Effect of Biochar on the Stability of Soil Organic Carbon in the Context of Global Warming

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Abstract. Since the industrial revolution, the mean global temperature has increased by more than 0.6°C, and this has led to serious ecoenvironmental problems, such as melting ice sheets, retreating glaciers, species extinction and extreme weather-climate events, which have substantially affected human social life. The issue of how to reduce global warming has become a worldwide concern. Soil is one of the primary carbon emission sources, and maintaining the stability of soil organic carbon (SOC) plays a crucial part in reducing soil carbon emission. Soil-biochar has great potential as a natural carbon sequestration solution. Biochar produces positive/negative stimulation effects on soil organic carbon when applied to soil. In this review, the direct and indirect effects of biochar on the soil environment are described, with a focus on priming effects and influencing factors of biochar. In terms of direct effects, biochar and its surface dissolved organic carbon can directly replenish the organic carbon source required by the soil carbon cycle. In terms of indirect effects, biochar can influence SOC mineralization by affecting the species, number, and activity of microorganisms in soil. Soil properties, vegetation type, biochar raw material, and pyrolysis temperature as well as their aging effects are the key factors affecting soil-biochar carbon sequestration. This review will contribute to the understanding of the contribution of biochar to the reduction of soil emissions.

Keywords: Soil organic carbon, Biochar, Microorganisms, Carbon sequestration, Priming effects.

1. Introduction

Human civilization has developed rapidly since the Industrial Revolution. However, this has also resulted in global warming and its associated environmental and ecological problems, such as melting ice sheets, retreating glaciers, species extinction, and extreme weather-climate events, which have had a huge impact on human social life [1]. Global warming usually refers to the increase in the temperature of the global atmosphere and oceans over a certain period due to the greenhouse effect. According to the Intergovernmental Panel on Climate Change (IPCC) report data, the mean global temperature has increased by 0.6°C ± 0.2°C since the mid-19th century. Because global warming is an established fact, determining how to limit further global warming has become a common global concern.

IPCC AR5 points that human activities (>95% probability) are the core factor triggering > 50% of the mean surface temperature increase since 1950s, mainly due to the following three aspects: (1) humans emit large amounts of CO_2 gas when using large amount of fossil fuels; (2) humans emit large amounts of greenhouse gases such as CH_4, CO_2, and N_2O in agricultural and industrial activities; and (3) human land use behaviors, including urbanization, vegetation destruction, and deforestation, exacerbate global warming. Among them, soil emits about 76 GtC of CO_2 into the atmosphere each year, which is 16 times more than emissions from fossil fuel combustion. Therefore, soil carbon emission is one of the main carbon emission sources [2], and maintaining the stability of soil organic carbon (SOC) is crucial in supporting the reduction of soil carbon emission. In terms of soil carbon reduction technologies, soil-biochar carbon sequestration is a highly promising natural carbon sequestration solution. Biochar was first discovered in the black soils of the Amazon rainforest basin in Latin America and has been present for thousands of years [3]. Biochar usually refers to a highly aromatic solid carbon-rich material produced by pyrolysis (including high-temperature pyrolysis, hydrothermal synthesis, and microwave charring) under strict oxygen limitation conditions [4]. The raw materials are mostly lignocellulosic materials, such as wood, straw, and traditional Chinese herb residue. As a carbon-rich material, biochar has high stability, and some carbon components can be stably stored in soil for a long time after biochar application [5]. Biochar has a complex aromatic structure, and a large amount of organic matter will remain on its surface during the pyrolysis process. Biochar also forms a rich porous structure and contains abundant trace elements during the pyrolysis process. As these special physicochemical properties, biochar applied to soil can affect the stability of SOC mainly through priming effects [6]. The priming effect can be positive, i.e., accelerating the decomposition of SOC, or negative, i.e., inhibiting the decomposition of SOC. When applied to soil, biochar can regulate the physicochemical properties of the soil, increase fertilizer and yield, etc., and biochar can also directly replenish the organic carbon source needed for the soil carbon cycle [7]. Moreover, biochar can indirectly affect the decomposition and solidification of SOC by influencing the type, quantity, and activity of microorganisms in soil after application [8]. Therefore, biochar applied to soil can affect the stability of SOC in a multidimensional manner. In addition, soil-biochar carbon sequestration is influenced by multiple factors, including environmental and controlling factors. Among them, environmental factors include the effects of soil type and vegetation type, while controlling factors include biochar feedstock, pyrolysis temperature, and aging effects. The effect of biochar applied into soil is often the result of a combination of factors.

