019) Physicochemical properties and morphology of biochars as affected by feedstock sources and pyrolysis temperatures. Biochar 1:325–336

Aurangzeib M, Zhang S, Yan S, Zhou J, Niu X, Yan P, Wang J (2024) Biochar application can improve most of the chemical properties of acidic soils: a global meta-analysis. ACS Agric Sci Technol 4(3):292–306

Bai J, Huang Y, Bai Y, Chen D, Haider S, Song J, Moreira BRDA, Ren G, Yang G, Feng Y (2024) Impact of straw-biochar amendments on microbial activity and soil carbon dynamics in wheat-maize system. Soil Tillage Res 244:106284

Banerjee S, Walder F, Büchi L, Meyer M, Held AY, Gattinger A, Keller T, Charles R, van der Heijden MG (2019) Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots. ISME J 13(7):1722–1736

Bateman E, Baggs E (2005) Contributions of nitrification and denitrification to N 2 O emissions from soils at different water-filled pore space. Biol Fertil Soils 41:379–388

Beesley L, Moreno-Jiménez E, Gomez-Eyles JL (2010) Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ Pollut 158(6):2282–2287

Bi Y, Cai S, Wang Y, Xia Y, Zhao X, Wang S, Xing G (2019) Assessing the viability of soil successive straw biochar amendment based on a five-year column trial with six different soils: views from crop production, carbon sequestration and net ecosystem economic benefits. J Environ Manage 245:173–186

Bi Y, Cai S, Wang Y, Zhao X, Wang S, Xing G, Zhu Z (2020) Structural and microbial evidence for different soil carbon sequestration after four-year successive biochar application in two different paddy soils. Chemosphere 254:126881

Blagodatskaya E, Kuzyakov Y (2008) Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: critical review. Biol Fertil Soils 45:115–131

Bossio D, Cook-Patton S, Ellis P, Fargione J, Sanderman J, Smith P, Wood S, Zomer R, Von Unger M, Emmer I (2020) The role of soil carbon in natural climate solutions. Nat Sustain 3(5):391–398

Brown RW, Reed EY, Chadwick DR, Hill PW, Jones DL (2024) Agronomic amendments drive a diversity of real and apparent priming responses within a grassland soil. Soil Biol Biochem 189:109265

Buss W, Mašek O, Graham M, Wüst D (2015) Inherent organic compounds in biochar–their content, composition and potential toxic effects. J Environ Manage 156:150–157
Button ES, Pett-Ridge J, Murphy DV, Kuzyakov Y, Chadwick DR, Jones DL (2022) Deep-C storage: biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils. Soil Biol Biochem 170:108697
Cai F, Feng Z, Zhu L (2018) Effects of biochar on CH 4 emission with straw application on paddy soil. J Soils Sediments 18:599–609
Carvalho M, Madari B, Bastiaans L, Van Oort P, Leal W, Heinemann A, Da Silva M, Maia A, Parsons D, Meinke H (2016) Properties of a clay soil from 1.5 to 3.5 years after biochar application and the impact on rice yield. Geoderma 276:7–18
Case SD, McNamara NP, Reay DS, Whitaker J (2012) The effect of biochar addition on N2O and CO2 emissions from a sandy loam soil–the role of soil aeration. Soil Biol Biochem 51:125–134
Cayuela ML, Van Zwieten L, Singh B, Jeffery S, Roig A, Sánchez-Monedero M (2014) Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric Ecosyst Environ 191:5–16
Chen J, Sun X, Zheng J, Zhang X, Liu X, Bian R, Li L, Cheng K, Zheng J, Pan G (2018) Biochar amendment changes temperature sensitivity of soil respiration and composition of microbial communities 3 years after incorporation in an organic carbon-poor dry cropland soil. Biol Fertil Soils 54:175–188
Cheng Z, Guo J, Jin W, Liu Z, Wang Q, Zha L, Zhou Z, Meng Y (2024) Responses of SOC, labile SOC fractions, and amino sugars to different organic amendments in a coastal saline-alkali soil. Soil Tillage Res 239:106051
Chin-Pampillo JS, Alfaro-Vargas A, Rojas R, Giacomelli CE, Perez-Villanueva M, Chinchilla-Soto C, Alcañiz JM, Domene X (2021) Widespread tropical agrowastes as novel feedstocks for biochar production: characterization and priority environmental uses. Biomass Convers Biorefin 11:1775–1785
