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Advancement of Climate Mitigation through Biochar Applications in Agriculture

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Abstract

Humanity faces pressing challenges related to greenhouse gas emissions, climate change and declining soil quality. Biochar showed potential, with straw-based biochar application reducing total carbon emissions by about 47%. In this paper, we assess feed variability, pyrolysis conditions, and their effects on soil fertility, carbon storage, and greenhouse gas emissions by systematically analyzing more than 80,000 scientific studies and machine learning meta-analyses. Our approach highlights a cross-regional comparison of biochar aging effects and soil interactions, revealing new insights into its long-term carbon stabilization mechanisms. The results show that biochar can store organic carbon in the soil for hundreds of years, reduce carbon dioxide emissions by up to 50%, and increase crop productivity. Notably, biochar produced by high-temperature pyrolysis at 600 °C had high stability (up to 97% inert carbon) and enhanced soil cation exchange capacity. This study innovatively quantifies the synergistic effects of biochar and nitrogen co-application, providing a dual strategy for sustainable agricultural development and climate mitigation. This review is positioned as a scalable solution within the circular economy framework.

Keywords: Carbon storage; Pyrolysis; Greenhouse gas emissions; Sustainable agriculture; Biochar.
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1. Introduction

Global warming has become a prominent topic of discussion, largely due to the substantial emissions of greenhouse gas (GHG). Among these, nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) are particularly significant contributors. The increase in these GHG emissions is critically important in understanding and addressing the challenges posed by global warming.[1] Amidst the growing concern over global warming, the development of strategies to reduce atmospheric levels of carbon dioxide is crucial.[2] Soil carbon sequestration (SCS) is considered an important method for reducing climate change.[3] Soil has dual purposes of carbon storage (CS) and promoting agriculture, contributing to ecology and food security, which exacerbates its importance.[4]

Biochar (BC) is an aromatic, stable, solid with a high carbon density created through the thermal breakdown of biomass in an environment with limited oxygen.[5] It has high adsorption potential, large specific surface area (SSA), low cost,[6] it has the ability to retain organic carbon in the soil for hundreds to millennia.[7] It can also be used as an additive to improve soil quality.[8] BC is considered an effective method for decreasing GHG emissions and improve soil nutrient content and crop yields,[9] which can also mitigate global climate change.[10] After a comprehensive analysis of agricultural research in multiple countries around the world, it was found that BC materials exhibit dual environmental benefits.[11] They can significantly improve crop growth, increase agricultural output, improve soil nutrient structure, and achieve long-term fixation of GHGes via the carbon cycling mechanism of the soil system. This multifunctional feature makes it an important technological path for the

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coordinated promotion of modern agricultural sustainable development and carbon reduction strategies.[12]

Narayanan *et al.*[3] indicated that BC has demonstrated excellent efficacy in enhancing SCS and has become a highly promising and effective tool. Singh *et al.*[13] found that rice straw BC, an environmentally friendly waste treatment technology, can purify wastewater, reduce environmental risks, and be converted to soil conditioner, improving soil nutrient retention, long-term supply of silicon to crops. BC has shown significant performance in reducing GHG emissions, enhancing CS, and improving soil characteristics.

Soil acts as the largest storage of organic carbon in terrestrial ecosystems, the carbon stored in soil (including peatlands, wetlands, and permafrost) is much higher than that stored in the atmosphere and plays an important role in the carbon cycle.[14] Minor alterations in the soil carbon pool can greatly influence climate change.[15] BC prepared from biomass in soil is an effective way to deal with global climate change,[2] because it can promote plant growth, strong resistance to degradation, and inherent chemical stability.[16] Owing to the high chemical resistance and carbon content of BC, its application in soil is considered a promising CS strategy.[17,18]

From an agricultural and environmental standpoint, the sustainable management of low-fertility and arid soils can be achieved by using carbon-rich organic materials, like compost and BC, is a pressing concern that warrants careful attention.[19] Considering the stability of BC, it is expected that the incorporation of BC will improve the soil's overall carbon level. In addition, BC may increase natural soil organic carbon (SOC) as it improves nutrient and the ability to retain water.[20] The effectiveness of CS in BC is significantly influenced by its persistent presence in the soil and its capacity to enhance the decomposition of primary organic matter. Research has shown that factors such as the preparation process, weathering process, and soil clay composition of BC can regulate the decomposition dynamics of primary organic carbon, thereby affecting its CS efficiency. Specifically, the production method of BC materials will change their physical and chemical (PAC) properties, and their ageing process in soil may enhance carbon stability. The composition of clay minerals is influenced by adsorption processes, which contribute breakdown of organic material within the original soil.[17] Jia *et al.*[21] in their study, found the use of BC as a synergistic approach to nitrogen enhancement in soil, can significantly increase SCS through mechanisms involving carbon-nitrogen interactions. This research offers innovative technological strategies for the establishment of low-carbon and sustainable agricultural ecosystems.

