Biochar-based agricultural soil management: an application-dependent strategy for contributing to carbon neutrality

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Abstract

Biochar has received increasing attention in agricultural and environmental fields as an integrated solution to agricultural waste recycling, soil amendment, carbon sequestration, and greenhouse gas (GHG) reduction. However, obtaining the environmental benefits of biochar is limited by an inadequate number of soil applications. Currently, the willingness to use biochar in soil management is relatively low, which results from the insufficient understanding and promotion of the roles of biochar in soil management and climate change mitigation. This review article presents biochar applications based on carbon-neutral strategies in agricultural soil systems. The primary roles of biochar in soil improvement and remediation are discussed and the main soil application methods are introduced. The focus of this article is on biochar-based soil management strategies for contributing to carbon neutrality. Carbon sequestration using biochar is an application-dependent strategy, as the key to obtaining this ecological benefit is to store biochar products in soil via effective agricultural management. This article offers insights into biochar-based soil management strategies and their contribution to carbon neutrality in agricultural soil systems, with recommendations for appropriate government involvement in promoting biochar-based soil management and for incorporating biochar into the carbon trading market.

Keywords: Biochar; Agricultural soil management; Climate change; Carbon neutrality; Carbon sequestration; Greenhouse gases

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Highlights

- The non-CO_2 GHGs account for the majority of carbon emission via agricultural soil.
- Incorporating biochar into the global carbon trading market is recommended.
- Using biochar to help achieve carbon neutrality is an application-dependent strategy.

Abbreviations

GHGs	Greenhouse gases
HMs	Heavy metals
IBI	International Biochar Initiative
LCA	Life cycle assessment
SOC	Soil organic carbon
WMO	World Meteorological Organization

1. Introduction

Mitigating climate change arising from anthropogenic emissions of greenhouse gases (GHGs) is urgently necessary. Since the start of the industrial era, human activities such as burning fossil fuels and developing land have sharply increased the concentration of atmospheric GHGs. According to the World Meteorological Organization (WMO) Greenhouse Gas Bulletin, the average concentrations of atmospheric CO_2, CH_4, and N_2O in 2019 reached respectively 410.5 ±0.2 ppm, 1877 ±2 ppb, and 332.0 ±0.1 ppb, which exceeded the pre-industrial (1750) levels by 48%, 160% and 23% [1]. Among these main GHGs, CO_2 accounted for 75% of global anthropogenic GHG emissions from 2010 to 2019 and was the greatest contributor to global warming. The increase of atmospheric GHG concentrations has caused climate changes primarily manifested as global warming, leading to increased glacial ablation and rising sea levels, outbreaks of pests and diseases in agricultural production, desertification of land, increased atmospheric instability, and more frequent occurrences of extreme weather such as floods, droughts, typhoons, high temperatures and heatwaves [2, 3].

As a result, many policies and measures have been put in place to control or reduce GHG emissions and thus mitigate climate changes, and the concept of "carbon neutrality" was developed. Carbon neutrality refers to counterbalancing the GHG emissions produced by enterprises, groups, or individuals in a certain period of time with an equivalent amount of CO_2 offset through afforestation, energy conservation, emission reduction, and other CO_2 mitigation strategies [4]. The ultimate goal of carbon neutrality is to obtain a net-zero carbon footprint. In order to tackle global climate change, many countries and enterprises have undertaken specific efforts and have set carbon-neutral goals. For example, China has aimed to have a CO_2 emission peak before 2030 and has promised to be carbon-neutral before 2060 [5]. The proposed carbon-neutral goals put forward new requirements for low-carbon development of global agriculture and set a higher benchmark for achieving green agriculture.

Agricultural activities and soils are important sources of global GHG emissions, though not the most major source (Fig. 1). Compared with the direct combustion of fossil fuel, cultivation and agricultural soils are not evident sources of GHG emissions, but improper farming practices, such as excessive application of nitrogenous fertilizers, can result in considerable GHG emissions from agricultural soils [6]. Therefore, active soil management is needed in order to realize GHG emission reduction. Additionally, as the core of the terrestrial ecosystem, soil serves as the largest terrestrial carbon pool [7]. The soil carbon pool stores about three times the carbon of the atmospheric pool, which makes the soil carbon cycle significant in global climate change strategies [8]. Most agricultural soils are depleted of soil organic carbon (SOC) due to long-term cultivation activities, and therefore, the agricultural soil carbon pool is far from being saturated, providing excellent potential for carbon sequestration [9, 10]. Terrestrial ecosystems have usually been considered in global carbon cycle studies in recent years, and the results suggest that utilizing agricultural soils as carbon sinks is an important mechanism to reduce carbon emissions and mitigate global climate change.