Therefore, biochar, a carbon-rich material, plays a crucial part in the stability of SOC. Clarifying the mechanism and factors affecting the effect of biochar on SOC will aid in in-depth research on soil-biochar carbon sequestration. Therefore, in this review, the mechanism of biochar carbon sequestration in terms of both direct and indirect effects is described. The effects of biochar carbon sequestration in terms of soil type, vegetation type, biochar feedstock, and biochar pyrolysis temperature as well as aging effects to gain a deeper understanding of soil-biochar carbon sequestration are also presented.

2. Mechanism of Biochar Carbon Sequestration

Soil-biochar carbon sequestration refers to the difference value between the greenhouse gas emission flux from soil after biochar applied to soil and the greenhouse gas emission flux from soil without biochar application. To examine the effect of soil-biochar system on SOC stability, it is necessary to consider the physicochemical properties of biochar and their effects on soil properties, i.e., to examine both direct effect and indirect effect. The interaction between soil and biochar is shown in Figure 1.

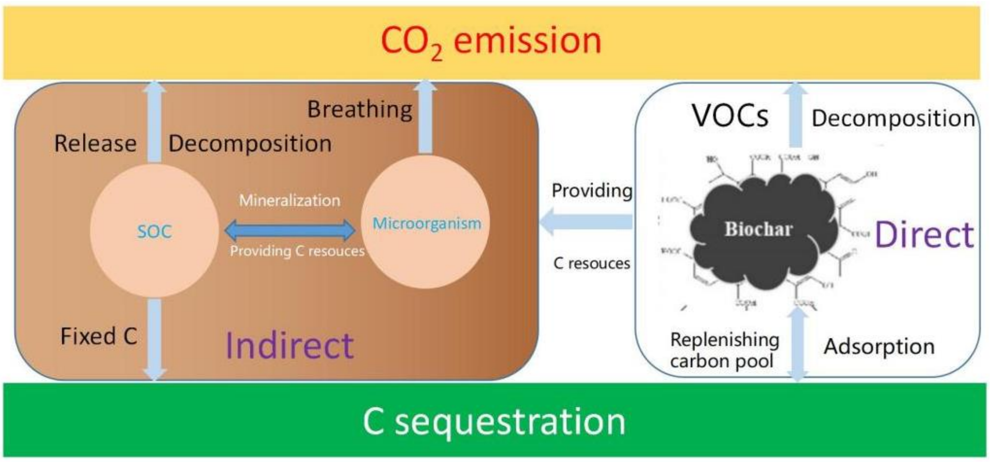

Figure 1. Interaction between biochar and soil

2.1. Direct Effects

Biochar forms a complex aromatic structure during its preparation process, and a large amount of dissolved organic carbon (DOC) and some volatile organic compounds (VOCs) remain on its surface. When the biochar product is applied to the soil environment, it has a complex interfacial reaction with multiphase bodies in the soil. The solid, liquid, and gaseous materials in soil and DOC on biochar surface undergo mutual migration and diffusion and mutual adsorption, and these interactions are important for carbon sequestration by biochar. When the biochar product is applied to the soil environment, a series of physicochemical effects occur: (1) the stable components in biochar greatly enrich the SOC pool and exist stably in the soil environment for a long incubation, thus increasing and enriching the soil carbon pool. (2) the DOC on the surface of biochar can also increase the SOC pool after being released into the soil. (3) the interaction between biochar and SOC mainly occurs through adsorption and its surface material can combine with SOC through hydrogen bonding, π–π interaction, electrostatic interaction, covalent bonding, and other adsorption methods, which reduce the migration of SOC, thereby avoiding the decomposition of SOC by microorganisms in soil and increasing the stability of SOC [9]. (4) biochar can also directly adsorb greenhouse gases, reducing the greenhouse gases from soil emission into the atmosphere.