The preparation of BC includes methods such as hydrothermal carbonization, microwave-assisted pyrolysis, gasification, pyrolysis, and liquefaction. Pyrolysis is a well-established and relatively traditional method for the heat processing of biomass. It stands as the most frequently employed process for the production of biomass and its conversion into BC.[22] The pyrolysis process can be separated into flash, fast , medium and slow pyrolysis.[23] The pyrolysis conditions and types of raw materials bring significant changes to the nutritional composition, pH value, and structure of BC products.[8,24,25] Li *et al.*'s[26] life cycle assessment showed that BC produced from pyrolysis, gasification and hydrothermal carbonization of agricultural land can serve as a carbon sink for farmland and can replace fossil fuels as an energy source. Yang *et al.*[27] demonstrated that the pyrolysis temperature (PT)for BC produced from rice straw and rapeseed stems has an impact on the form of inorganic phosphorus in soil treated with BC. Studies have shown that there is a strong correlation between the phosphorus content in BC-rich soils and the phosphorus content of BC and improved soils. Microwave-assisted pyrolysis has the ability to increase the carbonization rate of BC under the condition of reducing the PT. This process can greatly affect the PAC characteristics of the BC generated.[28] Gasification is an environmentally sustainable technology, and BC prepared by the 900 °C gasification method promotes the DIET process through a high aromatic condensed carbon structure, and enhances enzymatic catalytic activity.[29] There is a significant correlation mechanism between the preparation process of BC and its physicochemical properties and environmental functions. As a mainstream preparation technology, the temperature parameters of pyrolysis directly affect the carbon stability and surface characteristics of BC: high-temperature pyrolysis at 600 °C can make the inert carbon content of BC reach 97% , and the SSA increases by 3-5 times, and the specific surface area of BC increases by 3-5 times, the porosity increased to 0.8-1.2 cm^3/g, significantly enhancing SCS capacity.[2,8] The type of raw material determines the elemental composition. The carbon content of woody BC (65-80%) is significantly higher than that of manure (40-50%), and feedstocks with cellulose content > 50% subjected to medium-

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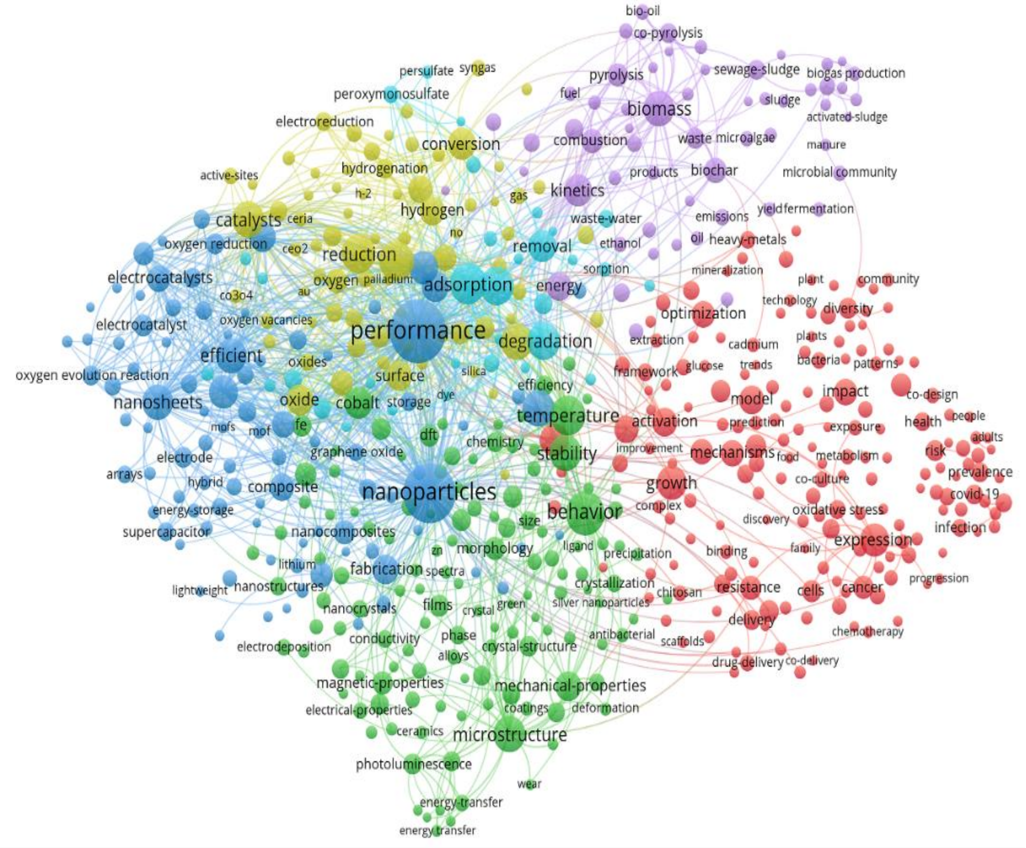

Fig. 1: Visualisation of literature network.

rate pyrolysis(10 °C/min) can form well-developed pore structures with pore sizes of 2-50 nm.[22] The spherical nanostructures (diameter 50-200 nm) formed by hydrothermal carbonization (200-250 °C) have a density of oxygen-containing functional groups that is 2-3 times higher than that of pyro carbon, significantly increasing the heavy metal(HM) adsorption capacity.[5] The preparation process extended the carbon half-life of BC in soil from 10-100 to 500-1000 years of conventional organic matter by regulating the structure-activity relationship of carbon matrix,de[17] providing a theoretical basis for the optimization of carbon sequestration technology.