Ciais P, Gasser T, Paris J, Caldeira K, Raupach M, Canadell J, Patwardhan A, Friedlingstein P, Piao S, Gitz V (2013) Attributing the increase in atmospheric CO2 to emitters and absorbers. Nat Clim Change 3(10):926–930
Cornelissen G, Rutherford DW, Arp HPH, Dörsch P, Kelly CN, Rostad CE (2013) Sorption of pure N2O to biochars and other organic and inorganic materials under anhydrous conditions. Environ Sci Technol 47(14):7704–7712
Cotrufo MF, Wallenstein MD, Boot CM, Denef K, Paul E (2013) The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob Change Biol 19(4):988–995
Dai Z, Zhang X, Tang C, Muhammad N, Wu J, Brookes PC, Xu J (2017) Potential role of biochars in decreasing soil acidification-a critical review. Sci Total Environ 581:601–611
Das SK, Ghosh GK, Avasthe R, Sinha K (2021) Morpho-mineralogical exploration of crop, weed and tree derived biochar. J Hazard Mater 407:124370
Deng B, Yuan X, Siemann E, Wang S, Fang H, Wang B, Gao Y, Shad N, Liu X, Zhang W (2021) Feedstock particle size and pyrolysis temperature regulate effects of biochar on soil nitrous oxide and carbon dioxide emissions. Waste Manag 120:33–40
Dewi RK, Gong Y, Huang Q, Li P, Hashimi R, Komatsuzaki M (2024) Addition of biochar decreased soil respiration in a permanent no-till cover crop system for organic soybean production. Soil Tillage Res 237:105977
Dong Y, Zhang X, Wang X, Xie C, Liu J, Cheng Y, Yue Y, You X, Li Y (2024) Modified biochar affects CO2 and N2O emissions from coastal saline soil by altering soil pH and elemental stoichiometry. Sci Total Environ 954:176283
Duniway MC, Bestelmeyer BT, Tugel A (2010) Soil processes and properties that distinguish ecological sites and states. Rangelands 32(6):9–15
Enebe MC, Ray RL, Griffin RW (2025) Carbon sequestration and soil responses to soil amendments–a review. J Hazard Mater Adv. https://doi.org/10.1016/j.hazadv.2025.100714
Fan X, Gao D, Zhao C, Wang C, Qu Y, Zhang J, Bai E (2021) Improved model simulation of soil carbon cycling by representing the microbially derived organic carbon pool. ISME J 15(8):2248–2263
Fang C, Moncrieff J (2001) The dependence of soil CO2 efflux on temperature. Soil Biol Biochem 33(2):155–165
Fang Y, Singh B, Singh BP (2015) Effect of temperature on biochar priming effects and its stability in soils. Soil Biol Biochem 80:136–145
Fernández JM, López-de-Sá EG, Polo A, Plaza C (2014) Short-term stabilization of organic matter in physically, chemically, and biochemically protected pools in soils amended with municipal wastes. CLEAN-Soil Air Water 42(4):487–493
Genesio L, Miglietta F, Lugato E, Baronti S, Pieri M, Vaccari F (2012) Surface albedo following biochar application in durum wheat. Environ Res Lett 7(1):014025
Geng N, Kang X, Yan X, Yin N, Wang H, Pan H, Yang Q, Lou Y, Zhuge Y (2022) Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. Ecotoxicol Environ Saf 232:113241
Gillam K, Zebarth B, Burton D (2008) Nitrous oxide emissions from denitrification and the partitioning of gaseous losses as affected by nitrate and carbon addition and soil aeration. Can J Soil Sci 88(2):133–143
Gong Y, Hou R, Fu Q, Li T, Wang J, Su Z, Shen W, Zhou W, Wang Y, Li M (2024) Modified biochar reduces the greenhouse gas emission intensity and enhances the net ecosystem economic budget in black soil soybean fields. Soil Tillage Res 237:105978
Grutzmacher P, Puga AP, Bibar MPS, Coscione AR, Packer AP, de Andrade CA (2018) Carbon stability and mitigation of fertilizer induced N2O emissions in soil amended with biochar. Sci Total Environ 625:1459–1466
Guo K, Zhao Y, Liu Y, Chen J, Wu Q, Ruan Y, Li S, Shi J, Zhao L, Sun X (2020) Pyrolysis temperature of biochar affects ecoenzymatic stoichiometry and microbial nutrient-use efficiency in a bamboo forest soil. Geoderma 363:114162
