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Citation for published version:
Lyu, H, Zhang, H, Chu, M, Zhang, C, Tang, J, Chang, SX, Masek, O & Ok, YS 2022, 'Biochar affects greenhouse gas emissions in various environments: A Critical Review', *Land Degradation and Development*. https://doi.org/10.1002/ldr.4405

Digital Object Identifier (DOI):
10.1002/ldr.4405

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Land Degradation and Development

Biochar affects greenhouse gas emissions in various environments: A critical review

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ACKNOWLEDGEMENTS

This work was partially supported by (1) the National Natural Science Foundation of China [42177218, 41877372, U18062162], (2) the National Key R&D Program of China [2018YFC1802002], (3) Hebei Outstanding Youth Science Foundation [D2019202453], (4) China Postdoctoral Science Foundation [2019M660967], and (5) the 111 Program, Ministry of Education, China [T2017002]. This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1A2C2011734), Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2021R1A6A1A10045235), and OJEong Resilience Institute, Korea University, Republic of Korea.

Abstract

Biochar application to the soil is a novel approach to carbon sequestration. Biochar application affects the emission of greenhouse gases (GHGs), such as CO_2, CH_4, and N_2O, from different environments (e.g. upland soils, rice paddies and wetlands, and composting environments). In this review, the effect of biochar on GHGs emissions from the above three typical environments are critically evaluated based on a literature analysis. First, the properties of biochar and engineered biochar related to GHGs emissions was reviewed, targeting its relationship with climate change mitigation. Then, a meta-analysis was conducted to assess the effect of biochar on the emissions of CO_2, CH_4, and N_2O in different environments, and the relevant mechanisms. Several parameters were identified as the main influencing factors in the meta-analysis, including the pH of the biochar, feedstock type, pyrolysis temperature, biochar application rate, C/N ratio of the biochar, and experimental scale. An overall suppression effect among different environments was found, in the following order for different greenhouse gases: $N_2O > CH_4 > CO_2$. We conclude that biochar can change the physicochemical properties of soil and compost in different environments, which further shapes the microbial community in a specific environment. Biochar addition affects CO_2 emissions by influencing oligotrophic and copiotrophic bacteria; CH_4 emissions by regulating the abundance of functional genes, such as *mcrA* (a methanogen) and *pmoA* (a methanotroph); and N_2O emissions by controlling N-cycling functional genes, including *amoA, nirS, nirK, nosZ*. Finally, future research directions for mitigating greenhouse gas emissions through biochar application are suggested.

KEYWORDS

Biochar, Black carbon, Pyrolysis, Gasification, UN Sustainable Development Goals

1. Introduction

Climate change has accelerated with industrial development and the need to address this challenge is widely accepted by society and policymakers. Several pathways to zero carbon (C), or even a negative-C future, have been charted; however, achieving these goals is an enormous task, requiring multilateral efforts and different approaches, including emission reductions, CO_2 capture, and atmospheric greenhouse gas (GHG) removal. Among the six major GHGs listed in the Climate Change Control Inventory, CO_2, CH_4, and N_2O contribute the most to global climate change, with relative contributions of 60, 20, and 10%, respectively (Josep et al., 2019). The concentration of CO_2 in the atmosphere has increased from 280 ppm in the 1700s to over 400 ppm, reflecting a rapid increase in CO_2 emissions since the Industrial Revolution (Sriphirom et al., 2020). Various approaches aimed at mitigating or minimising climate change have been proposed to address the rising emissions of GHGs and their concentrations in the atmosphere (Song et al., 2019).

Carbon sequestration can directly decrease the emission of CO_2 into the atmosphere, and a new class of technologies, GHG removal technologies, have emerged to aid in reducing GHG concentrations in the atmosphere. Biochar is one piece of this puzzle as it has considerable global potential to sequester atmospheric C. The ability of biochar to sequester C from the atmosphere by plants has been the driving force behind its development. Biochar production itself can offset GHG emissions because it converts the organic C in the feedstock into stable C to prevent the degradation of biomass from releasing CO_2 and CH_4 into the atmosphere (Zhang & Ok, 2014). The application of biochar is supposed to be able to offset a maximum of 12% of current anthropogenic CO_2-C equivalent (CO_2-C_e) emissions (i.e., 1.8 Pg CO_2-C_e per year of the 15.4 Pg CO_2-C_e emitted annually; 1 Pg=1 Gt) (Woolf et al., 2010). As an important indicator of the effectiveness of C sequestration, the stability of biochar in different soils has been extensively studied (Lian & Xing, 2017), and it is now widely accepted that the stability of most of the C contained in biochar is of the order of hundreds or even thousands of years (Spokas & Reicosky, 2009).

Biochar is produced from different feedstocks and is widely used in various environmental processes. The main functions of biochar can be summarised as follows: (1) The production of biochar, combined with energy recovery, is a good method for managing agricultural waste and has been practised both in China and around the world (Lee et al., 2017). (2) Biochar is widely used as a soil conditioner to improve soil quality and crop yield (Pariyar et al., 2020) because its porous structure can improve soil quality by enhancing soil aeration, reducing soil hardening, and increasing soil cation exchange capacity (CEC). In addition, the nutrient content of biochar is important for plant growth and crop yields. (3) Biochar can be used for the remediation of soil and water contaminants (Xiao et al., 2020). In addition, engineered biochars have been developed to enhance biochar functions, such as adsorption, reduction, oxidation, and catalysation of specific pollutants (Lyu et al., 2020). Biochar has also been applied to increase the efficiency of waste treatment processes such as composting. (4) Biochar can be used for C sequestration and as an adsorbent for GHGs, such as CO_2, to mitigate climate change (Huang et al., 2015).

Biochar also plays an important role in mitigating climate change by regulating GHG emissions from the soil and different environmental processes. Biochar application can change soil properties and hence affect microbial biomass, community structure, and activity, resulting in changes in soil GHG emissions. As microbial communities in uplands are quite different from those in paddy soils and wetlands, the application of biochar will have a different effect on GHG emissions in these two environments. For example, CH_4 emissions from rice paddy fields are much higher than those from upland fields, and the emissions from a rice paddy in the monsoon season in Asia account for ~25–36% of global CH_4 emissions (Zhang et al., 2020b) because of extensive rice cultivation. It has been estimated that the application of biochar to paddy soils reduces seasonal CH_4 emissions by 40% (Sriphirom et al., 2020). Emissions of CO_2 are the main concern in upland agriculture, where biochar can reduce the net ecosystem CO_2 exchange in crop production by 144–283% (Azeem et al., 2019). Another GHG is N_2O, which has a much higher global warming potential and can be a key factor in both paddy and upland fields (Aamer et al., 2020). Although biochar generally reduces N_2O emissions from soil (Thangarajan et al., 2018), in some cases, it can enhance N_2O emissions from upland fields when water content increases (Troy et al., 2013). In addition to paddy and upland fields, biochar may also affect GHG emissions from industrial sites such as composting, anaerobic digestion, and bioremediation sites.

To date, several review papers have been published that focus on the effects of biochar on soil GHG emissions. These studies have summarised the effect of biochar on the properties and GHG emissions in the soils of a certain type of environment, such as forest soils (Li et al., 2018) or agricultural soils (Sri et al., 2021). However, no systematic review has compared the effects of biochar on GHG emissions from microbial processes in various environments (e.g. upland soils, rice paddies and wetlands, and composting environments), which is important for mitigating GHG emissions and promoting the application of biochar. In this study, we systematically evaluated the effects of biochar on GHG emissions in various environments (i.e. upland soils, rice paddies and wetlands, and composting environments) and the mechanisms involved. First, recent research and development on biochar production related to climate change mitigation are summarised. Second, the effects of biochar application on GHG emissions in upland fields, rice paddies and wetlands, compost systems, and the mechanisms involved (including the mechanisms that control GHG emissions based on the effects of biochar on soil physicochemical and microbial properties) are summarised.