This study is based on the Web of Science Core Collection Database, the combined search strategy of subject keyword (TS = (biochar) and title keyword (Ti = (soil * OR carbon * OR CO *)) was used to search all literatures (including online pre-published results) up to January 7,2025. The search formula was optimized by morphological truncation, synonym expansion and subject thesaurus assistance, and 80,409 articles were obtained. In order to improve the precision, multi-level exclusion criteria are set: excluding non-research literature such as conference abstracts and book reviews, limiting English language, and excluding irrelevant items based on manual abstract screening and VOS viewer keyword co-occurrence network analysis. After Doi deduplication, synonymous keyword merging and frequency threshold screening (≥155 times), 568 high-frequency keywords were finally extracted to construct a knowledge map, and the performance mechanism and application challenges of BC in soil carbon cycle were analyzed in combination with 27395 total link strength (Fig. 1). This method ensures the coverage of the literature, and ensures the subject focus and analysis depth of the research conclusion through structured data cleaning and multimodal verification.

2. Application of biochar in soil carbon storage

Soil, as the primary CS carrier in terrestrial ecosystems, is composed of two significantly different components: soil inorganic carbon and SOC.[30] BC is a porous carbon matrix that is converted from various types of biomass and can effectively sequester carbon over a long period (See Fig. 2ab).[31] BC inhibits soil GHG emissions through anti-degradation and adsorption characteristics, providing a new path for climate governance and sustainable agriculture.[32] It can also regulate soil acidity and alkalinity, optimize fertilizer retention, enhance farmland productivity, etc.[33]

The use of BC in soil has proven to be an effective method of carbon management, which reconstructs the carbon cycle of

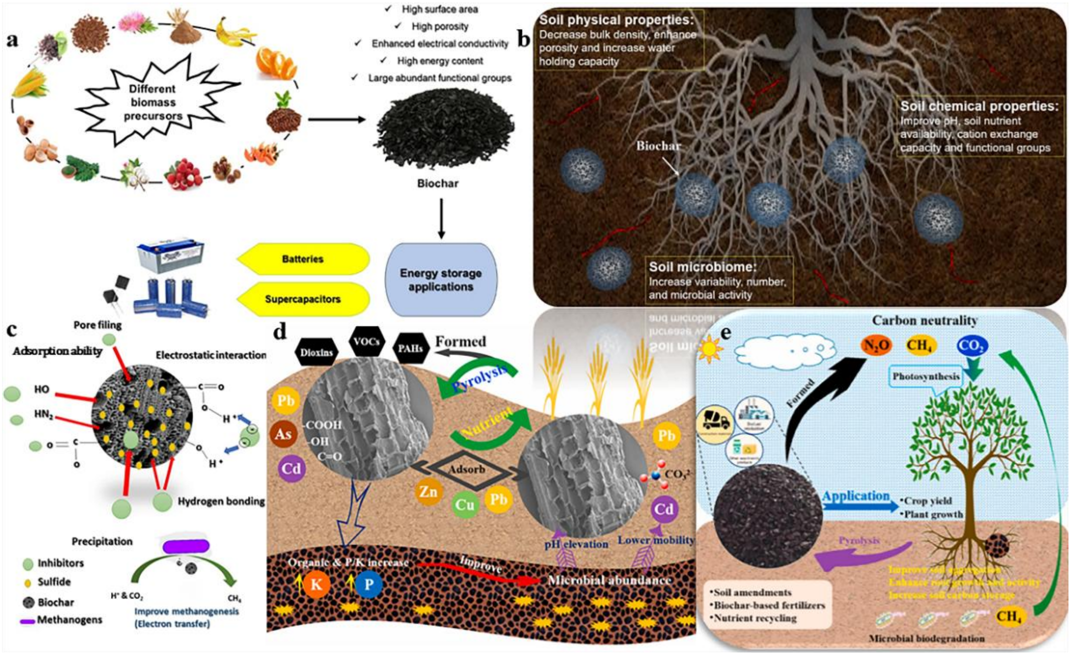

Fig. 2: (a) Preparation of BC from biomass and its energy storage application. Reproduced from.[31] (b) Adjusting soil chemical properties, improving physical structure, and optimizing microbial communities. Reproduced from.[31] (c) The surface porosity is achieved through mechanisms such as adsorption, precipitation, bonding, and pore retention. Reproduced from.[31] (d) Effectively remove H. Reproduced from.[48] (e) Application in the field of environment. Reproduced from.[48]

agricultural ecosystems by enhancing soil carbon pool stability and optimizing carbon turnover processes.[34] The sustainable management of soil nutrients faces significant challenges, and BC application of a substance to the soil may alter its properties.[35] The common application methods of BC in the agricultural field mainly include surface mixing, layered deep application, and crop topdressing supplementation, among other conventional technologies.[36] In terms of material modification, the current technological system covers diversified processes such as acid-base chemical modification, gas activation treatment, outdoor aging and curing, and ball milling. These treatment approaches aim to optimize the physical chemistry properties of BC are used for a variety of applications.[37,38] Sun *et al.*[16] discovered that incorporating BC enhanced levels of SOC and microbial biomass. Applying BC rich in phytoliths in agricultural systems can increase soil acidity, nutrient availability, and cation exchange capacity. Lu *et al.*[39] demonstrated that the effectiveness of crop residue BC in increasing soil pH and buffering capacity and reducing CD availability in soil depends on the type of raw materials used to produce BC.