2.2. Indirect Effects

Microorganisms are an important part of the soil and can perform oxidation, nitrification, ammonification, nitrogen fixation, and sulfation reactions in the soil to promote SOC decomposition and nutrient conversion. After biochar is applied to the soil, it can affect the stability of SOC by affecting the types, numbers, and physiological activities of microorganisms in the soil, mainly in the following ways: (1) Biochar usually contains some toxic substances and free radicals, which have toxic effects on some microorganisms and thus inhibit their physiological activities. This reduces the utilization of SOC by microorganisms, thus achieving the effect of emission reduction and carbon sequestration [10]. (2) Biochar can provide a suitable growth environment for some microorganisms to promote SOC mineralization, which in turn affects SOC stability. SOC mineralization is the process by which microorganisms in the soil maintain their own metabolic processes and use their decomposition products by breaking down reactive organic carbon in the soil, which can effectively reflect the stability of organic carbon. The degree of SOC mineralization is related to its stability and bioavailability as well as microbial activity in the soil. First, certain specific active substances contained in biochar can be used by soil microorganisms to promote SOC mineralization through co-metabolism [11]. This process is more prominent at the beginning of biochar applied to the soil. Second, biochar often has abundant chemical functional groups on its surface, and its chemical components are mainly C, N, H, O, N, K, P, Mg, Ca, etc., which effectively improve soil physicochemical properties, such as pH, moisture content, and temperature and can promote the growth and reproduction of soil microorganisms and accelerate SOC mineralization after biochar application [12]. Finally, biochar provides a good habitat for soi; microorganisms and promotes SOC mineralization due to its porous structure [13]. (3) Biochar increases the soil aeration. When biochar is applied into the soil environment, the act of application itself and adsorption by biochar pore structure introduces a large amount of oxygen gas, thus inhibiting microbial anaerobic processes and reducing CH_4 emissions to emission reduction and achieve carbon sequestration [14]. (4) Biochar can adsorb and fix the nutrients required by soil microorganisms and utilize the steric hindrance effect formed by the organic–mineral complex, thereby reducing the availability of nutrients by microorganisms and inhibiting the growth and metabolism of microorganisms [15]. However, because both soil and biochar are complex aggregations of materials and indirect effects do not result from a single mechanism, the effects of biochar on SOC stability after being applied to soil result from a combination through one or several mechanisms.

3. Factors Affecting Soil-Biochar Carbon Sequestration

Because both biochar and soil have complex physicochemical properties, many factors affect soil-biochar carbon sequestration (Figure 2). Specifically, they can be divided into environmental factors and controlling factors. Among environmental factors, soil type, vegetation type, and microorganisms play a leading role; among controlling factors, biochar feedstock, pyrolysis temperature, and aging are key factors.

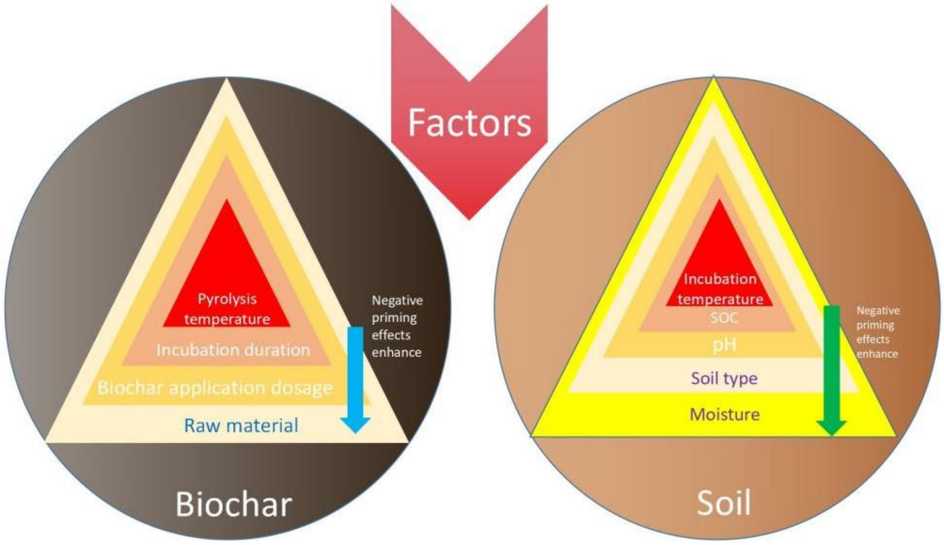

Figure 2. Effect factors of SOC stability in soil-biochar system

3.1. Environmental Factors

The effect of biochar applied into soil the environment on SOC is the combination of a complex series of chemical reactions and biological activities. When environmental factors change, the effect of biochar on SOC also varies. Different soil types and cultivated vegetation affect soil properties and the types, numbers, and physiological activities of microorganisms, etc.