2. Properties of pristine and engineered biochar relevant to climate change mitigation

2.1 Properties of biochar relevant to climate change mitigation

Biochars have been widely applied to soil improvement in various environments, including uplands, rice paddies, wetlands, and composting environments. When biochar is applied to the soil, its impact on soil physicochemical properties (e.g. porosity, water holding capacity, pH, and CEC) varies depending on biochar properties such as specific surface area, porosity, and functional groups (Sun et al., 2020). These changes caused by the different properties of biochar affect GHG emissions from the soil and other environmental processes.

Biochar feedstock is a key factor in determining biochar composition (Liu et al., 2019). In general, feedstock type affects the surface area, pH, and content of stable C in the biochars. For instance, owing to the higher content of lignin in wood biomass, biochar produced from wood typically has a higher surface area than that produced from grass and forms more organo-mineral layers to provide a nutrient shelter for microbes, thus improving microbial activities and changing soil GHG emissions (Hagemann et al., 2017). In contrast, biochars produced from feedstocks with higher cellulose and hemicellulose contents (e.g. sugarcane straw and rice husk) are characterised by higher pH values and nutrient concentrations (Higashikawa et al., 2016). For acidic paddy and wetland soils, the addition of alkaline biochar increases the soil pH (Sri et al., 2021). A higher soil pH is helpful for the growth of methanotrophs, resulting in decreased CH_4 emission from paddy soils (Dong et al., 2013). Applying biochar with high nutrient concentrations to the soil is conducive to increasing microbial nutrients and improving the activity of microorganisms. Moreover, a meta-analysis of 154 studies reported that biochars produced from biosolids had the best ability to retain nitrogen (N) in soils, followed by those produced from animal wastes. Compared with the biochars produced from animal wastes and biosolids, the woody and herbaceous biochars exhibited a better ability to mitigate N_2O emissions from soil (Li et al., 2019). There is abundant available N in animal waste and biosolid biochars, which may stimulate the growth of denitrifiers and contribute to N_2O emissions. Therefore, feedstock type should be considered an important factor affecting the properties of biochar when used for environmental applications and climate change mitigation. However, the results for biosolid-derived biochar are highly variable because of the diverse physicochemical properties of the feedstocks and the limited availability of studies on biosolid-derived biochar. Therefore, further research on the impact of biosolid-derived biochars on GHG emissions is needed to formulate comprehensive recommendations.

The pyrolysis temperature of biochar has been recognised as another important factor affecting its properties (Liu et al., 2019). As the pyrolysis temperature increases, the pH, electrical conductivity, ash content, and C stability of the biochar increase, whereas the yield of biochar decreases. Compared to biochars produced at medium (350-600 °C) and high temperatures (> 600 °C), biochars produced at low temperatures (≤ 350 °C) generally contain a higher organic nutrient content which increases the co-metabolic interaction between biochars and microorganisms, thus resulting in the enhancement of microbial biomass and activities, especially for bacteria and fungi (Zhang et al., 2018b). In addition, biochar produced at low temperatures (250-400 °C) stimulates C mineralisation, whereas biochar produced at high temperatures (525-650 °C) suppresses C mineralisation, ultimately decreasing CO_2 emissions (Wang et al., 2019b). However, high-temperature biochars may contain higher relative concentrations of toxic compounds (i.e. polycyclic aromatic hydrocarbons), affecting soil microbial biomass and activity (He et al., 2017). Simultaneously, the yield of high-temperature biochars was lower. Therefore, when choosing the biochar pyrolysis temperature, not only the impact of biochar on soil GHG emissions but also the cost savings of biochar production should be considered.

2.2 Properties of engineered biochar relevant to climate change mitigation

Biochar properties can also be affected by post-treatment biochar production, that is, the production of engineered biochars. The properties of engineered biochars vary depending on the modification technologies, including physical (e.g. ball milling and magnetisation) and chemical (e.g. acidification, alkalisation, oxidation, and impregnation) methods (Panahi et al., 2020). Biochar modification is often used to increase its surface area, pore volume, surface functional groups, and surface chemistry properties. Through modification, biochar has a highly porous structure, which can improve a range of soil physical properties such as porosity and pore size distribution. This may further improve soil aeration, thereby stimulating the decomposition of soil organic C and the activity of methanotrophs (Liu et al., 2019). The engineering of biochar through ball milling has recently attracted significant research interest. Compared to pristine biochars, N-engineered biochar prepared by milling a mixture of biochar, bentonite, pregelatinised maize flour, and urea presents better environmental performance and lowers GHG emission intensity (Puga et al., 2020).

Few studies have reported the application of engineered biochars, including Fe-, N-, and phosphorus (P)-engineered biochars, in soil improvement. The biochar-supported FeS composite (FeS/biochar) can not only immobilise Cr(VI) through fractional precipitation in soil, but can also increase soil organic matter content, microbial activity, and CO_2 emissions (Lyu et al., 2018). As conductive and semi-conductive materials, biochar and Fe may enhance direct interspecies electron transfer among soil microorganisms affecting GHG emissions (Liu et al., 2020). P-engineered biochars have improved stability owing to the formation of a P-containing compound that protects biochar C from oxidation (Guo & Chen, 2014). The co-pyrolysis of biomass with phosphate fertiliser could reduce C loss in soil. The role of minerals in biochar and their effects on biochar C stability are complex. Some inherent minerals in biochar can enhance the stability, whereas some extraneous minerals, such as Fe-bearing materials, reduce the stability of biochars. In contrast, inherent minerals can also reduce biochar C stability, whereas some extraneous minerals can enhance it (Buss et al., 2019). The incubation of biochar with soil minerals such as $FeCl_3$, $AlCl_3$, $CaCl_2$, and kaolinite could also increase the oxidation resistance of biochar (Yang et al., 2016). Clay types such as montmorillonite (MMT), red earth (RE), and bentonite have been used to synthesise engineered biochars as an efficient way to increase the stability of biochar in soil (Premarathna et al., 2019).

Therefore, it is important to develop new engineered biochars for better C sequestration and mitigation of GHG emissions. However, the relationship between stabilisation and GHG emissions remains an interesting topic for further research.

3. Effect of biochar on GHG emissions from various environments

The addition of biochar could be used as a low-cost and highly efficient technology that might contribute to both climate change mitigation and adaptation (improving or maintaining soil quality), ensuring that the yield of upland and paddy crops is improved or maintained despite the changing climate (Pradhan et al., 2018). Reduced nitrogen loss, increased microbial activity, shorter time until maturity, and significantly less odour is observed when biochar is used as a compost amendment (Guo et al., 2020b). As the physicochemical properties and microbial communities of upland soils, paddy and wetland soils, and compost are quite different, the application of biochar has different effects on GHG emissions in these three environments. **Tables 1 and 2** summarise recent studies on GHG emissions resulting from the addition of biochar to upland fields, paddy fields, and wetland soils. In the following sections, we discuss how biochar application affects the emissions of CO_2, CH_4, and N_2O in different environments. Moreover, a meta-analysis considering the interaction between these changes and GHG emissions is provided in **Figures 1a-3a**. Specifically, a literature search was conducted using Web of Science and Google Scholar databases from 1950 to 2021 using the keywords 'biochar' AND 'upland' OR 'paddy' OR 'composting' OR 'greenhouse gas' OR 'GHGs' OR 'CO_2' OR 'CH_4' OR 'N_2O' OR 'global warming potential (GWP)'. Since most of the related studies separately assessed the effects of biochar application on GHGs emissions, physicochemical properties of biochar, and soil microbial properties, only 81 observations from 24 peer-reviewed studies were collected (**listed in the supplemental material as Section 1**). These results were discussed to clarify the different effects of biochar on GHGs emissions from upland, paddy, and wetland soils and composting environments.