Biocarbon can improve soil fertility and serve as a source of nutrients. This is because BC not only initially contains soluble nutrients, but also the unstable parts of its internal organic bound nutrients undergo mineralization. Furthermore, the potential of BC as a source of nutrients is strongly influenced by the temperature conditions during its production of raw materials and pyrolysis.[40] Studies have indicated that the incorporation of BC in acidic soils at different pH levels can stimulate nitrogen mineralization, but the effects on nitrification and uptake of nitrogen are different.[41] The use of straw BC has been proven to significantly improve acidic soil conditions while also impacting nitrogen and nitrous oxide (N_2O) emissions within the soil. Research indicates that, in comparison to a control group lacking BC supplementation, the inclusion of straw BC significantly decreases N_2O emissions from the soil.[42]

The preparation of wood BC under high-temperature pyrolysis conditions can effectively enhance the soil organic CS capacity due to its significantly increased proportion of carbon elements and stable properties. As a carbon-rich material, this type of BC can form a stable carbon pool through long-term CS mechanisms, which has important environmental benefits for managing the equilibrium of the global carbon cycle and addressing climate change.[25] Zhou *et al.*[43] found that the ferric salt electron transfer network improves BC carbon sequestration efficiency through a multi-stage cycle, and the system has a high carbon sink intensity, providing an engineering solution for agricultural carbon neutrality. Wu *et al.*[44] indicated that straw BC amendments improved the characteristics of soil, including its stability, soil aggregate distribution, gas and solid-liquid phases, and porosity. Biocarbon also enhances soil fertility by increasing soil availability (K, P, N) and nutrient content, SOC storage and active carbon sources, as well as soil biological characteristics. Zhang *et al.*[45] founded that in the sample plot, the combination of nitrogen fertilizer and BC significantly increased vegetable yield. However, there were insignificant differences in vegetable yield when only nitrogen fertilizer was applied, regardless of whether BC was used for soil improvement. From this, it can be seen that BC can be used as an efficient management tool to maintain crop yields in vegetable planting systems while lowering the release of nitrogen oxides in the soil. Amoakwah *et al.*[46] the use of maize BC in tropical sandy soils significantly improved soil chemical properties and biological activity. The growth of microbial biomass is due to the improvement of biological efficiency, especially the synergistic effect of high respiration quotient and soil basal respiration. At the same time, the overall carbon and overall nitrogen content of soil have steadily increased, becoming key indicators for measuring soil quality improvement. In addition, BC enhances the instability of C and N elements and has a positive impact on soil ecosystems (Fig. 2c).[31] Soil HM pollution represents a significant global challenge, necessitating the implementation of various remediation techniques to mitigate the environmental and health hazards linked to HM in contaminated soils.[47] In recent years, BC has emerged as a widely adopted solution, demonstrating unique advantages in the treatment of soil environments, particularly in the cleanup of HM contamination. BC has proven to be very effective in the immobilizing HM due to its unique surface properties and the availability of a variety of functional groups. It facilitates the stabilization of pollutants by using processes like adsorption and ion exchange. The interaction between BC and metal ions mainly due to its porous design and active surface sites, which effectively enhance the chemical complexation and physical accumulation of HM in the soil.[48]

Studies have indicated that BC can regulate the forms of HM occurrence in soil, significantly reducing the proportion of migratory states through adsorption and fixation and inhibiting its bioavailability in soil-plant systems.[49,50] The composition of BC and the temperature conditions during pyrolysis can affect its potential efficacy as a soil HM fixative.[51] Another experiment showed that jujube seed-based BC has a significant removal effect on divalent metal ions. The material utilizes an ion exchange mechanism to achieve a removal rate of 57–72% for Fe^{2+}, Ni^{2+}, and Cu^{2+}. This adsorbent made from agricultural waste has great potential for application in HM pollution control, with an ion exchange capacity of above average level.[52] Therefore, BC exhibits excellent adsorption performance and long-term stability characteristics in the field of HM pollution control (Fig. 2d).[48] Li *et al.*[53] found that KOH activated magnetic bamboo based BC can efficiently remove norfloxacin and can be recycled, providing a basis for forest resources to be used for environmental remediation. BC is an efficient soil conditioner that significantly enhances SOC clumps.[54] Their unique properties, which encompass both physical encapsulation and chemical bonding, aid in the extended breakdown of organic material, thereby increasing the capacity for CS within soil.[55] In addition to improving the efficiency of SCS, BC is also crucial in reducing GHG emissions by optimizing the cycling of carbon and nitrogen. This dual function aids in addressing climate change challenges and supports the broader framework of terrestrial carbon cycling (Fig. 2e).[48]