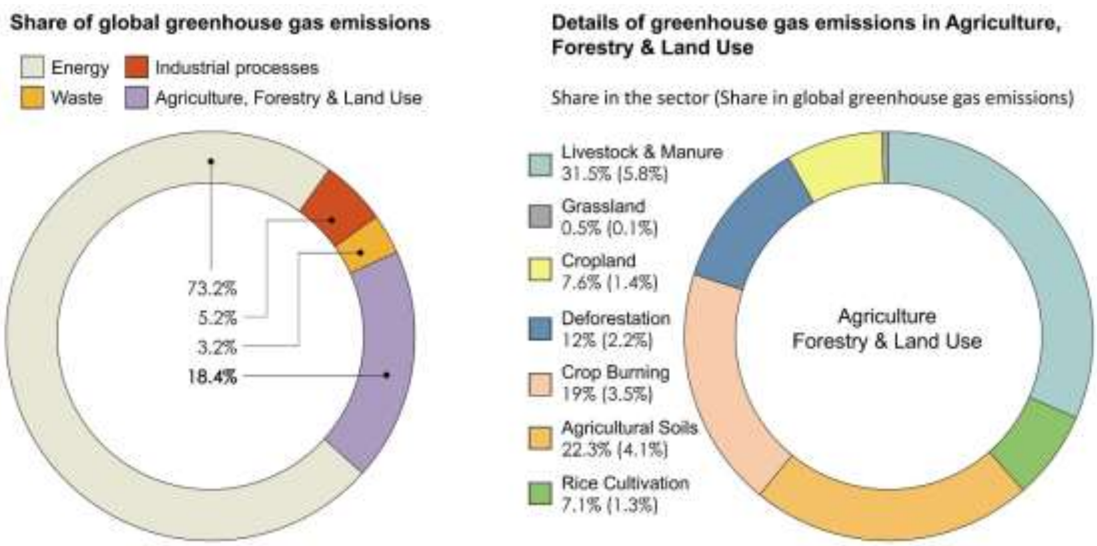

Fig.1. GHG emissions by sector and the details in agriculture, forestry and land use. Data were obtained from Our World in Data [11].

Production and application of biochar provide a feasible solution for utilizing the soil carbon sink to reduce carbon emissions and achieve carbon neutrality in agricultural activities. According to the precise definition of the International Biochar Initiative (IBI), biochar is a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment. Humans have been producing and using biochar for thousands of years (Fig. 2). The Amazonian Dark Earth, Terra Preta, is one of the many representative examples demonstrating that earlier civilizations applied biochar to the soil environment [12]. In the eastern suburb of Changsha in China, bio-charcoal was used to seal a timber burial structure in Mawangdui Tomb No.1 about 2000 years ago, and the use of bio-charcoal is considered to be one of the main reasons that a female corpse found in the burial structure was so well-preserved [13]. Although human concern for climate change goes back to 1856 when Eunice Foote reported that an atmosphere with increased CO_2 would cause the Earth's temperature to rise [14], the technological concept of applying biochar to soils for climate change mitigation was not proposed until 1993 when two classical papers that highlighted the roles of biochar in climate change mitigation were published [15, 16]. With the increasing use of the term "biochar" in the 21st century, the relationship between soil application of biochar and climate change mitigation gradually became clear, and the development of biochar is flourishing worldwide.

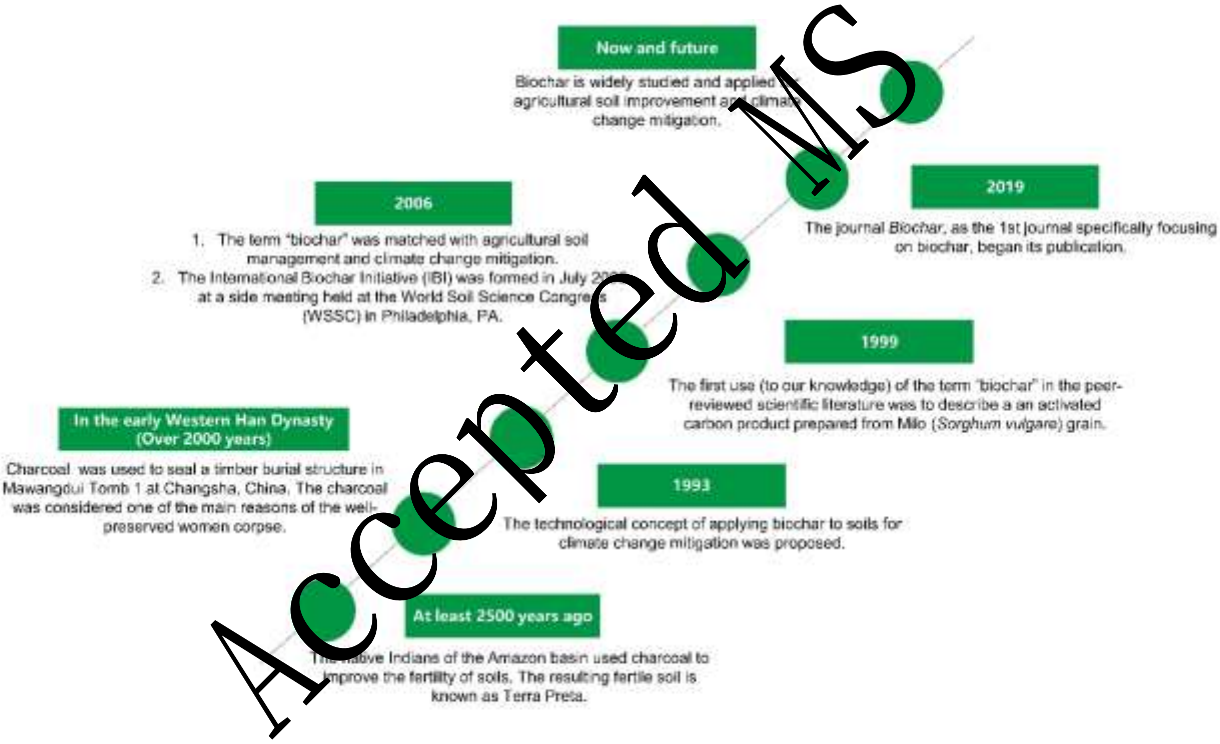

Fig.2. A brief history of biochar. The timeline was summarized based on ref. [12] (2500 years ago), ref. [13] (the early Western Han Dynasty), ref. [15, 16] (1993), ref .[17] (1999), ref. [18, 19] (2006), and ref. [20] (2019).

Biochar is widely used as a soil amendment, and it can reduce GHG emissions and make the soil more fertile at the same time [21]. Additionally, production and application of biochar can reduce agricultural waste and can produce clean renewable energy [22, 23]. Through large-scale biochar production and effective agricultural soil management, it is possible to achieve more than two goals through a biochar-soil system simultaneously. At present, a large amount of agricultural and forestry biomass waste, such as rice straw, peanut shells, corn cobs, dry branches, and fallen leaves, are burned or discarded in the open, and these disposal methods release considerable CO_2 and CH_4 into the atmosphere. Converting biomass waste into biochar can reduce the production of GHGs generated by burning and decomposing biomass waste. The present level of GHG emissions can be reduced by an estimated 12% if biochar is produced at the global level [24].