3.1.1. Effect of Soil Type

Different soil types lead to different physicochemical properties. According to soil classification standards, common soils can be divided into three types: sandy, clayey, and loamy, and these three soil types mainly differ based on pH, SOC content, texture, moisture content and temperature [16]. In the soils with low SOC content, biochar is applied to provide soil microorganisms with the necessary substances to enhance SOC mineralization, while the organic matter adsorbed on the biochar surface can limit the dissolution and oxidation of biochar by enzymes, bacteria, and other substances [17]. pH is an important soil property. Soil pH can affect the number, types, and biological activity of microorganisms, which in turn affects the SOC stability. In general, the biological activity of microorganisms is usually lower in soils with lower pH, which in turn hinders the SOC mineralization [18]. Because biochar is an alkaline material, it increases soil pH when applied into soil, which in turn effectively enhances the biological activity of microorganisms and promotes SOC mineralization. Regarding soil texture, the application of biochar into soils with high clay content produces a strong negative priming effect, which in turn reduces the SOC mineralization rate, whereas the application of biochar to sandy soils with low clay content produces a positive priming effect. This is because clay minerals can form stable soil aggregates by interacting with biochar and SOC, which protects SOC from decomposition [19]. Soil moisture content is also one of the important influencing factors. Soil moisture content can obviously affect the physicochemical characteristics of biochar. Biochar in unsaturated condition is more susceptible to mineralization than in saturated wet conditions. Therefore, when biochar is applied into the soil environment, soils with higher moisture content tend to produce a stronger negative priming effect. Soil temperature is another key factor. After biochar is applied into the soil environment, soil temperature also has a significant effect on the physicochemical characteristics of biochar. The higher the soil temperature is, the stronger the negative priming effect triggered by biochar will be [6]. This is because high temperature facilitates the migration of SOC molecules in the soil, thus making it extremely easy for SOC molecules to enter the micropores of biochar and reducing the probability of usage by soil microorganisms. While, some published researches have reported that the positive priming effect triggered by biochar increases gradually with increasing soil temperature [20].

3.1.2. Effects of Vegetation

Vegetation refers to the sum of plants in an area and is the product of vegetation cover and distribution patterns. Plants can influence soil properties by importing chemical compositions and organic matter, influencing hydrologic processes and surface soil temperatures, and providing habitat or resources for organisms. Common vegetation types include forest, grassland, farmland, tundra, etc. In areas covered by forest vegetation, there is usually a spatially structured plant distribution with more deciduous leaves and poor direct sunlight, more animal species and activities, less human intervention, and adequate rainfall. Therefore, soils covered by forests usually have the following properties: higher moisture content, lower topsoil density, high organic matter content, and high variety and number of microorganisms. In grasslands, nomadic activities are often dominant, plant types are homogeneous, mostly herbaceous, with almost no tall plants, and rainfall is usually low. Therefore, soils covered by grassland vegetation tend to be predominantly sandy and loamy, have less organic matter than forest soils, usually have a lower moisture content, and are richer in microbial types and counts. Farmland vegetation is highly influenced by seasons and human activities, and soil properties vary greatly by region. Hence, vegetation types can affect soil's natural environment and basic properties, which in turn influences the effects of biochar on SOC stability.

3.2. Controlling Factors

3.2.1. Effect of Physicochemical Properties of Biochar

The physicochemical characteristics of biochar play a crucial part in SOC stability and are influenced by raw material, pyrolysis temperature, and soil environment, etc. The priming effect of biochar applied into soil is related to its carbon concentration and aromatization degree, and different raw materials and pyrolysis temperatures produce biochar with different carbon concentration and aromatization degree [21]. Usually, 550°C–650°C is a suitable temperature for biochar preparation. Biochar produced at lower pyrolysis temperatures tend to have higher yields and hydrophobicity and are thus more likely to trigger a positive priming effect; as the pyrolysis temperature increases, the positive priming effect decreases [22]. The physicochemical characteristics of biochar prepared from various raw materials often vary remarkably. Biochar prepared from raw materials with higher lignin content tends to have fewer polar groups and ash and higher carbon content, thus producing a stronger negative priming effect; when the cellulose component of the raw materials is higher, biochar products tend to have higher ash content (higher K^+ and Mg^{2+} content) and lower carbon content, thus producing a stronger positive priming effect [23]. Using the same raw materials at the same pyrolysis temperature, the carbon concentration of biochar and degree of aromatization increase with the increase in pyrolysis time, thereby resulting in an increase in the negative priming effect. In addition, the application dosage of biochar is an important factor. With a reasonable range of biochar application dosage (1*w*%–5*w*%), the negative priming effect produced by it gradually increases, the intensity of SOC mineralization decreases, and the carbon sequestration effect increases as the application dosage increases.