Guo F, Wang C, Wang S, Zhao X, Li G, Sun Z (2024) The native SOC increase in woodland and lawn soil amended with biochar surpassed greenhouse—a seven-year field trial. Sci Total Environ 907:167924
Gurau S, Imran M, Ray RL (2025) Algae: a cutting-edge solution for enhancing soil health and accelerating carbon sequestration – a review. Environ Technol Innov 37:103980
Han X, Sun X, Wang C, Wu M, Dong D, Zhong T, Thies JE, Wu W (2016) Mitigating methane emission from paddy soil with rice-straw biochar amendment under projected climate change. Sci Rep 6(1):24731
Hofstra N, Bouwman A (2005) Denitrification in agricultural soils: summarizing published data and estimating global annual rates. Nutr Cycl Agroecosyst 72:267–278
Horel Á, Tóth E, Gelybó G, Dencső M, Farkas C (2019) Biochar amendment affects soil water and CO2 regime during *capsicum annuum* plant growth. Agronomy 9(2):58
Huang S, Zhu X, Fang J, Zhang X, Zhang H, Zhang Z, Wu X, Zhu X (2023) Pyrolysis temperature dependent effects of biochar on shifting fluorescence spectrum characteristics of soil dissolved organic matter under warming. Sci Total Environ 892:164656
Hütsch B (1998) Methane oxidation in arable soil as inhibited by ammonium, nitrite, and organic manure with respect to soil pH. Biol Fertil Soils 28:27–35
Ippolito JA, Cui L, Kammann C, Wrage-Mönnig N, Estavillo JM, Fuertes-Mendizabal T, Cayuela ML, Sigua G, Novak J, Spokas K (2020) Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2:421–438
Jafri N, Wong W, Doshi V, Yoon L, Cheah KH (2018) A review on production and characterization of biochars for application in direct carbon fuel cells. Process Saf Environ Prot 118:152–166
Ji C, Tao E, Cheng Y, Yang S, Chen L, Wang D, Wang Y, Li Y (2024) Preparation of Mn modified waste dander biochar and its effect on soil carbon sequestration. Environ Res 247:118147
Jiang Y, Liu J, Li Y, Xiao P, Liu S, Shao J, Cai Y, Yan X, Fan L (2023) Biochar amendment reduces biological nitrogen fixation and nitrogen use efficiency in cadmium-contaminated paddy fields. J Environ Manage 344:118338
Jiang Y, Liu J, Wei X, Wang R, Li Y, Liu Y, Xiao P, Cai Y, Shao J, Zhang Z (2024) Biochar leachate reduces primary nitrogen assimilation by inhibiting nitrogen fixation and microbial nitrate assimilation. Sci Total Environ 918:170608
Jones D, Edwards A (1998) Influence of sorption on the biological utilization of two simple carbon substrates. Soil Biol Biochem 30(14):1895–1902
Kavdır Y, Ekinci H, Yüksel O, Mermut A (2005) Soil aggregate stability and 13C CP/MAS-NMR assessment of organic matter in soils influenced by forest wildfires in Canakkale, Turkey. Geoderma 129(3–4):219–229

Khadem A, Raiesi F, Besharati H, Khalaj MA (2021) The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar 3(1):105–116
Khan TF, Ahmed MM, Huq SMI (2014) Effects of biochar on the abundance of three agriculturally important soil bacteria. J Agric Chem Environ 3(02):31
Klüpfel L, Keiluweit M, Kleber M, Sander M (2014) Redox properties of plant biomass-derived black carbon (biochar). Environ Sci Technol 48(10):5601–5611
Kumar NV, Sawargaonkar G, Rani CS, Pasumarthi R, Kale S, Prakash TR, Triveni S, Singh A, Davala MS, Khopade R (2024) Harnessing the potential of pigeonpea and maize feedstock biochar for carbon sequestration, energy generation, and environmental sustainability. Bioresour Bioprocess 11(1):5
Lefebvre D, Williams A, Kirk GJ, Meersmans J, Sohi S, Goglio P, Smith P (2021) An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology. J Clean Prod 312:127764
Lehmann J, Joseph S (2024) Biochar for environmental management: science, technology and implementation. Taylor & Francis
Li S, Tasnady D (2023) Biochar for soil carbon sequestration: current knowledge, mechanisms, and future perspectives. C 9(3):67