Mitigating climate change by implementing biochar-based agricultural soil management is currently in the early stages of rapid development. Though biochar shows tremendous potential, it is necessary to manage biochar-soil systems scientifically. Additionally, the key to obtaining the carbon sequestration benefit of biochar is to put a plentiful amount of biochar into soils, and this process is mainly implemented via biochar-based soil management. Therefore, the contribution of biochar to carbon neutrality largely depends on its soil application, including the willingness of farmers to use biochar. In a case study in Poland, it was found that only 27% of the surveyed farmers were familiar with biochar and 43% of the surveyed farmers were not willing to adopt biochar in their agricultural practice [25]. These results indicate that promoting the understanding and roles of biochar in soil management and climate change mitigation is necessary.

This article presents biochar-based agricultural soil management strategies and how these strategies can help achieve carbon neutrality in agricultural soil systems. The objective of this article is to (i) summarize the main strategies and application methods of biochar for agricultural soil management; (ii) discuss the potential and mechanisms of biochar for carbon neutrality in agricultural soil systems, and (iii) identify future research priorities. In contrast to other related articles that focus on the physicochemical properties and environmental behaviors of biochar, this paper highlights the application-dependent characteristic of using biochar-based soil management strategies for contributing to carbon neutrality. This article offers insights into biochar-based soil management strategies and their contribution to carbon neutrality in agricultural soil systems, and provides guidance for positive publicity and promotion of biochar soil applications for facilitating social applicability and acceptance of biochar.

2. Methodology

Based on the research theme, database retrievals and Internet searches were conducted as part of a comprehensive literature search. Preliminary screening was performed by searching the online database Web of Science and Google Scholar with keywords containing "biochar", "biochar application", "soil", "soil amendment", "biochar amendment", "climate change", "carbon sequestration", "greenhouse gas", "emission", "CO_2", "CH_4", "N_2O", "carbon neutral", and "carbon neutrality". Additional records were identified and collected through Internet searches. Next, eligible articles were selected for full-text assessment by reviewing the the title and abstract of each article. During the full-text reading, articles with less relevant data or outcomes for the objective were excluded, and the remaining articles were included in the subsequent literature review. These articles were then categorized into "soil management application", "climate change mitigation", and "others" for further analysis and discussion. Representative articles were cited in this article to support our viewpoints and statements.

3. Agricultural soil management with biochar

3.1. Biochar for agricultural soil improvement

The use of biochar can improve agricultural soil by loosening soil, retaining moisture, and preserving fertility (Fig. 3). Due to excessive land utilization and inappropriate soil management, many countries and regions face serious soil degradation problems such as soil acidification, soil hardening, and soil fertility decline [26].The abundant pores of biochar help to improve soil aeration, stabilize soil aggregates, and increase the water-holding capacity of soil. It was reported that biochar could settle between soil particles without blocking the existing pores, thus increasing the overall porosity of the soil-biochar system [27]. Thus, crop growth could be enhanced as a result of improved water uptake and root respiration. The most beneficial effect of biochar on soil physicochemical properties is in improving the water-holding capacity, but this is closely related to the soil texture, and therefore, not all biochar treatments will increase soil moisture [28]. Generally, biochar applied to droughty, sandy soils or coarse-textured soils has a more significant effect on the improvement of water-holding capacity compared to other soils [29-31].

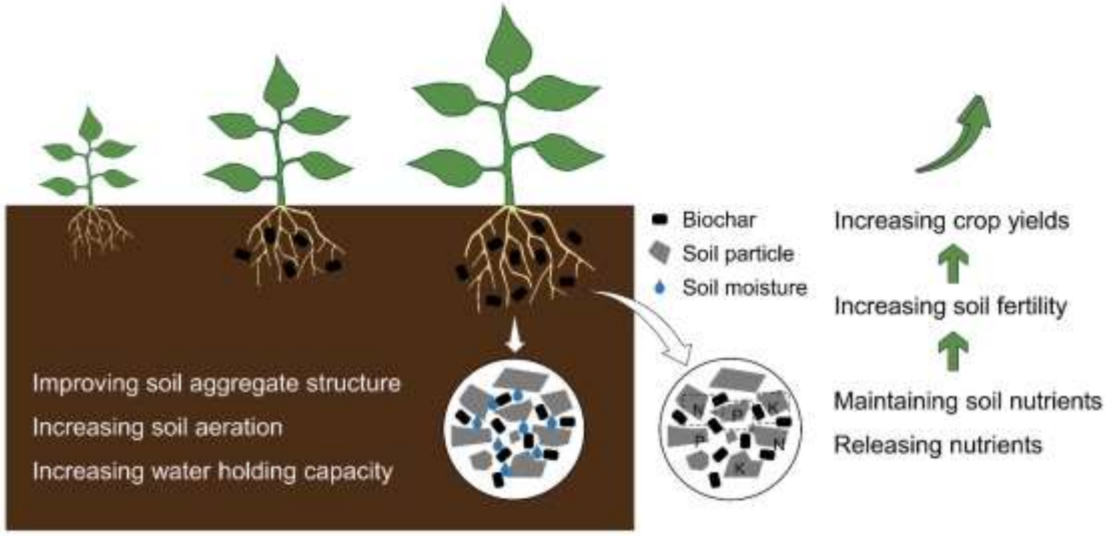

Fig.3. Schematic diagram of using biochar for agricultural soil improvement.