3.2.2. Effect of Aging

At the initial stage of biochar applied into the soil, about 3*w*% of the unstable fraction of biochar is rapidly released into the air through physicochemical erosion and microbial assimilation. As incubation duration increases, the aging effect of biochar gradually increases. Because biochar lasts a long time in natural soil, its separation from soil is difficult when aging occurs. Therefore, at present, a lot of published researches on biochar aging are account of laboratory simulation, and the main simulation aging methods can be divided into physical, chemical, and biological methods, including temperature-controlled aging, humidity-controlled aging, oxidant aging, biological aging, and environmental media aging. To simulate the real natural environment, various aging methods are generally used in combination. Therefore, after aging, the physicochemical characteristics of biochar changes significantly, including electrical conductivity, pH, specific surface area (SSA), elemental composition, cation exchange capacity, mineral composition, surface morphology, and oxygencontaining functional groups. During aging process, leaching of soluble salt ions (Na^+, K^+, Ca^{2+}, and Mg^{2+}) is a key process. In terms of elemental concentration, elemental C concentration gradually decreases and elemental O concentration gradually increases. On the biochar surface, the concentrations of carboxyl and hydroxyl groups increase. In terms of microstructure, the porous structure of biochar collapses, leading to a decrease in SSA [5]. Factors affecting the aging of biochar include oxygen content, moisture content, soil temperature, pH, and type and the number, types, and biological activity of microorganisms. Therefore, the priming effect on soil gradually changes from positive to negative as the aging of biochar continues to increase under general conditions.

4. Soil-Biochar Carbon Sequestration Result

4.1. Short-Term Result

Short-term effects generally refer to the priming effects caused by biochar last for less than one year. The effect of biochar on SOC mineralization did not show a significant linear relationship with the biochar application dosage, and the summaries of short-term results are listed in **Table 1**. Orlova et al. [24] prepared woody biochar at 550°C using birch and aspen wood as the raw materials; three types of Podzol Antric soils with different SOC concentrations (1.3*w*%, 1.5*w*%, and 2.5*w*%) were selected; the biochar application dosage was 0*w*%–1*w*%; and a 90-day incubation test was carried out. The results showed that there was almost no effect on the SOC mineralization when biochar application dosage was 0.1*w*% level; when biochar application dosage was 1*w*%, the SOC mineralization increased by 15%–18%. The higher the SOC concentration in the soil, the more significant the mineralization effect. Zhang et al. [25] carried out a meta-analysis of 129 researches to quantify the effects of biochar physicochemical properties on the emissions of soil greenhouse gas. The results showed that CO_2 emissions from soil were reduced by 36% when biochar application dosage exceeded 80 t/hm^2. In terms of soil types, the effect of biochar on the SOC mineralization was highly significant for different soil types. El-Naggar et al. [26] conducted a 90-day study on sandy loam soil (59.72% sand content) and sandy soil (94% sand content) added with 30 t/ha biochar, and CO_2 emissions were measured periodically. The results showed that biochar applied into soil elevated SOC concentration and had a positive priming effect. CO_2 emissions from sandy loam soils increased by 2–4 times compared with that from sandy soils. Fang et al. [16] selected surface soil (0–15 cm) in four different areas, namely, entisol, inceptisol, vertisol, and oxisol, and the biochar application dosage prepared by *Eucalyptus salinga* Sm. trees was 2*w*%. They conducted a 365-day study with CO_2 emissions selected as the detection. The results demonstrated that the interactions between biochar and mineral and the unique chemical recalcitrance of biochar were crucial factors in determining the long-term carbon sequestration potential of biochar in soils; in particular, they had a positive priming effect on SOC in the inceptisols and promoted CO_2 emission. In terms of vegetation types, differences in vegetation can indirectly affect soil properties. Pokharel et al. [27] used pine wood chips as raw material, and biochar was prepared at low temperature (300°C) and high temperature (550°C) and applied into forest soil and grassland soil at 1.5*w*% and incubated in the laboratory for 100 days. The results revealed that biochar produced at 550°C without steam activation (BC550) significantly reduced CO_2 emissions (by 16.4%) in forest soil but not in grassland soil; the application of biochar had no significant effect on CH_4; BC550 and biochar produced at 550°C with steam activation (BC550-S) reduced N_2O cumulative emissions from forest soils by 27.5% and 31.5%, respectively, and from grassland soils by 14.8% and 11.7%, respectively. Biochar prepared at low temperature did not have a significant effect on cumulative soil CO_2 and N_2O emissions. The effects of the pyrolysis temperature and raw material type of biochar on the SOC mineralization were also significant. Liu et al. [28] obtained biochar with different physicochemical properties using rice husk, pecan shell, and bamboo as raw materials, which were pyrolyzed at 550°C for 1.5 h. Among these three types of biochar products, bamboo biochar had the highest C concentration (up to 68%), whereas rice husk biochar had only 30.9% C concentration. The pH of rice husk biochar was weakly alkaline, whereas that of pecan shell and bamboo biochar ranged 8.5–9.0. The SSA of rice husk biochar was