Li C, Liu C, Feng C, Lan T (2023) Exploring the impacts of service life of biological activated carbon on dissolved organic nitrogen removal. Environ Pollut 323:121214
Liang J, Li Z, Dai S, Tian G, Wang Z (2023) Production of hemicelluloses sugars, cellulose pulp, and lignosulfonate surfactant using corn stalk by prehydrolysis and alkaline sulfite cooking. Ind Crop Prod 192:115880
Liao F, Yang L, Li Q, Li Y-R, Yang L-T, Anas M, Huang D-L (2018) Characteristics and inorganic N holding ability of biochar derived from the pyrolysis of agricultural and forestal residues in the southern China. J Anal Appl Pyrolysis 134:544–551
Liao X, Mao S, Shan Y, Gao W, Wang S, Malghani S (2024) Impact of iron-modified biochars on soil nitrous oxide emissions: variations with iron salts and soil fertility. J Environ Manage 356:120571
Lipczynska-Kochany E (2018) Humic substances, their microbial interactions and effects on biological transformations of organic pollutants in water and soil: a review. Chemosphere 202:420–437
Liu S, Zhang Y, Zong Y, Hu Z, Wu S, Zhou J, Jin Y, Zou J (2016) Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy 8(2):392–406
Liu Z, Zhu M, Wang J, Liu X, Guo W, Zheng J, Bian R, Wang G, Zhang X, Cheng K (2019) The responses of soil organic carbon mineralization and microbial communities to fresh and aged biochar soil amendments. GCB Bioenergy 11(12):1408–1420
Lu G-Y, Ikeya K, Watanabe A (2016) Size distribution of carbon layer planes in biochar from different plant type of feedstock with different heating temperatures. Chemosphere 163:252–258
Lu J, Zhang W, Liu X, Khan A, Wang W, Ge J, Yan S, Xiong Y-C (2024) Can converting raw straw into biochar incorporation achieve both higher maize yield and lower greenhouse gas emissions intensity in drought-prone environment? Environ Technol Innov. https://doi.org/10.1016/j.eti.2024.103683
Luo Y, Durenkamp M, De Nobili M, Lin Q, Brookes P (2011) Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biol Biochem 43(11):2304–2314
Luo Y, Durenkamp M, De Nobili M, Lin Q, Devonshire B, Brookes P (2013) Microbial biomass growth, following incorporation of biochars produced at 350 C or 700 C, in a silty-clay loam soil of high and low pH. Soil Biol Biochem 57:513–523
Madari BE, Silva MA, Carvalho MT, Maia AH, Petter FA, Santos JL, Tsai SM, Leal WG, Zeviani WM (2017) Properties of a sandy clay loam Haplic Ferralsol and soybean grain yield in a five-year field trial as affected by biochar amendment. Geoderma 305:100–112
Mamedov A, Levy G (2013) High energy moisture characteristics: linking between some soil physical processes and structure stability. Quantify Model Soil Struct Dynamics 3:41–74
Massaccesi L, Nogués I, Miritana VM, Passatore L, Zacchini M, Pietrini F, Carloni S, Marabottini R, Moscatelli M, Marinari S (2024) Short-term effects of biochar and compost on soil microbial community, C and N cycling, and lettuce (*Lactuca sativa* L.) yield in a Mediterranean environment. Appl Soil Ecol 199:105411
Mechler M, Jiang R, Silverthorn T, Oelbermann M (2018) Impact of biochar on soil characteristics and temporal greenhouse gas emissions: a field study from southern Canada. Biomass Bioenerg 118:154–162
Mohan D, Preetiva B, Chaubey AK, Singsit JS, Mina U, Pittman CU Jr (2024) Eggplant growth in wheat straw-, wheat straw biochar-and compost-amended soils: a field study of CO2 emission dynamics, soil physicochemical, microbial, and nutrient effects. Waste Manag Bull 1(4):143–157
Mooshammer M, Wanek W, Hämmerle I, Fuchslueger L, Hofhansl F, Knoltsch A, Schnecker J, Takriti M, Watzka M, Wild B (2014) Adjustment of microbial nitrogen use efficiency to carbon: nitrogen imbalances regulates soil nitrogen cycling. Nat Commun 5(1):3694
Mori T, Tsuboi Y, Ishida N, Nishikubo N, Demura T, Kikuchi J (2015) Multidimensional high-resolution magic angle spinning and solution-state NMR characterization of 13C-labeled plant metabolites and lignocellulose. Sci Rep 5(1):11848