Biochar preserves soil fertility by reducing soil nutrient loss, and the mechanism is generally regarded as a combined effect of physicochemical and biological processes [32]. The high ion exchange capacity and strong adsorption capacity of biochar for soil nutrients decrease nutrient leaching, and the physical retention of dissolved nutrients in the soil solution increases with the biochar-induced increase of water-holding capacity [33, 34]. The applied biochar may act on the soil microbial community involved in nutrient cycling and thus promote nutrient immobilization via biological mechanisms [34-36]. Additionally, biochar itself retains a large amount of mineral components from the original biomass, such as N, P, K, and Ca, which are effective nutrient supplements for improving soil fertility and promoting crop growth [37]. In general, the effect of increasing fertility by applying biochar is more significant in relatively infertile soil, such as acidic soils and highly leached soils [38]. Using biochar as a soil ameliorant can optimize soil fertilization and support the development of new fertilizers, providing effective substitutions for conventional chemical fertilizers. The alkaline nature of biochar enables it to act as an acidic soil ameliorant to recover and even increase soil productivity. The $CaCO_3$ equivalents and total alkaline cations in biochar are mainly responsible for the acid soil improvement [39]. Wu et al. [40] studied the effects of biochar on acidic soil properties and found that biochar improved acidic soil properties and reduced fruit acidity more than lime treatment. These results support the use of biochar to replace lime for improving acidic soils for cultivating calciphobous plants, such as tea [41]. In summary, biochar can improve multiple types of degraded soils, and targeted measures for biochar-based soil management should be implemented in practical applications according to the specific purpose of use.

3.2. Biochar for agricultural soil remediation

Using biochar to remedy contaminated agricultural soil has been extensively studied, with the purpose of recovering soil function and improving agricultural product quality (Fig. 4). Pollutants such as heavy metals (HMs) and pesticides readily accumulate in the soil via pesticide application, sewage irrigation, and industrial waste dumping [42]. These pollutants usually cause soil dysfunction and soil quality deterioration. Biochar shows a high adsorption capacity for many HMs (such as Pb, Zn, Cd, Cu, and Ni) and pesticides (such as parathion, terbuthylazine, imazamox, atrazine, and imidacloprid) as a result of its adsorbent characteristics, i.e., a porous structure and multiple functional groups [43-48].

attraction, pore-filling, hydrogen bonding, π-π interactions, partitioning to non-carbonized fractions, and hydrophobic interactions [53]. Among these recognized mechanisms, partitioning to non-carbonized fractions is one mechanism not common in other carbonaceous adsorbents. It is difficult to completely carbonize biochars, even when the productive pyrolysis process is conducted at relatively high temperatures [54]. In describing adsorption for organics, the non-carbonized fractions of biochar are usually identified as a partition phase (linear adsorption), while the carbonized fractions are represented as a surface adsorption phase (nonlinear adsorption) [55]. These two phases of biochar dominate the total adsorption of organic molecules, and the partitioning effect is the primary adsorption mechanism of organics by low-temperature biochars that contain more non-carbonized fractions [56]. Apart from the properties of biochar itself, the hydrophobicity of the organics also affects the relative contributions of biochar partitioning and surface adsorption, with the adsorption of less hydrophobic organics by biochar mainly occurring via the partitioning mechanism [57]. These adsorption characteristics enable biochar to play a role in remediating polluted soils. The adsorption effect of biochar can stabilize soil pollutants, reduce their phytotoxicity and bioavailability, and thus decrease pollutant uptake by crops and enhance the yield and quality of agricultural products.

3.3. Methods and limitations for biochar application to agricultural soil

In practical applications, proper application methods are essential for using biochar to manage agricultural soil (Table 1). For conventional crop fields, biochar is usually applied to the soil by broadcasting over the soil surface and then mixing with the soil by manual operation or special machines. The broadcasting procedure is normally performed by hand, or by using a spreader or fertilizer broadcaster [58]. After broadcasting, the biochar is mixed with the soil by common tillage methods such as plowing, harrowing, and hoeing [59]. Additionally, in-furrow application, in which biochar is applied to a trench near the crop rhizosphere, is frequently used to add biochar fertilizers. This application method allows biochar to be applied to the soil after crop planting, and to act directly on crop roots, thus reducing soil disturbance and the amount of biochar that is applied [60]. In addition to the direct application to soil, biochar can be mixed with other soil amendments, such as compost, manure, and lime, or used as a slow-release carrier of other soil amendments [61-65]. These indirect application methods are conducive to increasing the tillage efficiency and realizing long-term improvement of soil quality and crop yield.

Wind loss and water erosion are the main problems in the practical use of biochar. A field trial of biochar application in Canada showed that an estimated 25% of the biochar was blown away during application with a spreader, causing a wind loss of 1.4 t/ha [66]. To avoid wind loss, applying biochar in windless or wet days is recommended. Wetting biochar with a sprayer is also feasible, but biochar that is overly wet may adhere to tillage implements during the subsequent turning of the soil [67]. In addition to wind loss, rainstorms and slopes may cause biochar loss by water erosion [68, 69]. This typically occurs in the form of rain splash, rill erosion, and gully erosion [70]. Therefore, biochar applied to sloping fields or rainy areas may also require soil management practices, such as straw mulch, to minimize the water erosion of biochar [71]. According to the 3R Principle (reduce, reuse, and recycle), it is recommended that biochar is applied to fields in the form of granules (not powder) under moist conditions or by incorporating it into other fertilizers and then thoroughly mixing it with the rhizosphere soil [72].

Table 1
Examples of biochar application to field.