3. The carbon storage mechanism of biochar in soil

BC is generally considered a stable form of carbon.[56] BC has excellent resistance to decomposition due to its stable composition and high carbon levels (60–90%). Research indicates that the application of this method can enhance SOC levels by 20–50%. Observations conducted over ten years have demonstrated that its long-term CS effectiveness surpasses that of traditional organic fertilizers, leading to direct carbon fixation (Fig. 3a).[3] In addition, BC can also have indirect carbon protection effects due to its high stability, which can effectively increase soil porosity, make the gaps between soil particles more reasonable. Over time, the structure of the soil is optimized and its fertility is significantly improved.[57] BC, exhibit excellent water and fertilizer-holding properties, effectively maintaining the material stability of ecosystems.[58] Zhang *et al.*[59] found that hydrothermal activation at 180 °C resulted in a hierarchical porous system with a 42% increase in modifier adsorption driven by SSA amplification, a 57% decrease in reaction energy barrier, and an exponential increase in pyrolysis rate. Islam *et al.*[60] found in their analysis that regardless of changes in BC, experiments, and soil conditions, the use of BC can improve soil aggregates by 16.4 ± 2.5%. The response ratio (lnR) of soil aggregates induced by BC varies significantly in different studies. The chemical stability and environmental function of BC mainly depend on its stable carbon, nitrogen, hydrogen, and oxygen element ratio characteristics. The combination characteristics of this element, as a key determining factor, not only regulate the structural stability and functional persistence of BC in the soil environment but also fundamentally determine its carbon fixation efficiency. Research has shown that this specific element ratio relationship plays a decisive role in the chemical stability of BC in environmental systems by regulating its

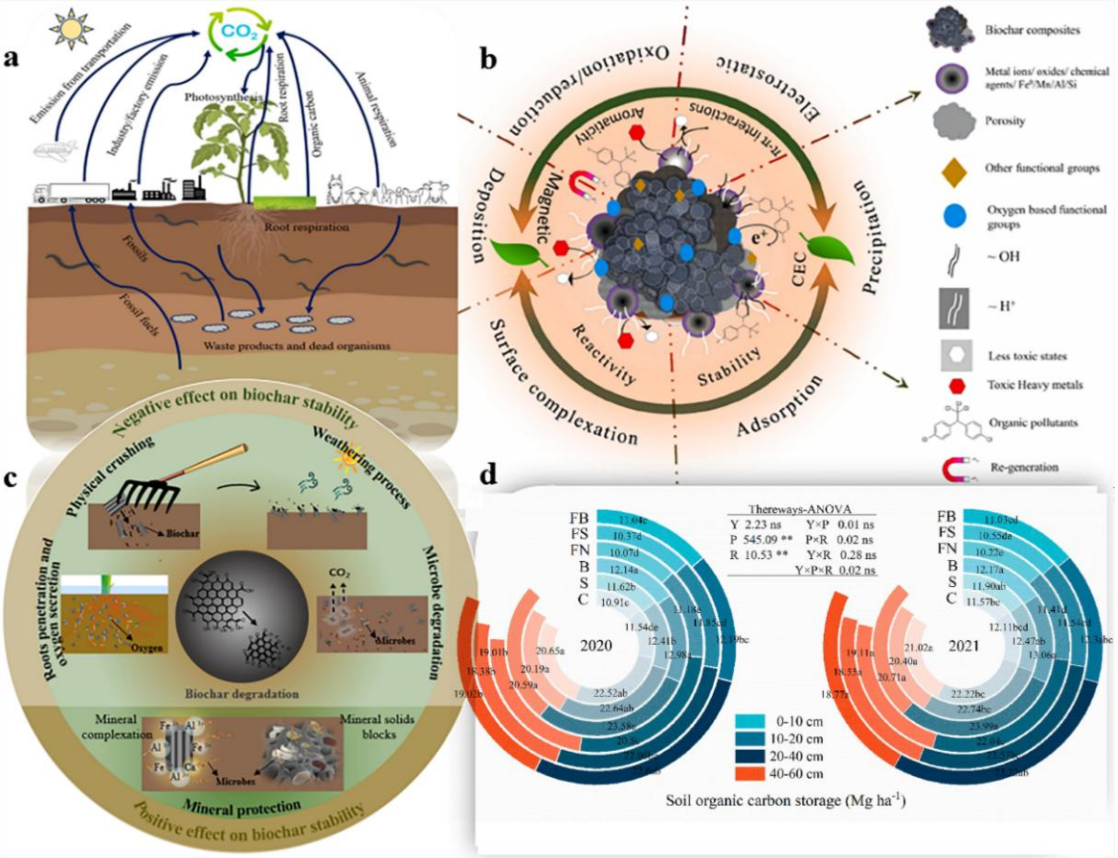

Fig. 3: (a) Carbon cycle accumulation process in soil BC system. Reproduced from.[3] (b) The interface reaction mechanism of metal-loaded BC for immobilizing HM. Reproduced from.[67] (c) The interface way BC interacts with soil elements. Reproduced from.[69] (d) Soil organic carbon storage under different straw-derived carbon input treatments at different stages. Reproduced from.[70]