10 times higher than that of pecan shell and bamboo biochar. These three types of biochar had an obvious negative priming effect on SOC after 15 days of application into the soil, which increased as application duration increased. Bamboo biochar and rice husk biochar had a more significant negative priming effect than pecan shell biochar. Ouyang et al. [29] selected fresh dairy manure and pine woodchip as raw materials and obtained the biochar via pyrolysis at 300-700°C (200°C interval) for 1 h. These two types of biochar exhibited significant differences in physicochemical properties. In the first 80 days after application into soil, biochar enhanced soil enzyme activity and promoted SOC mineralization; in the long term, biochar promoted SOC sequestration, and the higher the pyrolysis temperature, the more significant was the effect.

4.2. Long-Term Results

The priming effects caused by biochar last for more than one year is referred to as long-term effects. During long-term incubation, biochar undergoes aging in soil, leading to significant changes in its physicochemical properties and thus causing changes in the SOC priming effect of biochar. In existing studies (Table 1), the long-term effects are mainly dominated by negative priming effect. Bai et al. [30] prepared two types of biochar using rice straw and wheat straw as raw materials at pyrolysis temperatures of 500°C–600°C and applied these two types of biochar into a large field for a 6-year study. The results showed that biochar applied into soil increased the efficiency of fungal decomposition of biosolids in soil and reduced the number of pathogenic fungi and fungal CO_2 emissions. Fang et al. [6] conducted a 2-year observational study using wood biochar prepared by *Eucalyptus saligna* with four types of soils, with CO_2 emissions as an observation indicator. In the first few months of the experiment, biochar could produce a positive priming effect of SOC in the inceptisol, while it changed to a negative priming effect with increasing time in entisol, oxisol, and vertisol; incubation temperature was the key factor affecting the aging biochar, and the negative priming effect was more significant in the biochar under high temperature aging. Kubaczynski et al. [31] prepared woody biochar at lower temperatures (350°C–400°C), with Haplic Luvisol soil and a biochar application dosage of 0–30 Mg/ha, and the following conclusions were drawn from 5 years of experimental observations. The addition of fresh biochar increased redox potential (Eh), soil pH, DOC concentration, and SOC concentration. When biochar was aged, it inhibited the emission of CH_4 from soil, but the inhibition was lower than that by fresh biochar. Fresh biochar increased CO_2 emissions from soil, which was not observed after 5 years of aging. Although there are some studies on the long-term carbon sequestration effects of biochar, most of them are based on laboratory experiments and lack a large scale of field trial data to support them.

Table 1. Soil-biochar carbon sequestration result

Biochar type	Physicochemical properties of biochar	Soil type/biochar application dosage	Results	Ref.
Silvergrass biochar	Pyrolysis temperature: 600℃; pH: 10.23; C concentration: 92.26%; moisture: 1.34%	Soil type: Sandy loam soil(sandy: 59.72%), Sandy soil(sandy: 94%); biochar application dosage: 30 t/ha	After biochar applied into soil, the SOC concentration increased, especially for sandy soil.	[26]
Paddy straw biochar	Pyrolysis temperature: 500℃; pH: 10.50; C concentration: 86.28%; moisture: 2.07%			
Umbrella tree biochar	Pyrolysis temperature: 500℃; pH: 9.50; C concentration: 89.31%; moisture: 1.46%			
Maize stover biochar	Pyrolysis temperature: 400℃; pH: 10.7; CEC: 63.5 cmol/kg; C concentration: 66%	Sandy loam, biochar application dosage: 20Mg/ha	SOC mineralization: the degree of SOC mineralization of 0-137 days was similar to the control group,	[32]