Type of biochar	Application purpose	Application method (application amount)	Reference
Sugarcane bagasse biochar	Increasing soil fertility and crop yield	Broadcasting (5 and 10 t/ha) and furrow application (5 and 10 t/ha)	[60]
Rice straw biochar	Mitigating Cd accumulation in greenhouse lettuce production	Broadcasting (6, 12, and 18 t/ha) and band application (5 and 8 t/ha)	[73]
Red oak biochar	Assessing the cost of biochar application and the return on investment	Broadcasting (10, 20, 40, and 60 t/ac)	[74]
Seed screenings biochar	Improving soil quality for winter wheat growth	Broadcasting (18 t/ha)	[75]
Peanut shell biochar	Improving soil quality for increasing rice yield in saline-sodic paddy soil	Broadcasting (33.75, 67.5, and 101.25 t/ha)	[76]
Wood biochar	Improving soil quality for earthworm populations	Broadcasting (5, 7.5, and 10 t/ha)	[77]
Bamboo biochar	Improving the quality of forest soil	Furrow application (2.22, 4.44, 6.67, 8.89, and 11.11 t/ha)	[78]
Prosopis juliflora biochar	Improving soil quality for maize growth	Furrow application (5 and 10 t/ha) and mixing with fertilizers (0.05 and 0.1 t/ha)	[79]

4. Biochar-based soil management strategies for carbon neutrality

As a new approach to mitigate global climate change, the use of biochar-based soil management strategies to achieve carbon neutrality has been increasingly adopted in agricultural production activities and land utilization management. This will promote the development of green global agriculture, as soil management applications are the main pathway by which biochar contributes to carbon neutrality (Fig. 5). Biochar mainly functions to achieve carbon-neutral goals through two mechanisms: carbon sequestration and emission reduction.

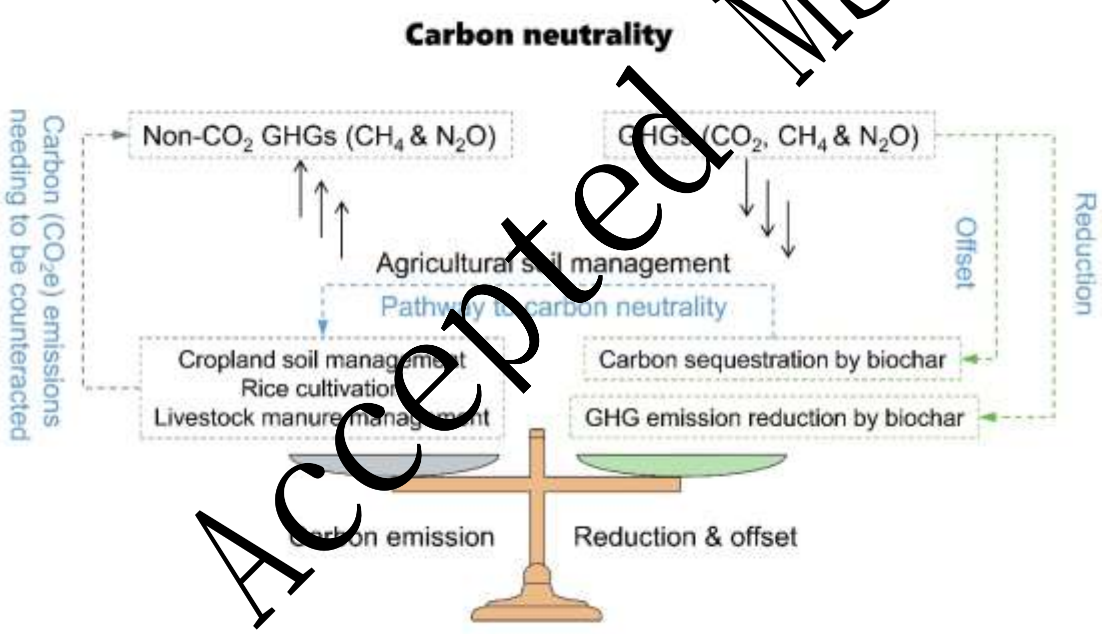

Fig.5. Agricultural soil management as the main pathway of biochar to contribute to the carbon neutrality.

4.1. Carbon emissions through agricultural soil systems

Agricultural soil carbon has received wide attention due to its close relationship with agricultural activities such as ploughing, irrigation, and fertilization. Carbon input and carbon emission determine the carbon balance of agricultural soil. Carbon input to the agricultural soil system mainly comes from crop residues, root exudates, and organic fertilizers, while the carbon emission pathway mainly includes soil respiration, plant uptake, and carbon eluviation. Soil respiration, including root respiration and microbial respiration, is the major pathway of CO_2 emissions from the soil system to the atmosphere [80]. However, only the non-CO_2 sources are included in the statistical analysis of agricultural GHG emissions, as the absorption and emission of CO_2 can reach a natural balance [81]. The main non-CO_2 GHGs in the agriculture sector include CH_4 and N_2O, and their agricultural emissions accounted for the largest percentage (48%) of global emissions of non-CO_2 GHGs in 2015 [82]. Therefore, the carbon emission here refers to the emission of CO_2 equivalents (CO_2e) of CH_4 and N_2O. As presented in Table 2, the non-CO_2 GHG emissions from agricultural soil systems primarily come from cropland soil management (mainly N_2O from nitrogenous fertilizer application), rice cultivation (mainly CH_4 from anaerobic decomposition of organic matter in flooded rice fields), and livestock manure management (both CH_4 and N_2O emissions). The global non-CO_2 GHG emissions from these three sources, namely, cropland soil management, rice cultivation, and livestock manure management, reached 1941, 624, and 572 million metric tons of CO_2 equivalents ($MtCO_2e$) in 2015, respectively. In China, the GHG emissions from cropland soil management, rice cultivation, and livestock manure management were respectively 138, 187, and 288 $MtCO_2e$, which accounted for 16.7%, 22.6%, and 34.7% of the total agricultural GHG emissions in 2014 [83]. These CO_2e emissions from agricultural soil systems are the carbon emissions that need to be counteracted in the soil management strategies for carbon neutrality. However, the soil for agricultural production usually has lower organic matter than natural soil due to decreased carbon input (from regular harvest and crop residue removal, for example), accelerated organic carbon decomposition (from frequent tillage), and severe soil erosion [84]. It is estimated that most cultivated land has lost 30%–75% (30–40 ton carbon per hectare) of their antecedent organic carbon pool, and the current organic carbon content is far below the potential capacity [85]. The global topsoil (≤ 1 m) contains 1325 Pg of organic carbon, and croplands have a carbon sequestration potential of 0.90–1.85 Pg carbon per year [86, 87]. Therefore, maximizing the agricultural soil carbon pool with active soil management is an effective strategy for decreasing carbon emissions from agricultural soil system.