aromatization degree and surface functional group distribution and directly affects its long-term CS effect in the global carbon cycle.[61] BC amendments can effectively increase SOC content and stabilize soil aggregates. Li *et al.*[62] studied the effects of different amounts of BC application in acid soil were studied. The results showed that the acidic tea garden soil (pH 3.92) underwent significant changes after BC improvement where the pH value increased to 4.28, and the organic carbon components showed differentiated responses. The increase in SOC reached 6.68–187.02%, respectively. On the contrary, the dissolved organic carbon content decreased by 6.97%. Mahmoud *et al.* demonstrated that soil enhanced with nano BC and nano water treatment residues exhibits a notably high level of aggregate stability. This stability can be attributed to several key factors, including elevated nutrient levels, increased organic carbon content, clay composition, and exceptional CEC. These attributes not only contribute to improved soil fertility and increased crop yields but also facilitate a more efficient utilization of rice straw resources.[63] By promoting the carbon fixation effect of the straw-returning process, this technology system has significant benefits in reducing carbon emissions in agricultural systems. Wang *et al.*[64] found through 8 years of field experiments that apple branch BC prepared at a PT of 550 °C exhibited significant soil improvement effects during long-term application. When the application rate reached 3% and 5% (1% application rate had no significant effect), it could effectively promote the fixation of organic carbon in clay loam soil. This CS effect not only enhances the stability of soil carbon pools but also has a positive effect on reducing GHG emissions from agricultural. BC amendments significantly influence the emission of carbon dioxide in the soil, with effects that vary according to both soil and BC types.[65] BC can interact with soil organic matter (SOM) in two distinct ways. On the one hand, it may stimulate the degradation of SOM, leading to a positive activation effect that could diminish the CS potential of the BC itself. Conversely, BC can protect SOM from degradation, generating negative excitation effects that can enhance the SCS capacity following its application.[66] Additionally, recent studies indicate that environmental ageing can notably alter the performance of BC (Fig. 3b).[67] The research system of BC in agricultural applications is becoming increasingly widespread, and its core advantages stem from the unique mineral component occurrence characteristics and long-term

Table 1: Properties of BC generated from various feedstocks at different PTs.

Raw material type	PT (°C)	Time (min)	Surface area (m^2 g^{-1})	C (%)	H (%)	O (%)	pH	Fixed carbon (%)	Ref
Peanut shell	600	60		50.12	5.41	42.8		10.77	[87]
Corn straw	500	180	232.7	77.3	2.35	11.26		29.9	[88]
Soybean straw	500		126.32	75.14	2.13	21.81			[89]
Rice hull	700	60	6.81	44.14	0.85	54.57	9.38	42.12	[90]
Wheat straw	600	60	16.8	43.14	5.21	40.32		16.8	[87]
Corncob	500	60	10.27					14.24	[91]
Bamboo	600	60	307.1	88.43	2.71	8.58	10.07	85.16	[92]
Mugong stem	600	60	261.78	84.87	2.29	12.47	10.14	84.07	[92]
Chickpea straw	600	60		48.1	5.23	42.31		10.86	[87]
Orange peel	650	60	42.4	41.05	6.1	51.94		16.18	[93]
Walnut shell	500	180	112.71	83.1	3.39	11.3		77.36	[94]
Spruce wood	600	30	564	87	0.91	0.91		88.1	[95]
Eucalypt	450	60	155.45	74.52	1.98	23.03	7.69	62.82	[90]
Poplar wood	600	300		75.9	2.3	17.9			[96]
Apricot shell	500	180	110.44	84.52	3.38	10.15		78.3	[94]
Poplar bark	600	300		68.1	4.4	20.1			[96]
Poplar leaves	600	300		53.2	2.11	17.5			[96]
Coconut shell	500	180	24.83	84.82	3.24	10.39		79.12	[94]
Pig manure	600	45		54.62	1.71	3.1		52.55	[97]
Sewage sludge	500	60	5.88	22.66	1.25	5.04	9.27		[98]

stability, which synergistically improve soil fertility indicators and carbon fixation efficiency.[68] The use of BC in soil has a dual regulatory effect on carbon cycling processes: on the one hand, it enhances soil CS capacity to improve carbon sink function, and on the other hand, it significantly reduces GHG emissions such as CH_4 and CO_2 by inhibiting methane production and regulating organic matter mineralization processes. The core mechanism of this regulatory effect stems from the high stability of BC, providing an important technological pathway for global carbon reduction (Fig. 3c).[69] BC enhances carbon sequestration and efficiency, enhances soil fertility and maize yield in drylands, and promotes agricultural sustainability. (Fig. 3d).[70] Criscuoli *et al.*[66] found that after applying soil amendments for three weeks, whether using BC alone or mixing BC with compost, BC-treated land exhibited higher total SOC with an average growth rate of 144 ± 22%. The average growth rate of carbon stock was 66 ± 10% after 1 year and 72 ± 13% after 2 years. Liang *et al.*[71] found that hydrogel BC composites can synergistically regulate water and slow release nutrients, alleviate crop drought, improve fertilizer efficiency, and provide innovative solutions for sustainable agriculture in arid areas.

4. Factors affecting the carbon storage efficiency of biochar

The enduring stability characteristics of BC in soil can affect CS processes through multiple pathways. Its direct effect is reflected in the CS increment brought by its input, while its indirect effect is achieved through several mechanisms. Numerous elements influence the CS efficiency of BC in soil, such as the basic materials utilized to prepare BC, the temperature and time of pyrolysis, soil type, soil pH value, moisture, and other conditions.