			that from 137 to 365 is lower than the control group.	
Pearl millet stalk biochar	Pyrolysis temperature: 400℃; pH: 10.6; CEC: 57.6 cmol/kg; C concentration: 64%		SOC mineralization: the degree of SOC mineralization of 0-270 days was higher to the control group, that from 270 to 365 is lower than the controlling group.	
Rice straw biochar	Pyrolysis temperature: 400℃; pH: 8.6; CEC: 97.3 cmol/kg; C concentration: 60%		SOC mineralization: the degree of SOC mineralization during the whole process is higher than the control group	
Wheat straw biochar	Pyrolysis temperature: 400℃; pH: 8.76; CEC: 10.9 cmol/kg; C concentration: 64%		SOC mineralization: the degree of SOC mineralization of 0-270 days was higher to the control group, that from 270 to 365 is lower than the controlling group.	
Birch and aspen wood biochar	Pyrolysis temperature: 550℃; pH: 7; C/N: 273; C concentration: 79.2%; moisture: 1.92%	Podzol Antric soils: low SOC, C concentration: 1.3%, pH=5.3; biochar application dosage: 0-1.0*w*%	A 90-day test: 0.1*w*% of biochar application dosage could not affect the SOC mineralization, while 1.0*w*% of biochar application dosage could improve 15%-18%.	[24]
		Podzol Antric soils: medium SOC, C concentration: 1.5%, pH=5.7; biochar application dosage: 0-1.0w%	● Low SOC soil: no change compared with the control group ● Medium SOC soil: the degree of HA 1 mineralization increased by 16%, and the degree of HA 2 mineralization was no change.	
		Podzol Antric soils: high SOC, C concentration: 2.5%, pH=6.0; biochar application dosage: 0-1.0w%	● High SOC soil: biochar could enhance the mineralization of some components in SOC, the HN mineralization is the most significant (> 20%), and the HA 1 concentration decreased 14%-18% faster than control group.	
Rice straw biochar	Pyrolysis temperature: 500℃; pH: 9.89; C concentration: 42.2%; ash: 39.2%	Soil: SOC concentration 13.8 g/kg	● The decreased bioactivity of β-glycosidase enzymes is the main reason for the reduced SOC mineralization by biochar ● A 60-day CO_2 emission of control group: 399 mg CO_2-C/kg ● A 60-day CO_2 emission of rape straw biochar: 388 mg CO_2-C/kg ● A 60-day CO_2 emission of rice straw biochar: 374 mg CO_2-C/kg ● A 60-day CO_2 emission of corn straw biochar: 355 mg CO_2-C/kg ● A 60-day CO_2 emission of wheat straw biochar: 288 mg CO_2-C/kg	[33]
Wheat straw biochar	Pyrolysis temperature: 500℃; pH: 9.40; C concentration: 57%; ash: 26%			
Corn straw biochar	Pyrolysis temperature: 500℃; pH: 9.64; C concentration: 57.5%; ash: 19.2%			
Rape straw biochar	Pyrolysis temperature: 500℃; pH: 9.63; C concentration: 64.5%; ash: 14%			
Wheat straw biochar	Pyrolysis temperature: 300/700℃; pH: 7.57/9.59; C concentration: 49.75/59.65%	Loamy sand soil: C concentration 0.33%; pH=7.49; 57.2% sand, 18.2% clay	● Biochar prepared at low temperature released DOM into soil to replenish soil carbon pool ● Biochar prepared at high temperature reduced DOM	[34]