Mukherjee A, Lal R (2013) Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 3(2):313–339
Mukherjee A, Zimmerman AR, Harris W (2011) Surface chemistry variations among a series of laboratory-produced biochars. Geoderma 163(3–4):247–255
Murray J, Keith A, Singh B (2015) The stability of low-and high-ash biochars in acidic soils of contrasting mineralogy. Soil Biol Biochem 89:217–225
Murtaza G, Ahmed Z, Usman M (2022) Feedstock type, pyrolysis temperature and acid modification effects on physiochemical attributes of biochar and soil quality. Arab J Geosci 15(3):305
Nan H, Yin J, Yang F, Luo Y, Zhao L, Cao X (2021a) Pyrolysis temperature-dependent carbon retention and stability of biochar with participation of calcium: implications to carbon sequestration. Environ Pollut 287:117566
Nan Q, Xin L, Qin Y, Waqas M, Wu W (2021b) Exploring long-term effects of biochar on mitigating methane emissions from paddy soil: a review. Biochar 3(2):125–134
Ngo P-T, Rumpel C, Ngo Q-A, Alexis M, Vargas GV, MdlLM G, Dang D-K, Jouquet P (2013) Biological and chemical reactivity and phosphorus forms of buffalo manure compost, vermicompost and their mixture with biochar. Biores Technol 148:401–407
Ngo PT, Rumpel C, Janeau J-L, Dang D-K, Doan TT, Jouquet P (2016) Mixing of biochar with organic amendments reduces carbon removal after field exposure under tropical conditions. Ecol Eng 91:378–380
Niu Y, Ma X, Liang J (2024) Characterization of organic materials in regulating soil carbon sequestration of urban greenspaces: links to microbial necromass and community composition. J Environ Manage 370:122894
Nwabunwanne N, Vuyokazi T, Olagoke A, Mike O, Patrick M, Anthony O (2021) Improving the solid fuel properties of non-lignocellulose and lignocellulose materials through torrefaction. Materials 14(8):2072
Nwokolo NL, Enebe MC (2024) Methane production and oxidation—A review on the pmoA and mcrA genes abundance for understanding the functional potentials of the agricultural soil. Pedosphere 35(1):161–181
Nwokolo N, Mamphweli S, Makaka G (2016) An investigation into heat recovery from the surface of a cyclone dust collector attached to a downdraft biomass gasifier. Appl Therm Eng 98:1158–1164
Nwokolo N, Mukumba P, Obileke K (2020) Thermal performance evaluation of a double pipe heat exchanger installed in a biomass gasification system. J Eng 1:6762489
Pariyar P, Kumari K, Jain MK, Jadhao PS (2020) Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. Sci Total Environ 713:136433
Pausch J, Kuzyakov Y (2018) Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. Glob Change Biol 24(1):1–12
Plaza C, Giannetta B, Fernández JM, López-de-Sá EG, Polo A, Gascó G, Méndez A, Zaccone C (2016) Response of different soil organic matter pools to biochar and organic fertilizers. Agric Ecosyst Environ 225:150–159
Prescott CE (2022) Sinks for plant surplus carbon explain several ecological phenomena. Plant Soil 476(1):689–698

Qi L, Ma Z, Chang SX, Zhou P, Huang R, Wang Y, Wang Z, Gao M (2021) Biochar decreases methanogenic archaea abundance and methane emissions in a flooded paddy soil. Sci Total Environ 752:141958
Qian L, Chen B (2013) Dual role of biochars as adsorbents for aluminum: the effects of oxygen-containing organic components and the scattering of silicate particles. Environ Sci Technol 47(15):8759–8768
Qin X, Wang H, Liu C, Li J, Wan Y, Gao Q, Fan F, Liao Y (2016) Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: a four-year case study in south China. Sci Total Environ 569:1390–1401
Ray RL, Griffin RW, Fares A, Elhassan A, Awal R, Woldesenbet S, Risch E (2020) Soil CO_2 emissions from an experimental research farm: effects of organic amendments, temperature, and rainfall. Sci Rep 10:5849
Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361:114055