Table 2

Global emissions of non-CO_2 greenhouse gases (GHGs) in the agriculture sector [82].

Source categories	GHG type	Emission pathway	Emissions reached in 2015 ($MtCO_2e$)	Emissions projected in 2030 ($MtCO_2e$)
Cropland soil management	N_2O	Fertilizer consumption, crop residues incorporated into soils, and manure left on pasture	1941	2206
Rice cultivation	CH_4	Anaerobic decomposition of organic matter in flooded rice fields	624	617
Livestock manure management[a]	CH_4 and N_2O	Anaerobic decomposition of manure (CH_4), and nitrification and denitrification of the organic nitrogen content in livestock manure and urine (N_2O)	572	632

[a] The data of this source category exclude the emissions from the enteric fermentation of a normal mammalian digestive process as it is not directly related to the agricultural activities in soil management.

4.2. Carbon sequestration by biochar

Carbon sequestration refers to natural or artificial removal of atmospheric CO_2 and its storage in a stable solid form. Naturally, atmospheric CO_2 can be directly absorbed by plants via photosynthesis. Part of the absorbed CO_2 is released back into the atmosphere by respiration, and the rest is sequestered first as plant biomass and then as SOC during the decomposition process of the plant biomass. Further decomposition of SOC releases the carbon as CO_2 into the atmosphere within a short period of time. Therefore, the entire process is carbon neutral. Biochar is stable and its high content of aromatic carbon that is more difficult to decompose than plant biomass is the basis of the carbon sequestration benefits of biochar. The pyrolysis of plant biomass breaks the natural carbon cycle and realizes carbon sequestration by biochar storage in soil [88]. It is estimated that about 6 GtC/yr of biomass carbon is available for biochar production worldwide if 10% of net primary production is used, from which 3 GtC/yr of biochar can be produced [89]. Pyrolyzing agricultural biomass waste (mainly crop straw and livestock manure) and storing the resulting biochar in soils via agricultural soil management have the advantage of recycling solid waste and show great potential for carbon sequestration. According to a calculation method based on a life cycle assessment (LCA), 585 Mt/yr of crop straw and 610 Mt/yr of livestock manure are produced in China, and transforming them into soil biochar can sequester 264 and 172 $MtCO_2e$/yr, respectively [90]. More representative examples of using biochar for carbon sequestration in soils are shown in Table 3. Lefebvre et al. [91] used a modified

RothC model to evaluate the carbon sequestration potential of sugarcane residue biochar, and their results showed that 50 $MtCO_2e$/yr could be sequestered at a scale of the entire state of São Paulo in Brazil. Recently, Yang et al. [92] evaluated the carbon sequestration potential of various crop residue biochars through LCA at the country level and found that the annual carbon sequestration potential in China could reach 500 $MtCO_2e$/yr. These results demonstrated high carbon sequestration capacity of biochar from crop residues. In order to quantify the carbon sequestration effect precisely, many field experiments were conducted. For example, Yang et al. [93] applied corn residue biochar to a corn field under drip irrigation with mulching, and the results showed that the carbon sequestration increased by 16% in the upper 15-cm soil and CH_4 emission decreased by 132% after 30 t/ha of the biochar was applied. Additionally, the biochar amendment enhanced the corn yield by 7.4% over two years. This example suggests that proper application of biochar could contribute to agricultural soil management and climate change mitigation simultaneously.

Table 3

Representative examples of using biochar for carbon sequestration in soils.

Type of biochar	Assessing method	Carbon sequestration potential	Reference
Sugarcane residue biochar	Modified RothC model	50 $MtCO_2e/yr$	[91]
Crop residue biochar (grain, bean, tuber, oil crop, cotton, sugarcane, and hemp)	Life cycle analysis	500 $MtCO_2e/yr$	[92]
Corn residue biochar	Field experiment	With 30 t/ha biochar application, the carbon sequestration increased by 16% in the upper 15-cm soil.	[93]
Crop residues biochar (coconut husk, coconut shell, cotton stalk, olive pomace, palm shell, rice husk, sugarcane bagasse, and wheat straw)	Proximate analysis of raw feedstocks and biochars	550 $MtCO_2e/yr$ (21.3%–32.5% of the feedstock carbon)	[94]
Rice hull biochar	Field experiment	With 1.142 t/ha of biochar and pig manure compost (4: 6), the carbon sequestration increased from 1.28 to 2.94 t/h.	[95]
Apple wood biochar	Field experiment	With 20 t/ha biochar application, the carbon sequestration increased by 354.78% in a non-fertilized plot and by 316.52% in a fertilized plot.	[96]
Bamboo leaf biochar	Field experiment	The total carbon sequestration increased from 3.36 to 19.70 and 11.86 tCO_2e/ha with 5.0 and 15 t/ha biochar applications, respectively.	[97]