Several parameters were identified as the main influencing factors in the meta-analysis, including pH of biochar, feedstock, pyrolysis temperature of biochar, application rate, C/N ratio of biochar, and experimental scale. An overall suppression effect among different environments was found, in the following order for different GHGs: $N_2O > CH_4 > CO_2$. Moreover, the addition of biochar can cause changes in soil physicochemical properties (bulk density, soil water-holding capacity, soil cation exchange capacity, pH, etc.), which affect soil microbial properties, including microbial biomass, microbial activity, and microbial community structure, which are related to GHG emissions in various environments (Guo et al., 2020b). Herein, we summarise the microbial processes involved in the effects of biochar on GHGs emissions. The effects and mechanisms of biochar-mediated GHG emissions are summarised in **Figures 1b-3b**.

3.1 Effect of biochar on CO_2 emissions and its mechanism

As shown in **Figure 1a**, the meta-analysis results indicated that the overall reduction rate of CO_2 emissions intensity in the three different environmental processes of upland, rice paddies and wetlands, and composting was approximately 1%. However, the effect of biochar on the emission of CO_2 is quite different in the three different environments, showing an enhancing effect in uplands (a promotion rate of 9%, $P < 0.05$) and a suppression effect in paddy soil and composting processes (suppression rate of 10% and 2%, respectively, $P < 0.05$).

Specifically, as shown in **Figure 1a**, several parameters were identified in the meta-analysis as factors affecting CO_2 emissions in upland soil, including the pH of biochar, feedstock, pyrolysis temperature of biochar, application rate, and C/N ratio of biochar. Among them, the pH value and feedstocks showed a greater effect on increasing CO_2 emission intensity. That is, the addition of biochar promoted CO_2 emission intensity regardless of changes in pH and feedstocks of biochar (i.e. biochar pH and feedstock increased CO_2 emission intensity by 16% and 14%, respectively, $P < 0.05$). Moreover, the increase in soil CO_2 emission intensity was negatively correlated with biochar pyrolysis temperature, while positively correlated with biochar application rate and C/N. These results may be ascribed to the fact that lower pyrolysis temperature (500 °C) results in more microbial available C and nutrients in biochar than a higher pyrolysis temperature (> 500 °C), which promotes high soil microbial activities to decompose soil organic matter and release more CO_2 from soil. At the same time, high temperature biochars (> 500 °C) may contain higher relative concentrations of toxic compounds (i.e., polycyclic aromatic hydrocarbons), which affect soil microbial biomass and activity (He et al., 2017). Overall, in upland soils, enzymes and labile organic matter are adsorbed from the bulk soil to the biochar surface, which is more likely to cause significant microbial growth. In addition, the application of biochar to the soil directly affects the microbial community because of its unstable C components, which increase the apparent respiration rate of microorganisms and then increases soil CO_2 emissions (Irfan et al., 2019).

Unlike the trend in upland soils, the meta-analysis results showed that the addition of biochar usually decreases the cumulative CO_2 flux from paddy and wetland soils (**Figure 1a**).

For example, compared to untreated paddy soils (a field experiment), the biochar-amended soils exhibited reduced CO_2 emissions (from 68 962 to 55 422 kg CO_2-eq ha^{-1}) and increased rice yield (from 11.4 to 11.9 Mg ha^{-1}) (Wang et al., 2019b). Meta-analysis results suggested that biochar feedstock, application rate, and pyrolysis temperature could influence CO_2 emissions from rice paddies and wetlands. For example, biochar from wood (a suppression rate of 35%, $P < 0.05$) can induce a greater suppression effect on CO_2 emissions than rice straw (a suppression rate of 12%, $P < 0.05$), probably because of the higher surface area and graphitic structure of biochar from wood (Hagemann et al., 2017), which is conducive to the suppression of soil organic carbon mineralisation and the adsorption of soil CO_2 molecules by biochar (Yu et al., 2021). The effect of the pyrolysis temperature of biochar on CO_2 emissions in rice paddies and wetlands is quite different. Compared with higher (600-800 ℃) and lower temperature (< 400 °C) of biochars, which suppressed the CO_2 emissions intensity significantly, medium temperature biochars (450-600 °C) had less suppression effect on CO_2 emissions (a suppression rate of 4% for 550-600 °C, $P < 0.05$) and even greatly increased CO_2 emissions (a promotion rate of 45% for 450-500 °C, $P < 0.05$). This may be due because medium pyrolysis temperature of biochars contain moderate organic nutrient content, pore structure and surface area, and lower relative concentrations of toxic compounds, which increases the overall abundance and activities of microorganisms and promotes CO_2 emissions (Zhang et al., 2018a).

The meta-analysis results showed that the addition of biochar to solid organic compost can regulate and mitigate CO_2 emissions during composting (**Figure 1a**). The main influencing factors included pyrolysis temperature, raw materials, and initial C/N, all of which showed a low suppression effect on CO_2 emissions (suppression rate of 0.1%-3.7%, $P < 0.05$). The result of this suppression comes from a combination of several reasons. For example, He et al. (2019) studied the effects of biochar on GHG emissions during composting in laboratory-scale composting systems, and found that the application of bamboo biochar reduced CO_2 emissions arising from composting (He et al., 2019). This has been ascribed to the biochar-mediated protection of organic matter against chemical oxidation and biological degradation (Ngo et al., 2013). Moreover, the addition of biochar to composting promotes enzyme activities (e.g. dehydrogenase, protease, cellulase, amylase, and xylanase) and reduces CO_2 emissions by affecting the carbon and nitrogen cycle (Awasthi et al., 2020). However, other studies have reported the opposite effects of biochar addition, i.e., increased CO_2 emissions from the composting processes. The CO_2 emissions from chicken manure compost supplemented with biochar (27% w/w) increased by 6-8% in small-scale laboratory composters (Chowdhury et al., 2014). This may be due to the high porosity and specific surface area of biochar, which allows a compost pile to have more oxygen to facilitate aeration, thus increasing CO_2 emissions (Wojciech et al., 2015). Other research indicated that higher CO_2 emissions during composting of mixtures amended with biochar could result from abiotic oxidation of biochar or biochar available carbon, which functions as an energy source for microorganisms (Dias et al., 2010).