Reeves JB, McCarty GW, Rutherford DW, Wershaw RL (2007) Near infrared spectroscopic examination of charred pine wood, bark, cellulose and lignin: implications for the quantitative determination of charcoal in soils. J near Infrared Spectrosc 15(5):307–315
Rodrigues L, Budai A, Elsgaard L, Hardy B, Keel SG, Mondini C, Plaza C, Leifeld J (2023) The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice. Eur J Soil Sci 74(4):e13396
Rosinger C, Keiblinger K, Bieber M, Bernardini LG, Huber S, Mentler A, Sae-Tun O, Scharf B, Bodner G (2023) On-farm soil organic carbon sequestration potentials are dominated by site effects, not by management practices. Geoderma 433:116466
Saarnio S, Heimonen K, Kettunen R (2013) Biochar addition indirectly affects N2O emissions via soil moisture and plant N uptake. Soil Biol Biochem 58:99–106
Sadasivam BY, Reddy KR (2015) Adsorption and transport of methane in landfill cover soil amended with waste-wood biochars. J Environ Manage 158:11–23
Sae-Tun O, Bodner G, Rosinger C, Zechmeister-Boltenstern S, Mentler A, Keiblinger K (2022) Fungal biomass and microbial necromass facilitate soil carbon sequestration and aggregate stability under different soil tillage intensities. Appl Soil Ecol 179:104599
Saffari N, Hajabbasi M, Shirani H, Mosaddeghi M, Mamedov A (2020) Biochar type and pyrolysis temperature effects on soil quality indicators and structural stability. J Environ Manage 261:110190
Sahoo SS, Vijay VK, Chandra R, Kumar H (2021) Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo. Clean Eng Technol 3:100101
Sapkota S, Ghimire R, Bista P, Hartmann D, Rahman T, Adhikari S (2024) Greenhouse gas mitigation and soil carbon stabilization potential of forest biochar varied with biochar type and characteristics. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2024.172942
Sathish T, Muthukumar K, Saravanan R, Giri J (2024) Optimized thermal pretreatment for lignocellulosic biomass of pigeon pea stalks to augment quality and quantity of biogas production. Int J Thermofluids 24:100911
Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DA (2011) Persistence of soil organic matter as an ecosystem property. Nature 478(7367):49–56
Selvarajh G, Ch'ng HY, Zain NM, Wei LS, Liew JY, Azmin SNHM, Naher L, Abdullah PS, Ahmed OH, Jalloh MB (2024) Enriched rice husk biochar superior to commercial biochar in ameliorating ammonia loss from urea fertilizer and improving plant uptake. Heliyon. https://doi.org/10.1016/j.heliyon.2024.e32080
Policy SfE (2021) The Solution is in Nature. Future Brief 24. Brief Produced for the European Commission DG Environment. Science Communication Unit, UWE Bristol Bristol, UK
Sheng Y, Zhu L (2018) Biochar alters microbial community and carbon sequestration potential across different soil pH. Sci Total Environ 622:1391–1399
Sheng Y, Zhan Y, Zhu L (2016) Reduced carbon sequestration potential of biochar in acidic soil. Sci Total Environ 572:129–137
Si L, Xie Y, Ma Q, Wu L (2018) The short-term effects of rice straw biochar, nitrogen and phosphorus fertilizer on rice yield and soil properties in a cold waterlogged paddy field. Sustainability 10(2):537
Singh BP, Cowie AL (2014) Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. Sci Rep 4(1):3687
Six J, Feller C, Denef K, Ogle S, de Moraes Sa JC, Albrecht A (2002) Soil organic matter, biota and aggregation in temperate and tropical soils-Effects of no-tillage. Agronomie 22(7–8):755–775
Smebye A, Alling V, Vogt RD, Gadmar TC, Mulder J, Cornelissen G, Hale SE (2016) Biochar amendment to soil changes dissolved organic matter content and composition. Chemosphere 142:100–105
Smercina DN, Bailey VL, Hofmockel KS (2021) Micro on a macroscale: relating microbial-scale soil processes to global ecosystem function. FEMS Microbiol Ecol 97(7):fiab091
Sowińska-Świerkosz B, García J (2022) What are nature-based solutions (NBS)? Setting core ideas for concept clarification. Nat Based Solutions 2:100009