The heterogeneity of BC basic materials and the gradient regulation of pyrolysis conditions synergistically shape its acidification improvement efficiency. Through the dual mechanisms of surface alkaline functional group activation and mineral component slow-release, a dynamic soil pH buffering system can be established, thereby expanding the utilization range of BC.[72] The heterogeneity of BC raw materials significantly regulates the soil carbon cycling process, exhibiting differentiated carbon mineralization characteristics (Table 1). BC made from peanut shells is mainly beneficial for carbon (C) cycling, as it can reduce the carbon-to-nitrogen ratio (C/N) and increase key taxa in the phylum Actinobacteria.[61] Meng *et al.*[34] conducted a study demonstrating that BC derived from various raw material sources exerts significantly differing regulatory effects on soil carbon mineralization processes. Notably, rice husk BC showcases distinctive carbon stabilization characteristics, resulting in a reduction of soil basal respiration intensity by

10%. This impact is mainly due to the high content of silicon inhibiting the metabolic activity of microorganisms. Conversely, BC produced from manure, straw, and wood has been observed to increase CO_2 emission fluxes by 47.0%, 11.2%, and 8.7%, respectively.[34] Furthermore, the preparation processes of BC and its composite substances, along with the characteristics of the final products such as the adsorption and catalytic capabilities of the BC are influenced by numerous factors, which also extend to its effectiveness as an auxiliary agent in wastewater treatment applications.[6] Fang *et al.*[73] examined the impact of corn stover, rice husk charcoal, chicken manure liquefaction products, and other substances regarding the PAC characteristics of soil. A new soil amendment was prepared based on the comprehensive cost and improvement effect and applied to 100 hectares of farmland. It significantly improved soil properties, promoted corn yield, provided new strategies for improving saline-alkali land, and expanded the application scope of BC. Liu *et al.*[74] discovered that the use of BC derived from rice straw and corn straw has a notable positive impact on soil chemical properties.

The soil pH value shows an upward trend the levels of available phosphorus and available potassium are rising. The distribution of SOC functional groups is not only influenced by soil type but also significantly regulated by organic materials. The driving effect of organic materials on microbial metabolic activity is more prominent than that of soil matrix differences.[75] Compared to soil without corn stover BC, soil with BC significantly accumulates aromatic hydrocarbons and nitrogen-containing compounds, which will enhance the carbon and nitrogen sequestration mechanism and fertility of the soil.[76]

The temperature during pyrolysis is essential in determining the physicochemical characteristics of BC Table 1). on the one hand, as the temperature of pyrolysis varies, the SSA of BC significantly changes, and the characteristics of the pore system evolve regularly. The distribution of chemical groups on the surface of the material, and the relative proportions of carbon, hydrogen, and oxygen elements, have been systematically optimized.[77] Furthermore, The temperature at which pyrolysis occurs is a key factor in forming the PAC characteristics of BC, affecting combustion stability, SSA, and carbon level.[78] Additionally, variations in PT significantly affect the environmental behavior of BC. It has been observed that the acidity and alkalinity of BC tend to increase with rising raw material cracking temperatures. This relationship is reflected across different raw material systems.[79]

BC generated at a PT of 450 ºC demonstrates relatively low stability. In contrast, BC generated at a PT of 750 ºC may present biotoxicity concerns. Research indicates that the optimal PT range for achieving good stability in BC lies between 550 and 650 ºC.[22] Recent experimental research conducted by Geng *et al.*[72] show that the effectiveness of BC production is significantly influenced by the PT employed. The findings reveal that BC samples created at temperatures of 450 ºC and 600 ºC exhibit stronger positive effects on the target system in comparison to those generated at 300 ºC. Additionally, Yang *et al.*[27] noted that BC produced at 450 °C has the most pronounced impact on the validity of phosphorus in soil. Furthermore, Tomczyk *et al.*[8] reported that BC derived from higher PTs (ranging from 600 to 700 ºC) displays strongly fragrant characteristics and a structured carbon layer. Yang *et al.*[80] investigated carbon emissions associated with BC created in 300 ºC, 450 ºC, and 600 ºC. The results indicate that while BC generated at 300 ºC enhances the concentration and aromaticity of soluble organic matter, those produced at 450 ºC and 600 ºC result in an initial decrease followed by the minimal overall impact.

Soil type is an important influencing factor that affects nutrient availability levels, soil moisture content, and soil aeration.[81] In addition, soil properties have a major impact on the efficiency with which biofuels store carbon in the soil. Various soil conditions can significantly influence the effectiveness of BC in storing carbon. Research indicates that applying BC to alkaline clay soils can effectively mitigate carbon dioxide emissions, demonstrating enhanced potential for GHG emission reduction.[82] Rittl *et al.*[83] found that using Miscanthus altissima BC to improve tropical soil at high surface temperatures may lead to a decrease in the effect of increasing organic carbon content. However, by accurately controlling the application time in combination with soil and climate conditions, the adverse effects can be decreased.

The effect of BC on soil physicochemical properties varies significantly based on geological factors. BC has been shown to improve SOC storage and to help regulate the acid-base balance; however, its effectiveness is influenced by soil type.[84] In a controlled pot experiment, the impacts of BC application on nutrient dynamics were investigated across three different soil types namely, acidic loess, slightly alkaline yellow-brown soil, and neutral calcareous soil. The findings indicated that the total organic carbon levels increased with higher application rates across all soil types. Furthermore, in slightly alkaline soils, concentrations of ammonium nitrogen and Olsen-P exhibited an increase, whereas a marked decrease was observed in neutral soils.[85] Chen *et al.*[86] revealed that the use of BC produces a notable localized impact on soil acidity levels. Within 24 h of application, a pH gradient gradually develops around the BC particles.