Net ecosystem exchange of CO_2 (NEE) should also be considered when evaluating the effects of biochar amendment on soil CO_2 emissions. The NEE between terrestrial ecosystems and the atmosphere depends on the net C balance between the input and output of a given ecosystem and can be calculated as the difference between heterotrophic soil respiration and net primary production (Zhang et al., 2016). Azeem et al. (2019) conducted a two-year field trial in an arid agricultural zone to investigate the effects of biochar on NEE for a legume-cereal crop rotation. The NEE for wheat decreased by 200 and 147% in the first year, and by 283 and 265% in the second year, and wheat yield increased by 6.2-22.2% in soil amended with 0.25 and 0.5% biochar, respectively (Azeem et al., 2019). The results revealed that biochar application improved the soil's physical and chemical properties, such as increasing the porosity and water-holding capacity of the soil (Major et al., 2010). As a result, biochar applications to soils enhanced crop productivity and limited nutrient leaching (Biederman & Harpole, 2013). However, no significant difference was observed for NEE in the first year of the mash bean crop; the NEE decreased by 46.8-37.9% in the second season, and the mash bean yield increased by 3.9-9.5%. The reason for this phenomenon may be that high rainfall during mash bean growing cycles leads to increased soil respiration, and the improvement of soil physical properties results in enhanced crop productivity which leads to no or small differences in NEE (Azeem et al., 2019).

The overall mechanism by which biochar regulates CO_2 emissions in various environments is illustrated in **Figure 1b**. Generally, the governing mechanisms, including both abiotic and biotic mechanisms, are summarised as follows: (1) the increase in soil pH and the high content of alkaline metals on the surface of biochar facilitates the precipitation of CO_2 to carbonates; (2) the adsorption of organic matter by biochar may be protected from further mineralisation to produce CO_2; (3) the decrease in the abundance of two carbohydrate-mineralising enzymes (glucosidase and cellobiosidase) reduces CO_2 emissions; and (4) an increase in plant growth and plant biomass due to the addition of biochar increases the net exchange of CO_2 between the atmosphere and soil (Guo et al., 2020a). Many researchers have demonstrated that soil pH is the main factor affecting the microbial community structure.

Bacterial diversity was highest in neutral soils and lowest in acidic soils. Therefore, for paddy and wetland fields with lower pH, higher biochar addition led to a higher soil pH and bacterial diversity. For example, the enrichment of copiotrophic bacteria, such as *Bacteroidetes* and *Gemmatimonadetes*, and the decrease in oligotrophic bacteria, such as *Acidobacteria* in paddy and wetland fields were responsible for the decreased CO_2 emissions. However, when the biochar is added to the upland soil, the bacteria in the upland soil can adsorb to the surface of the biochar, making the bacteria in the soil less susceptible to soil leaching, thus increasing the number of bacteria in the soil. The biochar gaps are better able to protect microbes from competitors and thus enhance respiration of upland soil microbes in relation to soil available carbon (Li et al., 2021).

3.2 Effect of biochar on CH_4 emissions and its mechanism

As shown in **Figure 2a**, the meta-analysis results confirmed that the addition of biochar generally suppressed the release of CH_4 from the three environments (upland soil, paddy and wetland fields, and compost) (Guo et al., 2015; Pascual et al., 2020), with an overall suppression of about 7% ($P < 0.05$). The suppression effect among different environments was in the following order: composting environment > rice paddies and wetlands > upland soil. It is speculated that the primary reason for this suppression is that the changes in the physical and chemical properties affect microbial activities. Biochar increases soil oxygen content because of its large pore structure. Since methanogens are anaerobic bacteria, the aerated environment suppresses their activity, resulting in a decrease in the amount of CH_4 produced. However, the suppression of CH_4 emissions after biochar addition was not as strong in upland fields (a suppression rate of 3%, $P < 0.05$) as in other ecosystems (e.g. a suppression rate of 6% in rice paddies and wetlands), as shown in **Figure 2a**. This is because the low water content also suppresses the CH_4 oxidation process. Consequently, the promotion effect of biochar on methanotrophs in upland fields is weaker than in wet areas (Troy et al., 2013). Some studies have indicated that the addition of biochar can increase CH_4 emissions in uplands (Zhang et al., 2013). For example, a higher biochar application rate (> 5 t ha^{-1}) provides a large amount of substrate, promoting the production of CH_4 (a promotion rate of 10%, $P < 0.05$), as confirmed by the results of the meta-analysis on CH_4 emission intensity in uplands (**Figure 2a**).

CH_4 emissions from rice paddies and wetlands were much higher than those from upland fields. Routine drainage and flooding of wetlands increase CH_4 emissions into the atmosphere. The meta-analysis results showed that the application of biochar to rice paddies and wetlands suppresses CH_4 emissions in general (**Figure 2a**). For example, in a two-year field experiment conducted by Dong et al. (2013), rice straw and bamboo biochars were applied to paddy soils and CH_4 emissions were monitored for two growing seasons. The results showed that rice straw biochar had the most significant effect on the reduction of CH_4 emissions (causing 47.3-86.4% reduction) and raised rice yield by 13.5-6.1% during the two rice-growing cycles (Dong et al., 2013). This decrease may be ascribed to an increase in CH_4 oxidation and a decrease in methanogenic activity (Han et al., 2016). Specifically, biochar application decreases soil bulk density and increases soil aeration, thereby enhancing CH_4 oxidation (Liu et al., 2019). Moreover, soil pH is an important parameter to control soil CH_4 emission rates in paddy fields and wetlands because the biochemical activities of most methanogens are very sensitive to changes in soil pH. Soil pH increased after the addition of biochar. A higher soil pH was helpful for the growth of methanotrophs, resulting in reduced CH_4 emissions. However, different feedstocks of biochar have different effects on CH_4 emissions as shown in Figure 2a. Among them, biochar from straw suppressed CH_4 emissions intensity by 16% ($P < 0.05$), while biochar from wood significantly increased CH_4 emissions intensity by 34% ($P < 0.05$). The difference in the chemical properties of the biochars might explain this phenomenon. Compared with wood biochar, straw biochar generally has higher pH, which can significantly increase the degree of soil pH, increase the abundance of methane nutrient bacteria and promote methane oxidation (Dong et al., 2013). The higher pyrolysis temperature of biochar (> 500 ºC) resulted in an enhanced inhibitory effect of biochar on CH_4 emissions. This was related to the soil redox potential, which also contributed to the reduction in CH_4 emissions. A soil redox potential of < −150 mV is beneficial to CH_4 production (Lyu et al., 2018). The addition of biochar might increase the redox potentials of paddy and wetland soils by affecting the water-holding capacity, soluble organic C, and metabolism of plant roots, thereby reducing CH_4 emissions. The biochar application rate and C/N ratio also had significant effects on CH_4 emissions in paddy and wetland soils. A higher application rate and lower C/N ratio are beneficial for suppressing CH_4 emissions which may be the result of both adsorption and microbial activity.

The meta-analysis results shown in **Figure 2a** confirmed that the addition of biochar significantly suppressed CH_4 emissions during composting (a suppression rate of 15%, $P < 0.05$) by improving the internal structure of compost piles, increasing the formation of aerobic sites, suppressing the activity of methanogens, enhancing the activity of methane-oxidising bacteria, and reducing CH_4 emissions (Sonoki et al., 2013). The proportion of biochar added was positively correlated with the reduction in CH_4 emissions during composting, for example, after 15 days of composting, the CH_4 emission concentration decreased from 1000 to 750 ppm as the biochar application rate increased from 5% to 20% (w/w) (Liu et al., 2017). Overall, the addition of biochar suppressed CH_4 emission intensity regardless of changes in application rate, feedstocks and C/N ratio of biochar, suggesting that biochar application is a good strategy to mitigate CH_4 emissions in composting systems. In addition to the reason mentioned above that the addition of biochar improves the permeability of compost and changes the oxidation-reduction potential, so as to suppress the activity of methanogens and promote the activity of methane-oxidising bacteria, another reason for biochar to reduce CH_4 emission in compost is its adsorption of NH_4^+-N, which decrease nitrogen availability to methanogens (Liu et al., 2017).