Stringlis IA, Yu K, Feussner K, de Jonge R, Van Bentum S, Van Verk MC, Berendsen RL, Bakker PA, Feussner I, Pieterse CM (2018) MYB72-dependent coumarin exudation shapes root microbiome assembly to promote plant health. Proc Natl Acad Sci 115(22):E5213–E5222
Sun K, Wang Y, Zhang L, Shao Y, Li C, Zhang S, Hu X (2024) High yield of carbonaceous material from biomass via pyrolysis-condensation. Chem Eng J 485:149823
Taghizadeh-Toosi A, Clough TJ, Condron LM, Sherlock RR, Anderson CR, Craigie RA (2011) Biochar incorporation into pasture soil suppresses in situ nitrous oxide emissions from ruminant urine patches. J Environ Qual 40(2):468–476
Tang J, Li X, Luo Y, Li G, Khan S (2016) Spectroscopic characterization of dissolved organic matter derived from different biochars and their polycylic aromatic hydrocarbons (PAHs) binding affinity. Chemosphere 152:399–406
Tao E, Ji C, Cheng Y, Yang S, Chen L, Wang D, Wang Y, Li Y (2024) Effect of waste leather dander biochar on soil organic carbon sequestration. J Environ Chem Eng 12(3):112633
Tikuye BG, Ray RL, Gurau S (2025) Modeling carbon stock change and carbon dioxide emissions under different ecosystems in the Brazos River Basin, Texas, USA. Environ Chall 19:101138
Tomar RS, Rai-Kalal P, Jajoo A (2022) Impact of polycyclic aromatic hydrocarbons on photosynthetic and biochemical functions and its bioremediation by *Chlorella vulgaris*. Algal Res 67:102815
Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Biotechnol 19(1):191–215
Van Zwieten L, Kimber S, Morris S, Downie A, Berger E, Rust J, Scheer C (2010) Influence of biochars on flux of N2O and CO2 from Ferrosol. Soil Res 48(7):555–568
Van Zwieten L, Singh B, Kimber S, Murphy D, Macdonald L, Rust J, Morris S (2014) An incubation study investigating the mechanisms that impact N2O flux from soil following biochar application. Agr Ecosyst Environ 191:53–62
Wang S, Gao B, Zimmerman AR, Li Y, Ma L, Harris WG, Migliaccio KW (2015) Physicochemical and sorptive properties of biochars derived from woody and herbaceous biomass. Chemosphere 134:257–262
Wang J, Xiong Z, Kuzyakov Y (2016) Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8(3):512–523
Wang C, Liu J, Shen J, Chen D, Li Y, Jiang B, Wu J (2018) Effects of biochar amendment on net greenhouse gas emissions and soil fertility in a double rice cropping system: a 4-year field experiment. Agric Ecosyst Environ 262:83–96
Wang C, Shen J, Liu J, Qin H, Yuan Q, Fan F, Hu Y, Wang J, Wei W, Li Y (2019) Microbial mechanisms in the reduction of CH4 emission from double rice cropping system amended by biochar: a four-year study. Soil Biol Biochem 135:251–263
Wang S, Zhang H, Huang H, Xiao R, Li R, Zhang Z (2020) Influence of temperature and residence time on characteristics of biochars derived from agricultural residues: a comprehensive evaluation. Process Saf Environ Prot 139:218–229
Wang B, Liang C, Yao H, Yang E, An S (2021) The accumulation of microbial necromass carbon from litter to mineral soil and its contribution to soil organic carbon sequestration. CATENA 207:105622
Wang F, Zhang R, Donne SW, Beyad Y, Liu X, Duan X, Yang T, Su P, Sun H (2022) Co-pyrolysis of wood chips and bentonite/kaolin: influence of temperatures and minerals on characteristics and carbon sequestration potential of biochar. Sci Total Environ 838:156081

Wang X, Riaz M, Xia X, Babar S, El-Desouki Z, Li Y, Wang J, Jiang C (2024a) Alleviation of cotton growth suppression caused by salinity through biochar is strongly linked to the microbial metabolic potential in saline-alkali soil. Sci Total Environ 922:171407
Wang Y, Yin Y, Joseph S, Flury M, Wang X, Tahery S, Li B, Shang J (2024b) Stabilization of organic carbon in top-and subsoil by biochar application into calcareous farmland. Sci Total Environ 907:168046