4.3. Agricultural GHG emission reduction by biochar

In addition to direct carbon sequestration, biochar can benefit carbon neutrality by decreasing the emission of agricultural GHGs. The generation of N_2O in agricultural soil mainly occurs during the microbial transformation of soil nitrogen, especially denitrification and nitrification [98]. Applying biochar fertilizers decreases the use of nitrogenous fertilizers and livestock manure in agricultural production, thus decreasing the nitrogen input and N_2O generation of cropland soil management. Additionally, biochar can inhibit denitrification and nitrification processes and reduce the generation of N_2O. The main mechanisms for this include that the following: (1) biochar decreases the substrate and energy sources for denitrification and nitrification reactions by the adsorption of soil NH_4^+-N and organic matter [99]; (2) biochar increases nitrogen fixation by crops and other microorganisms, thus reducing the available nitrogen sources for denitrobacteria and nitrobacteria [100]; (3) direct action of biochar alters the abundance and composition of community of the azotobacters, denitrobacteria, and nitrobacteria [101]; and (4) biochar regulates soil physicochemical properties, such as pH, soil aeration, and moisture, indirectly affecting the denitrification and nitrification processes [102, 103]. Many studies have demonstrated the effectiveness of biochar for N_2O emission reduction, while other studies have found that biochar has no effect on soil N_2O emissions or even increases soil N_2O emissions [104-106]. These differences may result from the diversity of soil type and environmental conditions, and effective N_2O emission reduction by biochar is realizable if active soil management is implemented [107]. Some representative examples of using biochar to reduce N_2O

emissions from agricultural soils are shown in Table 4. Fan et al. [108] studied the effects of wheat straw biochar and pig manure biochar on N_2O emission reduction in an anthrosol, and found that both biochars reduced N_2O emissions by 12.9%–20.0% at an application amount of 40 t/ha. Their further analysis of the soil bacteria revealed that the biochars functioned by weakening the autotrophic nitrification that dominated the N_2O emissions. Aamer et al. [109] reported that biochar application increased the pH of acidic soil and mitigated N_2O emissions. In their experiments, the biochar reduced N_2O emissions by 81% and 235% when applied at 22.4 and 44.8 t/ha, respectively. In their mechanism analysis, they attributed the N_2O emission reduction to the increase of functional gene abundance. These examples suggest the complicated biological processes behind the N_2O emission reduction by biochar soil application. Global meta-analysis studies show that biochar amendment can reduce 12.4%–54% of N_2O emissions from agricultural soils [110-113]. Based on an estimated 1941 $MtCO_2e$ of N_2O emissions from cropland soil management in 2015 [82], an emission reduction amount of 241–1048 $MtCO_2e$ could be realized through bicohar application in soil.

The generation of CH_4 in agricultural soil in paddy fields mainly occurs as part of anaerobic decomposition of organic matter, such as root exudates, plant residues, and organic manure [114]. Recycling crop straw and livestock manure to produce biochar decreases the organic residue input and CH_4 generation in the rice cultivation process. Additionally, applying biochar affects soil CH_4 emissions mainly by interfering with the generation, oxidation, and release of CH_4. Similar to N_2O emission reduction, the mechanisms of CH_4 emission reduction by biochar application mainly include the following: (1) biochar decreases the activity and abundance of methanogens but increases those of methanotrophs [115]; (2) biochar increases the adsorption and oxidation of CH_4 in soils [116, 117]; and (3) biochar regulates the soil properties such as pH, aeration, and moisture, indirectly affecting CH_4 generation and release [118, 119]. Utilizing biochar production and application to replace the conventional practice of returning straw to the field plays a significant role in decreasing CH_4 emissions from rice fields. Scientific soil management is also needed to avoid the unintended consequence of an increase, not a decrease, in the amount of CH_4 released [120, 121]. Wang et al. [115] conducted a four-year study on CH_4 emission reduction in a double rice cropping system by applying biochar, and the results showed that the annual CH_4 emissions reduced by 20%–51% following 24 or 48 t/ha biochar application. It was further found that biochar application significantly reduced the ratio of methanogen/methanotrophs in four years. According to a separate meta-analysis, the biochar amendment reduced CH_4 emissions from paddy soils by 12% [122]. This is equivalent to an emission reduction of 74.9 $MtCO_2e$, based on the estimated CH_4 emissions from rice cultivation [82]. However, a meta-analysis by Jeffery et al. [118] showed that biochar application had the potential to both increase and decrease soil CH_4 emissions and that water management was the critical determining factor. This article highlighted the importance of soil management conditions during biochar application, which is consistent with the previously mentioned active soil management.

Table 4
Representative examples of using biochar to reduce GHG emissions from agricultural soils.

Type of biochar	Type of GHG	Reducing efficacy	Reference
Wheat straw biochar and pig manure biochar	N_2O	Both biochars reduced N_2O emissions by 12.9%–20.0% at an application rate of 40 t/ha.	[108]
Rice straw biochar	N_2O	The biochar reduced N_2O emissions by 81% and 235% with 22.4 and 44.8 t/ha biochar applications, respectively.	[109]
Hardwood tree (ash, oak, and cherry) biochar	N_2O	With 28 t/ha biochar application, N_2O emissions were reduced by 91% after four days.	[123]
Maize straw biochar	N_2O	The biochar reduced N_2O emissions by 31.5%–42.4 % at an application rate of 3, 6, or 12 t/ha in the first maize season.	[124]
Wheat straw biochar	CH_4	With 24 and 48 t/ha biochar applications, annual CH_4 emissions were reduced by 20%–51%.	[115]
Wheat straw biochar	CH_4	With 48 t/ha biochar application, CH_4 emissions were reduced by about 40%.	[125]
Wheat straw biochar	CH_4	With 7.5 and 15 t/ha biochar applications, CH_4 emissions were reduced by 13.2% and 21.5%, respectively, in the presence of optimal nitrogen fertilization.	[126]
Rice straw biochar	CH_4 and N_2O	With 20 and 40 t/ha biochar applications, the global warming potential of CH_4 and N_2O (CO_2e) emissions were reduced by 18.7% and 16.4%, respectively, under controlled irrigation over the two rice seasons.	[127]