The overall mechanism by which biochar regulates CH_4 emission in various environments is shown in **Figure 2b**. Three processes determine the release of CH_4: CH_4 production, CH_4 oxidation, and CH_4 transport from soil to the atmosphere. CH_4 emissions are mainly related to the relative abundances of methanogens and methanotrophs, which are responsible for the production and oxidation of CH_4, respectively (Henri et al., 2018). The ratio of methanogens and methanotrophs is opposite to the suppression effect of biochar on CH_4 emission, which was confirmed in the paddy soil with long-time application of biochar (Wang et al., 2019a). In addition, two genes related to CH_4 emissions, *mcrA* (a methanogen) and *pmoA* (a methanotroph), have been well studied, and there is a positive relationship between the copy number of *mcrA* and CH_4 emissions (Su et al., 2019). Methanogens are more active in weakly alkaline and neutral soils. Biochar addition generally results in an increase in pH and oxygen content in all three environments, which inhibited methanogens and reduced the emission of

CH_4 (Pascual et al., 2020). Moreover, NO_3^--N was found to inhibit the activity of methanogens and enhance the activity of methanotroph (Nan et al., 2022). This indicates that the emission of CH_4 is related to N cycle by changing the relative abundance of different types of microbial community, which deserve to be further studied in the future.

3.3 Effect of biochar on N_2O emissions and its mechanism

As shown in **Figure 3a**, the addition of biochar had the most obvious suppression effect on the release of N_2O from the three environments (an overall suppression rate of 31%, $P < 0.05$) compared with CO_2 and CH_4 (Dong et al., 2020). The suppression effect on N_2O emission intensity among different environments was in the following order: upland soil (a suppression rate of 62%) > rice paddies and wetlands (a suppression rate of 20%) > composting environment (a suppression rate of 10%), which might be related to the different conditions. A meta-analysis of 208 peer-reviewed studies reported that biochar increased symbiotic biological N_2 fixation (63%), improved plant N uptake (11%), reduced soil N_2O emissions (32%), and decreased soil N leaching (26%) (Liu et al., 2018). However, the soil type was not considered in this meta-analysis.

In this work, the meta-analysis showed that N_2O emissions from upland were suppressed regardless of changes in pH of biochar, feedstock, pyrolysis temperature of biochar, application rate, and C/N ratio of biochar (**Figure 3a**). Alkaline conditions are favourable for N_2O emissions. In some cases, the pH value of upland soils is higher than that of biochar (Dong et al., 2020). When biochar is applied to upland fields, it decreases soil pH and reduces N_2O emissions. The pyrolysis temperature of biochar is also an important factor affecting N_2O

emissions in upland soils. A 100-day laboratory incubation experiment by Pokharel et al. (2018) showed that a higher pyrolysis temperature of 550 °C reduces N_2O emissions by 27.5%, while biochar pyrolyzes at 300 °C without affecting N_2O emissions (Pokharel et al., 2018). These results are consistent with the meta-analysis results (**Figure 3a**) and might be ascribed to the fact that high-temperature biochar is more conducive to the transfer of electrons to soil-denitrifying microorganisms, leading to a more active N_2O reductase and an enhanced rate of N_2O reduction to N_2. The application rate was positive, and the C/N ratio showed a negative suppression effect on N_2O emissions in upland soil, which can be related to the physicochemical properties of soil, such as soil porosity, pH value, and air permeability, which need to be comprehensively considered. For example, biochar application could enhance soil porosity to adsorb NH_4^+ while reducing NO_3^- produced by nitrification and N_2O produced by denitrification in soil (Zhang et al., 2020a). Similarly, several studies have shown that biochar did not significantly reduce the release of N_2O and even promoted the release of N_2O in the absence of an external N source, indicating that N_2O release is regulated by soil saturated water content and plant N uptake (Zhang et al., 2012). Nevertheless, the application of biochar to upland fields is generally beneficial for alleviating the release of N_2O.

The reduction in soil N_2O emissions from paddy and wetland soils as a result of biochar application was confirmed in the meta-analysis results, as shown in **Figure 3a**. The fluctuation of changes in N_2O emission intensity among different parameters, including pH of biochar, feedstock, pyrolysis temperature of biochar, application rate, and C/N ratio of biochar, was lower in paddy and wetland soils (20%, $P < 0.05$) than in upland soils (62%, $P < 0.05$). N_2O emissions are predominantly generated via N transformation in soils (Ji et al., 2020b). The interaction between biochar and arbuscular mycorrhizal fungi affects N_2O emissions in paddy fields and constructed wetlands (Liang et al., 2019). This may be the reason why low pH favoured the suppression of N_2O emissions in paddy soils and constructed wetlands in the meta-analysis. The presence of arbuscular mycorrhizal fungi decreased the concentrations of chlorophyll and N in *Phragmites australis* and the concentrations of NH_4^+-N, NO_3^--N, inorganic N, and total N in paddy and wetland soils, thereby decreasing N_2O emissions. Moreover, biochar alters microbial activity and abundance, thereby affecting arbuscular mycorrhizal fungi and GHG emissions. In a field experiment, increasing the biochar application rate from 0 to 10 t ha^{-1}, 20 t ha^{-1}, and 40 t ha^{-1} reduced N_2O emissions from Cd- and Pb-contaminated soils by 7.1%, 30.7%, and 48.6%, respectively, and increased rice yield by 10.0%, 25.1%, and 26.3%, respectively (Zhang et al., 2015). The application rate of biochar was positively correlated with the suppression of N_2O emissions, which was consistent with the results of meta-analysis. Moreover, a meta-analysis of 88 studies on the effects of biochar on soil N_2O emissions concluded that on average, biochar application resulted in a 38% reduction in N_2O emissions (Borchard et al., 2019).

The emissions of N_2O from composting can be reduced by applying biochar, although the changes in N_2O emission intensity are low (a suppression rate of 10%, $P < 0.05$) (**Figure 3a**). The availability of N in the compost is one of the main factors affecting N_2O generation. Biochar can limit N availability by directly adsorbing NO_3^- and NH_4^+ and forming nutrient-rich organo-mineral complexes (Zwieten et al., 2010). Additionally, biochar can adsorb nitrate and dissolved organic C produced during composting, which can promote the complete denitrification of nitrate to produce N_2, thus reducing N_2O formation (Kammann et al., 2015).

In contrast, N_2O emissions from composting during the maturation stage mainly depend on the degree of completion of the denitrification reactions and the proportion of biochar added (Wang et al., 2013). The addition of biochar increases the oxygen content in the compost pile and suppresses the activity of denitrifying bacteria, thereby weakening the completion of the denitrification reaction (Singh et al., 2010). In pilot-scale treatments (2 tons of compost), Wang et al. (2013) found that an input of 3% (w/w) biochar reduces the abundance of denitrifying bacteria, suppresses denitrification, and reduces N_2O emissions. However, with a high biochar application rate (> 8%), the compost accumulates a large amount of NH_4^+-N, which facilitated the production of N_2O during the maturation stage.