Wei S, Zhu M, Fan X, Song J, Li K, Jia W, Song H (2019) Influence of pyrolysis temperature and feedstock on carbon fractions of biochar produced from pyrolysis of rice straw, pine wood, pig manure and sewage sludge. Chemosphere 218:624–631
Weng Z, Van Zwieten L, Tavakkoli E, Rose MT, Singh BP, Joseph S, Macdonald LM, Kimber S, Morris S, Rose TJ (2022) Microspectroscopic visualization of how biochar lifts the soil organic carbon ceiling. Nat Commun 13(1):5177
Wu D, Senbayram M, Zang H, Ugurlar F, Aydemir S, Brüggemann N, Kuzyakov Y, Bol R, Blagodatskaya E (2018) Effect of biochar origin and soil pH on greenhouse gas emissions from sandy and clay soils. Appl Soil Ecol 129:121–127
Xiao X, Chen B, Zhu L (2014) Transformation, morphology, and dissolution of silicon and carbon in rice straw-derived biochars under different pyrolytic temperatures. Environ Sci Technol 48(6):3411–3419
Xing J, Tang C, Xu R, Chen J, Peng L, Qin H (2024) Soil microbiome regulates community functions when using biochar-based fertilizers made from biodegradable wastes. Eur J Agron 161:127363
Xu P, Liu Y, Zhu J, Shi L, Fu Q, Chen J, Hu H, Huang Q (2020) Influence mechanisms of long-term fertilizations on the mineralization of organic matter in Ultisol. Soil Tillage Res 201:104594
Yadav SPS, Bhandari S, Bhatta D, Poudel A, Bhattarai S, Yadav P, Ghimire N, Paudel P, Paudel P, Shrestha J (2023) Biochar application: a sustainable approach to improve soil health. J Agric Food Res 11:100498
Yang W, Wang H, Zhang M, Zhu J, Zhou J, Wu S (2016) Fuel properties and combustion kinetics of hydrochar prepared by hydrothermal carbonization of bamboo. Bioresour Technol 205:199–204
Yang F, Zuo X, Yang H, Ke Q, Huang Y, Cao X, Zhao L (2022) Ionic liquid-assisted production of high-porosity biochar with more surface functional groups: taking cellulose as attacking target. Chem Eng J 433:133811
Yang F, Wang W, Wu Z, Peng J, Xu H, Ge M, Lin S, Zeng Y, Sardans J, Wang C (2024a) Fertilizer reduction and biochar amendment promote soil mineral-associated organic carbon, bacterial activity, and enzyme activity in a jasmine garden in southeast China. Sci Total Environ 954:176300
Yang S, Sun J, Wang C, Li S, Li Z, Luo W, Wei G, Chen W (2024b) Residue quality drives SOC sequestration by altering microbial taxonomic composition and ecophysiological function in desert ecosystem. Environ Res 250:118518
Yang W, Zhang R, Yang Y, Ji W, Zhang X, Zhang D, Wang L, Qu Z (2024c) Evaluation of net carbon sequestration and ecological benefits from single biochar-incorporated sorghum farmland systems in saline-alkali areas of Inner Mongolia, China. J Environ Manage 351:119979
Yi Q, Liang B, Nan Q, Wang H, Zhang W, Wu W (2020) Temporal physicochemical changes and transformation of biochar in a rice paddy: insights from a 9-year field experiment. Sci Total Environ 721:137670
Zhang Q, Wang Y, Wu Y, Wang X, Du Z, Liu X, Song J (2013) Effects of biochar amendment on soil thermal conductivity, reflectance, and temperature. Soil Sci Soc Am J 77(5):1478–1487
Zhang J, Hu A, Wang B, Ran W (2019) Al (III)-binding properties at the molecular level of soil DOM subjected to long-term manuring. J Soils Sediments 19:1099–1108
Zhang H, Liao W, Zhou X, Shao J, Chen Y, Zhang S, Chen H (2022) Coeffect of pyrolysis temperature and potassium phosphate impregnation on characteristics, stability, and adsorption mechanism of phosphorus-enriched biochar. Bioresour Technol 344:126273
Zhang S, Xue L, Liu J, Xia L, Jia P, Feng Y, Hao X, Zhao X (2024) Biochar application reduced carbon footprint of maize production in the saline− alkali soils. Agric Ecosyst Environ 368:109001
Zhao Q, Wang Y, Xu Z, Yu Z (2021) How does biochar amendment affect soil methane oxidation? A review. J Soils Sediments 21:1575–1586
Zimmerman AR, Gao B, Ahn M-Y (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol Biochem 43(6):1169–1179