5. Challenges and prospects of biochar carbon storage

The lasting impacts of BC on environmental factors and its impact on soil ecosystems, require further extensive monitoring and research. It is important to explore the combined effects of BC along with other soil improvement methods, as well as to evaluate its application across various climate zones and soil types. Additionally, the CS potential of BC is affected by various, including preparation temperature, type of raw materials, and specific soil characteristics, including pH and moisture content. BC prepared at high temperatures has high stability, but its decomposition rate may vary significantly under different climatic and soil conditions, affecting its long-term CS capacity. BC may indirectly accelerate the decomposition of existing organic matter by changing the behavior of soil microbial populations, which could lead to the loss of soil carbon pools, posing potential risks to soil ecosystems. In addition, excessive application may cause soil salinization or nutrient imbalance.

When BC is applied as an exogenous organic improvement material to soil, it usually leads to multidimensional environmental changes in the soil system. The multi-factor interaction network composed of soil microorganisms BC poses significant challenges for systematically analyzing its mechanism of action due to its complex synergistic and antagonistic relationships.[99] The proportion of field application of sewage sludge BC is relatively low, but its moderate application can effectively enhance soil physicochemical properties and promote microbial activity and crop growth. It should be noted that excessive application may cause an imbalance in microbial community structure and have negative effects on soil ecosystems.[100]

Raw materials and processes are poorly standardized, and the source and pyrolysis process have a significant impact on the physical chemistry properties of BC, resulting in a lack of unified quality standards. This heterogeneity may lead to unstable field application effects and increase the difficulty of large-scale promotion. Most developing countries have not yet established a specialized quality specification system for the standardization of BC and often rely on existing fertilizer or compost standards to regulate BC products. Since 2018, the Australian New Zealand BC Initiative has been developing BC standards in response to industry and government regulatory needs. The 2020 Australian New Zealand BC Conference annual academic investigation report shows that standardization construction has achieved phased results, and relevant technical specifications are being applied and verified in regional agricultural production systems.[101] Strict raw material management policies may inhibit the expansion space of the waste recycling industry, become a bottleneck restricting the promotion of BC technology, and thus threaten the sustainable development of the resource recycling system. Establishing an internationally unified technical specification system covering the entire industry chain plays an essential part in advancing the standardization efforts within the BC industry.[101]

Economic costs and sustainability challenges, such as BC production, involve energy consumption and equipment investment, with high transportation and application costs. If efficient recycling of waste biomass cannot be achieved, it may offset its environmental benefits. The disconnect between research and practice, existing research is mostly based on short-term small-scale experiments, lacking long-term field data support. For example, the way BC interacts with soil minerals and organic matter is not yet fully understood, which hinders the development of precise application strategies. In subsequent research, it is essential to prioritize enduring stability and maintenance effects of exogenous carbon and microbial metabolites.[102]

It is recommended that ongoing research into the interaction effects of different kinds of BC in conjunction with different crop varieties be pursued. Establishing long-term positioning experiments across diverse geographical regions will facilitate a systematic exploration of the lasting impacts of BC application on the enhancement of soil PAC properties, the dynamics of nutrient migration, and the processes influencing crop yield formation. This study will offer crucial scientific backing for the development of precise technical specifications for regional BC application.[103]

6. Conclusion

BC has demonstrated significant climate mitigation and agricultural sustainability benefits as a versatile carbon sequestration tool and Soil conditioner. Key findings suggest that BC application is able to store organic carbon in soils for hundreds of years while reducing CO_2 emissions by up to 50%, and that BC application can reduce CO_2 emissions by up to 50%, the crop yield was increased by improving soil structure, cation exchange capacity and pH balance. In particular, BC produced by high-temperature pyrolysis (600 °C) showed superior stability, with an inert carbon content of up to 97%, while feedstock selection and aging process had an important impact on its long-term carbon sequestration efficiency. Field studies have shown that straw-based BC systems can reduce agricultural carbon emissions by about 47%, highlighting their potential for large-scale application in climate-smart agriculture. Future research should focus on its long-term ecological impact, economic feasibility, soil-specific optimization, synergistic strategies, and life cycle assessment.

At the policy level, governments should incentivize the application of BC through subsidized production and inclusion in carbon credit schemes, and develop standardized quality and use guidelines to ensure its environmental safety and effectiveness. In summary, BC provides a practical solution to address global climate change and land degradation, and is one of the important ways to achieve net zero emissions targets.

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Conflicts of Interest

The authors declare no competing interests.

Supporting Information

Not applicable.

CRediT Statement

Chenglong Ma, Guanyan Li, Xiaochen Yue and **Xiangmeng Chen:** wrote the main text of the manuscript. **Yafeng Yang** and **Su Shiung Lam:** reviewed the manuscript. **Haiping Gu, Wanxi Peng** and **Yuli Dang:** were responsible for the revision and provided financial support.

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