The overall mechanism by which biochar regulates N_2O emission in various environments is summarised in **Figure 3b**. Generally, N_2O production involves two main microbial processes, nitrification and denitrification. N_2O-related functional genes, such as *amoA*, *nirS*, *nirK,* and *nosZ*, have been widely studied and can be used to elucidate ammonia oxidation, nitrification, and denitrification processes related to N_2O emissions (Harter et al., 2016). Variations in environmental factors, such as pH, oxygen, and water content, cause changes in the microbial activity involved in these two processes. There are five reasons for the reduction in N_2O release in soils as a result of biochar application. (1) Biochar reduces the activity of denitrifying bacteria and their enzymes by increasing soil porosity and permeability, thereby suppressing N_2O emissions (Singh et al., 2010). (2) Biochar may facilitate the transfer of electrons to soil-denitrifying microorganisms, leading to a more active N_2O reductase and an enhanced rate of N_2O reduction to N_2 (Cayuela et al., 2013). (3) Biochar produced from higher pyrolysis (> 500 °C) or feedstocks containing heavy metals may contain some toxic substances that inhibit nitrification and denitrification processes. (4) Biochar can immobilise the available N in the soil, thereby reducing the effective utilisation of N in nitrification and denitrification reactions (Dong et al., 2020). (5) Furthermore, low soil pH is another reason for the reduction in N_2O emissions from soils. The increase in pH caused by the addition of biochar affects the activities of related enzymes involved in denitrification (such as nitrous oxide reductase), which is more pronounced in rice paddies, wetlands, and compositing systems (Cayuela et al., 2014).

4. Conclusions and future research prospects

The widespread application of biochar and engineered biochar in different environments will affect soil and other biological processes that eventually affect GHG emissions. There has been much research on the application of biochar in the agricultural systems of upland and rice paddy fields and composting systems. Research to date suggests that biochar can improve soil quality by regulating soil pH, bulk density, water-holding capacity, and organic matter content, which can improve the agricultural productivity and quality of the composting process. Furthermore, biochar can regulate the emission of the three most important GHGs, i.e., CO_2, N_2O, and CH_4 in different environmental processes. In conclusion, the effect of biochar on the emission of CO_2 in all three environments is still not clear, as contradictory results were obtained (**Table 3**). This can be attributed to the properties of the biochar itself and the negative and positive priming effects of biochar on the decomposition of soil organic matter. Despite this, it is becoming apparent that biochar can decrease the N_2O emissions from upland and paddy soils and compost environments to a certain degree and considerably decrease the emission of CH_4 in paddy soils and composting systems. The emissions of CH_4 in upland soils did not appear to be affected by the addition of biochar. The emissions of CH_4 in upland soils increased because of the high pH value of some upland soils.

Based on our review, several future research directions are suggested.

(1) There are few reports on the effect of engineered biochar application on GHG emissions. Engineered biochars, such as nZVI-biochar composites, have been extensively studied and applied in the environment. The effects of these engineered biochars on GHG emissions differ from those of original biochars, and further studies are required. More importantly, engineered biochars can be developed with the primary or secondary aim of mitigating GHG emissions.

(2) A comprehensive analysis of the pyrolysis process, stability of biochar, and mitigation effect of biochar application should be carried out based on the concept of life cycle assessment (LCA) and compared with other processes, such as biogas fermentation, combustion, and direct application of biomass to the soil.

(3) Owing to the large number of fertilisers, such as nitrogen and organic fertilisers used in agricultural production, it is possible to study the relationship between the change mechanism of soil microorganisms and the change of GHGs in the process of simultaneously applying fertiliser and biochar to different soils.

(4) The effects of different feedstocks and production technologies of biochar on soil GHG emissions and crop yield need to be quantified and vetted. Guidelines on selecting and producing biochar formulations should be developed to improve soil health and environmental management, reduce the carbon footprint, abate climate change impacts on food production, and increase farmland profitability. Biochars can be tailored for specific applications through

feedstock selection by modifying process conditions through pre- or post-production treatments to adjust pH by increasing nutrient levels and availability, carbon persistence, and adsorptive properties.

Competing Interests

The author declares no competing financial interests.

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Table 1. Overview of the main impact of biochar addition on upland soils

Biochar types	Soil type	Region	Influence	Reference
Sawdust biochar，Sophora japonica bark biochar	Obsidian and loess	Loess Plateau， China	-Soil CO_2 emission flux shows an increasing trend with an increase in the amount of biochar added -Suppression of CH_4 emissions and no significant impact on N_2O emissions -Differences exist among treatments with different biochars	(Guo et al., 2015)
Bamboo char	Dystric Cambisols	Obu City, Aichi Prefecture, Japan	-No significant changes in greenhouse gas (GHG) emissions	(Watanabe et al., 2014)
Rice husks biochar	Orthic Anthrosols	Nanjing, China	-Increased CH_4 emissions -Reduced NO_2 emissions -Differences in GHG emissions between upland and wetland soils	(Wang et al., 2012)
Wheat straw biochar	Loamy soil	Central China Plain	-Reduced GHGs emissions -Enhanced crop productivity	(Zhang et al., 2012)
Barley straw biochar	Loamy soil	Sepung-ri, Gwangyang-eup, Gwangyang-si, and Jeollanam-do, South Korea	-Reduced N_2O emissions -The combined treatment of biochar and chemical fertilisers was more effective in suppressing N_2O emissions than the treatment alone	(Kang et al., 2018)
Municipal solid waste biochar	/	Chongqing， China	-CO_2 emissions increased in the first 2 weeks -Suppressed the total CO_2 emissions within 36 weeks	(Liu et al., 2015)
Ten types of biochar from Mediterranean agricultural residues	Sandy loam	Jumilla, Murcia, Spain	-CH_4 release was suppressed -The starting material of biochar determined the difference in CH_4 release flux	(Pascual et al., 2020)
Fir sawdust	Luvisol soil	Luancheng, HeBei, China	- Suppressed the production of N_2O in the soil -Stimulated the reduction of N_2O to N_2	(Dong et al., 2020)
Wheat straw	Orthic Black Chernozem	Flagstaff County, southeast Alberta, Canada	-Reduced N_2O emissions -No significant change in CO_2 or CH_4 emissions	(Wu et al., 2013)
Maize straw	Sandy loam soil	Fengqiu County, Henan Province, China	-Reduced N_2O emissions -Reduced denitrification potential	(Niu et al., 2017)