4.4. Strategy of biochar-based soil management for carbon neutrality

Under the impact of natural and human activities, agricultural soil systems are not only important carbon sinks, but are also non-negligible emission sources of GHGs. Agricultural activities are responsible for the main non-CO_2 GHG emission sources, including CH_4 emissions from rice cultivation and N_2O emissions from the application of nitrogenous fertilizers. Managing agricultural soils with biochar has great potential for emission reductions of CH_4 and N_2O, and for carbon sequestration. Although agriculture is not included in the key industries of carbon emissions in many countries, GHG emissions from agricultural activities matter. As an important factor of agricultural production, agricultural soil (arable land) plays a key role in both carbon emissions and carbon sequestration. Increasing the carbon sequestration capacity of agricultural soil systems by biochar application can be an effective way to help realize carbon neutrality. The basic strategy of biochar-based soil management for carbon neutrality is to reduce GHG emissions and increase soil carbon sinks via biochar production and application. The rice straw biochar is a typical example (Fig. 6). Utilizing rice straw for biochar production reduces CO_2 emissions from open burning and natural decomposition, and reduces CH_4 emissions from the straw that is directly returned to the field. The application of rice straw biochar for soil management further reduces the generation and release of CH_4 and N_2O, while significant amounts of carbon are stored in biochar. In summary, biochar-based soil management is carbon negative, but rational application methods to ensure the effects of emission reduction of non-CO_2 GHGs with biochar during soil management are still not sufficient.

5. Stability of biochar in soil

The long-lasting effects of carbon sequestration and soil management functions of biochar is of great significance for its practical use. The stability of biochar refers to its capacity to resist biotic and abiotic damage in the environment. Generally, biochar is highly stable in soils and can effectively sequester carbon for hundreds or even thousands of years. For example, the mean residence time of the stable carbon in rice straw biochar in paddy soil was found to be about 617–2829 years, indicating an excellent long-term effect of biochar for carbon sequestration [130]. Due to the high content of carbon, the primary consideration of biochar stability is the carbon stability or the stable carbon structures in biochar [131]. The carbon components of biochar are often described as labile carbon and stable carbon, with the stable carbon content generally accounting for 50%–85% [132]. During the natural mineralization process of biochar, the labile aliphatic carbon components are more easily decomposed, while the stable aromatic carbon components that account for the majority of biochar slowly decompose in later phases of mineralization [133]. Based on a two-pool (labile and stable) model fitting, the mean residence time of labile biochar carbon in soil is only 3–57 days, while the stable carbon fractions can remain in soil for 90–1616 years [134]. There are two main aspects of the stability mechanisms. First, the highly carbonized structure and closely stacked aromatic rings of biochar make it stable enough to resist destruction from physical erosion (such as swelling, abrasion, and water impact) and chemical decomposition (such as dissolution and oxidization) [135-137]. Thus, biochar with a higher degree of aromatic condensation is typically more stable. Second, organic macromolecules in biochar may combine with soil minerals to form agglomerates, that protect the biochar from being degraded by physicochemical erosion and soil microorganisms [138, 139]. In summary, the excellent stability of biochar supports long-lasting carbon sequestration in the soil carbon sink.

6. Considerations of economic and environmental benefits

Though applying biochar into agricultural soil systems provides multiple environmental benefits, it is vital to develop the potential of economic profit simultaneously when popularizing biochar-based soil management technologies, because, currently, the use of commercial biochar as an independent agricultural input is not generally cost-effective [140]. Technological advances have partially reduced the production cost and price of biochar, but not to the point where it is profitable for farmers [141]. The main economic benefit for farmers is the crop yield increase after biochar application. However, many environmental benefits of biochar are unpriced positive externalities, and the carbon sequestration and GHG emission reduction benefits that are generated after biochar application may be credited to farmers. It is recommended that substantial economic profit from the environmental benefits of biochar could be obtained via a national carbon trading system, in which the government may return the benefits to farmers in the form of financial subsidies and incentivize farmers to implement biochar-based soil management [142]. By establishing a carbon trading market that includes biochar, the carbon sequestration and

GHG emission reduction benefits derived from biochar applications in soils can be recognized, and thus the profitability of biochar application increases. A case study of wheat production in the state of Washington in the United States shows that applying biochar to soil may be profitable if the biochar price is lower than $100.73/t when the carbon offset price is $31/tCO_2$, and farmers may be willing to use biochar in this case [143].

7. Conclusions

Biochar is an excellent option for both agricultural soil management and climate change mitigation. Using biochar for soil management could help to retain moisture and preserve soil fertility, thus improving the crop growth and yield. The co-precipitation effect and partitioning to non-carbonized fractions are respectively highlighted mechanisms by which biochar adsorbs HMs and organic pollutants, compared to other carbonaceous adsorbents. Broadcasting and furrow application are the primary methods for biochar application to agricultural soil, and wind loss and water erosion are the main problems in the field application of biochar. Biochar contributes to carbon neutrality through carbon sequestration and GHG emission reduction. The non-CO_2 GHGs, including CH_4 and N_2O, are the CO_2 equivalents that need to be neutralized in the agricultural soil system. The key to obtaining the carbon sequestration benefit of biochar is to apply biochar to soils through effective biochar-based soil management, which makes it an application-dependent strategy. The production of biochar can reduce CH_4 and N_2O from the generation sources, while the application of biochar may inhibit the generation processes of these GHGs in soil. The aromatic carbon structure and agglomerates formed with soil particles are the main mechanisms underlying the long-term stability of biochar. The combined benefits of soil amendment, carbon sequestration, and GHG emission reduction simultaneously provided by biochar are the key to achieving a carbon-neutral application. Incorporating biochar into the carbon trading market can be a helpful way to facilitate the practice of biochar application in soil.

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