Cow manure biochar	Pyrolysis temperature: 300/700℃; pH: 7.80/10.02; C concentration: 53.81/56.76%		concentration via adsorption.	
Eucalyptus salinga Sm. trees biochar	Pyrolysis temperature: 450℃; pH: 8.64; C concentration: 67.4%	0-15 cm surface soil: inceptisol, entisol, oxisol, vertisol; biochar application dosage: 2%	Long-term C sequestration potential of biochar: the the chemical recalcitrance in biochar and interactions between biochar and mineral.	[16]
	Pyrolysis temperature: 550℃; pH: 9.96; C concentration: 73.19%			
Dairy manure biochar	Pyrolysis temperature: 300/500/700℃; pH: 7.46/9.28/9.70; C concentration: 39/19/28%	Loamy soil: 40% sand, 25% clay; C concentration: 1.07%; biochar application dosage: 5w%	● 0-80 days: biochar could improve the enzyme activity in soil to promote SOC mineralization ● Long-term: biochar could promote SOC sequestration, and the higher prepared temperature, the more obvious effect.	[29]
Woodchip biochar	Pyrolysis temperature: 300/500/700℃; pH: 7.16/7.96/10.1; C concentration: 51/43/31%			
Douglas fir biochar	Pyrolysis temperature: 900℃; pH: 10.6; C concentration: 90%; moisture: 4.8%	0-20cmWalla Walla silt loam soil: 70% silt, 12% fine; C concentration: 0.64%; biochar application dosage: 0/11.2/22.4/44.8 Mg/ha	Biochar could increase DOM concentration in soil, and the suitable biochar application dosage was less than 22.4 Mg/ha.	[35]
Maize cob biochar	Pyrolysis temperature: 350℃; pH: 7.3; C concentration: 81.9%	Sandy loam soil: 39% sand, 29% silt, 31% clay; biochar application dosage: 1%	Biochar had a negative priming effect on SOC in short term.	[36]
Rice husk biochar	Pyrolysis temperature: 550℃; pH: 7.34; C concentration: 30.9%; moisture: 8.49%	Loamy soil: pH=6.54, SOC concentration: 6.25 g/kg; biochar application dosage: 0/1/2/5%	● After 15 days, biochar had a negative priming effect on SOC, and it enhanced with incubation time increased. ● Negative priming effects: bamboo biochar>rice husk biochar>pecan shell biochar. ● Suitable biochar application dosage was 5%.	[28]
Pecan shell biochar	Pyrolysis temperature: 550℃; pH: 8.82; C concentration: 59.8%; moisture: 10.5%			
Bamboo biochar	Pyrolysis temperature: 550℃; pH: 8.52; C concentration: 68%; moisture: 9%			
Rice straw biochar	Pyrolysis temperature: 500-600℃	Surface soil; pH=8-9; 0-20 cm surface soil with high concentration of SOC, 20-40 cm deep soil with low concentration of SOC	After biochar applied into soil, SOC concentration increased by 64%. Macroaggregates increased while microaggregates decreased. The abundance of fungal colonies decreased.	[30]
Wheat straw biochar	Pyrolysis temperature: 500-600℃			
Eucalyptus saligna Sm. Wood biochar	Pyrolysis temperature: 450/550℃; pH: 8.64/9.96; C concentration: 67/73%	Vertisol soil: 0-10 cm, 53% clay, pH=8.1, SOC concentration 0.45%; biochar application dosage: 0/2w%	● Low LOM concentration: positive priming effect ● High LOM concentration: negative priming effect	[37]

Maize biochar	Pyrolysis temperature: 450-500℃; pH: 10.3; C concentration: 78.5%	0-20 cm surface sandy loam, SOCconcentration 1.7%; biochar application dosage: 5 Mg/ha	● Biochar-C could contribute the low diet of most microbial groups. ● Under extreme soil dryness, two gram-negative bacterial groups increased biochar-C uptake. ● After biochar addition, the degree of SOM mineralization decrease, and it could promote the potential of C sequestration.	[38]

5. Conclusion

In the context of global warming, soil, one of the main carbon emission sources, plays an crucial part in reducing carbon emissions. Soil-biochar system can be highly promising strategies. Biochar applied into soil can affect the SOC stability in multiple ways. This review briefly described the mechanisms, influencing factors, and effects of biochar on SOC stability to clarify the soil-biochar carbon sequestration pathway. In the context of global warming, although biochar is crucial in soil carbon sequestration and emission reduction, some gaps remain to be addressed in existing studies. Future research should focus on the following tasks:

(1) Conduct studies on the microscopic mechanism of biochar-soil carbon sequestration. To date, most studies on biochar's contribution to soil carbon sequestration have focused only on macroscopic data monitoring and analysis; thus, detailed microscopic mechanisms of action remain unclear. Clarifying the microscopic mechanism will further enhance the efficiency of biochar-soil carbon sequestration and increase its contribution to the reduction of global warming.

(2) Strengthen the development of long-term and large scale of field biochar aging experimental studies. Because there are multiple regional climatic conditions in nature, long-term large scale of field biochar aging experimental studies should be conducted in different geographical locations, including different soil types, vegetation types, and environmental conditions, to examine the long-term effects and mechanisms of biochar on soil carbon sequestration.

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