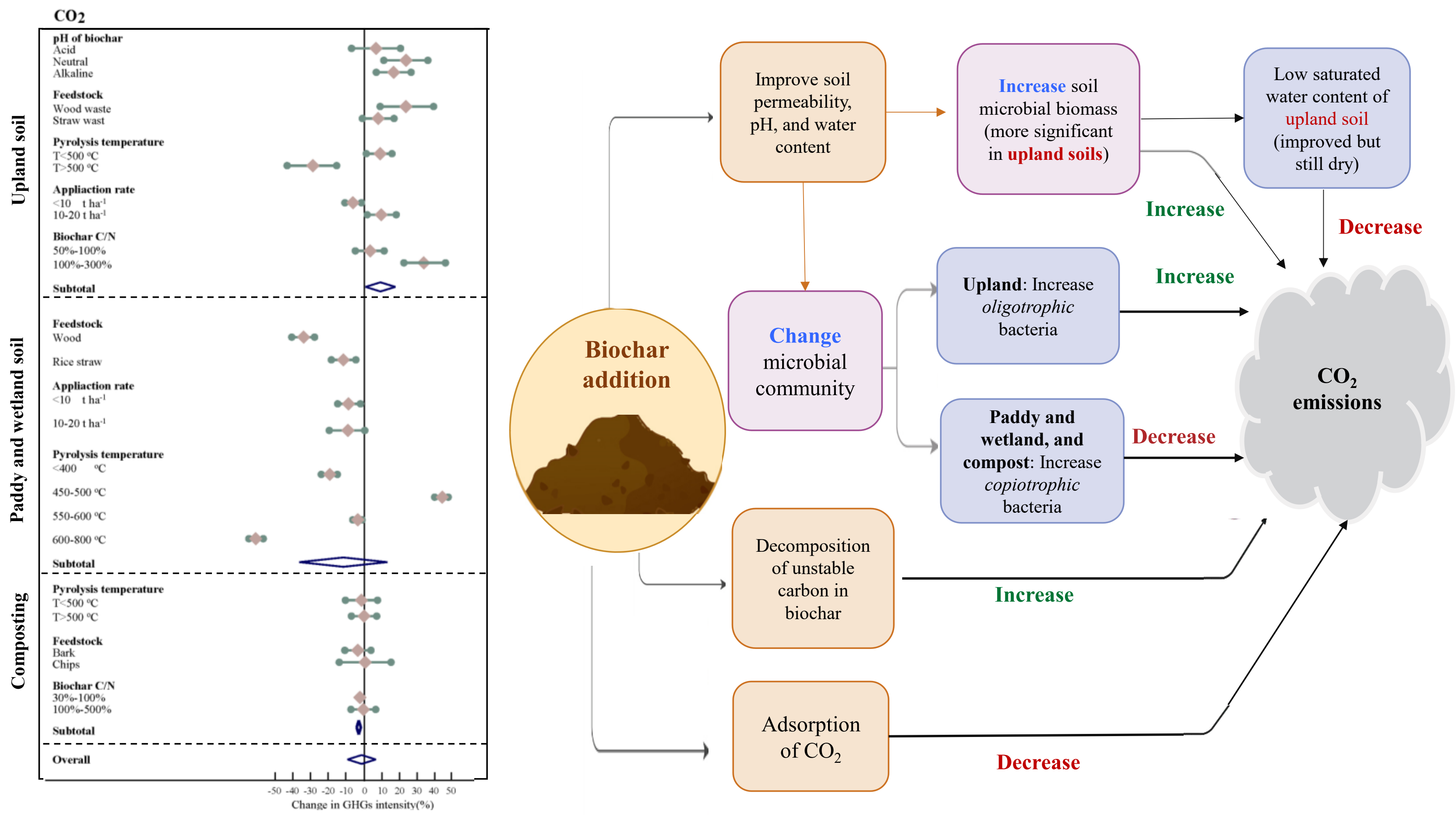
Table 2. Overview of the main impact of biochar addition on paddy and wetland soils

Biochar type	Soil type	Region	Influence	Reference
Rice straw biochar	Rice paddy	Subtropical rice paddy of China	-Biochar treatment decreased the cumulative CO_2 flux in the late paddy and for the complete year (early and late paddies) -Biochar treatment also decreased the cumulative CH_4 flux in the early paddy	(Wang et al., 2019b)
Wheat straw biochar	Rice paddy	Dongshan Town, Suzhou City, Jiangsu Province, China	-The application of 4% biochar significantly increased N_2O emissions during the 45-day incubation by 291 and 256%, respectively -The abundance and diversity of ammonia-oxidising bacteria increased	(Lin et al., 2017)
Wheat straw biochar	Cadmium- and lead-contaminated rice paddy soil	Tai lake Plain, China	-No change in soil CO_2 emissions was observed at 10 t ha^{-1} of biochar addition -Biochar treatment reduced soil CO_2 emissions by 16–24% at 20 and 40 t ha^{-1} -Biochar treatment increased rice yield by 25–26% and thus enhanced ecosystem CO_2 sequestration by 47–55% over the control -Seasonal total N_2O emissions were reduced by 7.1, 30.7, and 48.6% under biochar addition at 10, 20, and 40 t ha^{-1}, respectively	(Zhang et al., 2015)
Mangrove biochar	Rice paddy	Rangbua, Chombueng District, Ratchaburi Province, Thailand	-Relative to control, biochar application reduced seasonal CH_4 emissions by 40.6% -Biochar application enhanced soil organic carbon stock by 21.2%	(Sriphirom et al., 2020)
Rice straw biochar	Rice paddy	Yuhang District, Hangzhou, Zhejiang Province, China	-Biochar treatment reduced CH_4 emissions under ambient conditions and significantly reduced emissions by 39.5% under simultaneously elevated temperature and CO_2	(Han et al., 2016)
Rice straw biochar	Rice paddy	Hwasungsi, Gyeonggido, Korea	-Biochar amendment did not significantly increase the CO_2 or CH_4 emissions -Biochar addition increased the N_2O emissions -The microbial biomass and the abundance of methane related microorganisms were not changed by biochar addition	(Yoo et al., 2015)

Biochar type	Soil type	Region	Influence	Reference
Wheat straw and sawdust biochars	Rice paddy	Taihu Lake region of China	-Biochar decreased CH_4 emissions -Biochar application decreased N_2O emissions	(Zhou et al., 2018)
Rice chaff biochar	Rice paddy	Chunan-Si, Chungcheongnam-Do, Korea	-Biochar treatment reduced the soil NH_4^+ content and increased the NO_3^-content -Biochar addition increased C contents in the wet stable aggregates of size 53 to 1000 mm, and the water holding capacity	(Yoo et al., 2014)
Digested slurry biochar	Rice paddy	Graduate School of Horticulture, Chiba University, Matsudo, Japan	-Biochar treatment increased the CH_4 emissions -Biochar treatment increased the soil NH_4^+-N content	(Singla et al., 2014)
Tree branches biochar	Constructed wetlands	Yunnan University in Kunming, China	-Biochar treatment decreased the CO_2, CH_4, and N_2O emissions	(Ji et al., 2020a)
Cattail biochar (harvested from the wetland)	Constructed wetlands	Chongqing University, Chongqing, China	-Biochar reduced the global warming potential values of N_2O and CH_4 from 18.5% to 24.0% -N_2O fluxes and global warming potential decreased, while CH_4 and CO_2 fluxes increased with increasing COD/N ratios	(Guo et al., 2020a)

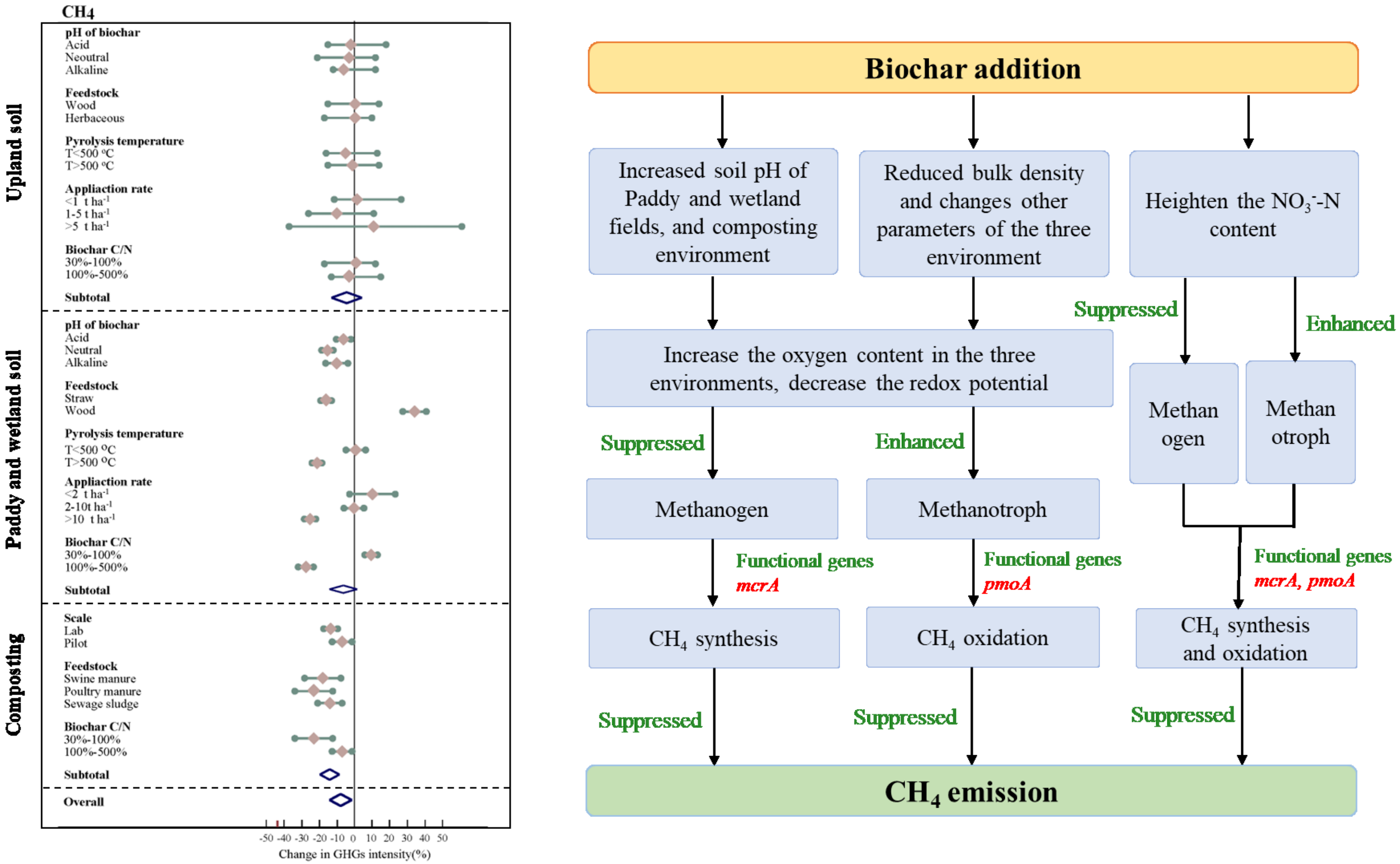
Table 3. Comparison of the mitigating effect of biochar in different environmental systems

System	CO_2 emissions	N_2O emissions	CH_4 emissions
Upland soils	Increase in the initial period, decrease in the long-term	Decrease	Small decrease or no effect
Rice paddy and wetlands	Changed based on conditions	Decrease	Decrease
Composting sites	Decrease	Decrease initially, increase at maturity	Decrease



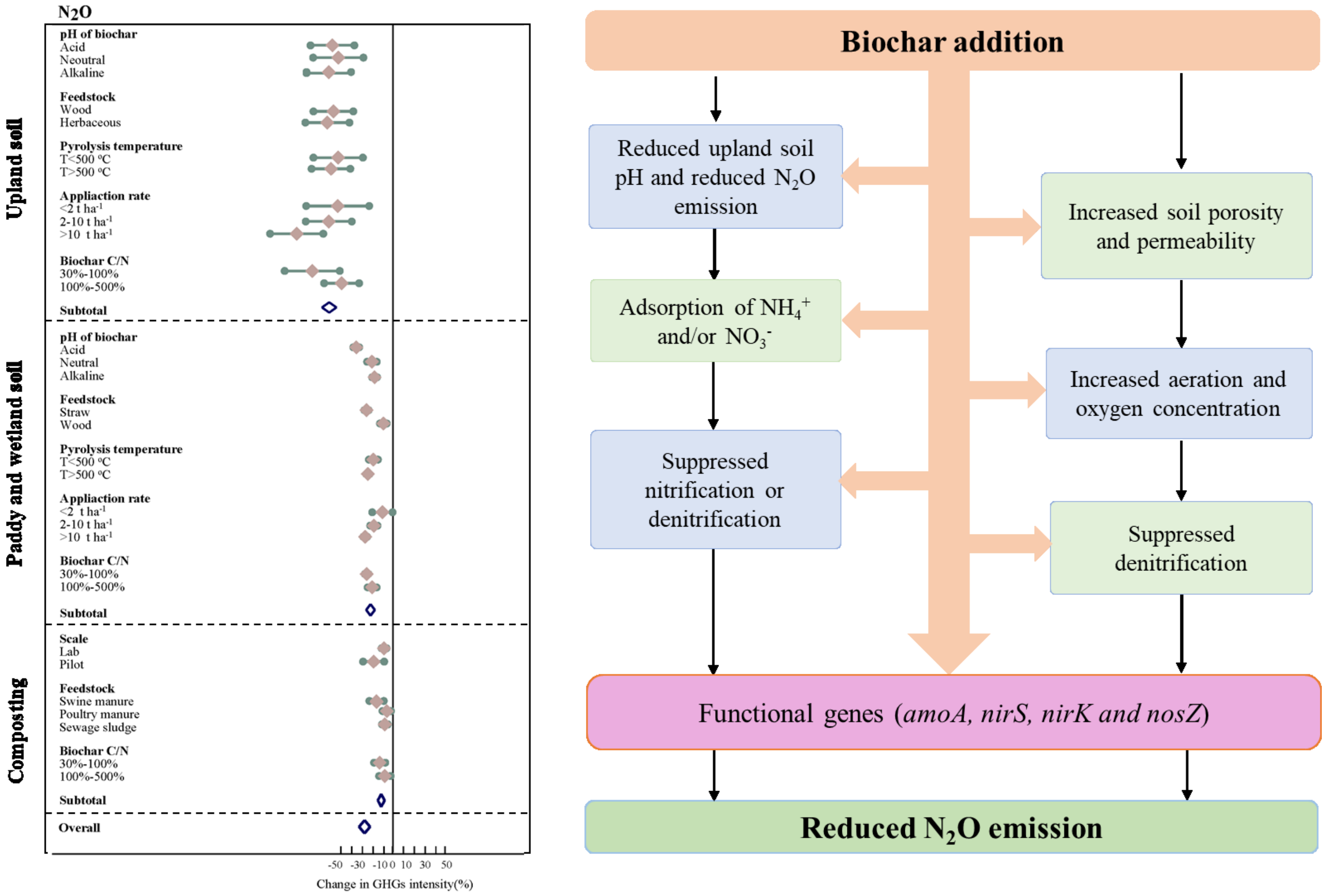
(a) (b)

Figure 1. (a) Changes in CO_2 intensity in upland, rice paddy and wetlands, and composting environments after biochar application as influenced by pH, feedstock, pyrolysis temperature, application rate, and C/N ratio of biochar. The black solid line at zero indicates no change in CO_2 intensity after biochar addition. (b) The effects and mechanisms of biochar application on soil CO_2 emissions.



(a) (b)

Figure 2. (a) Changes in CH_4 intensity in upland, rice paddy and wetlands, and composting environments after biochar application as influenced by pH, feedstock, pyrolysis temperature, application rate, and C/N ratio of biochar. The black solid line at zero indicates no change in CH_4 intensity after biochar addition. (b) The effects and mechanisms of biochar application on soil CH_4 emissions.



(a) (b)

Figure 3. (a) Changes in N_2O intensity in upland, rice paddy and wetlands, and composting environments after biochar application as influenced by pH, feedstock, pyrolysis temperature, application rate, and C/N ratio of biochar. The black solid line at zero indicates no change in N_2O intensity after biochar addition. (b) The effects and mechanisms of biochar application on soil N_2O emissions.