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Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: A review

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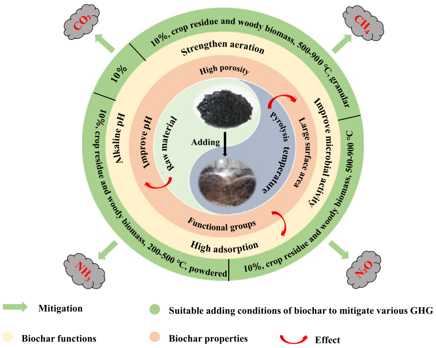
HIGHLIGHTS

- The effects of biochar on GHG emissions from compost were investigated.
- Raw materials and pyrolysis temperature affect the properties of biochar.
- Biochar mitigates GHG emissions by changing the properties of compost piles
- Appropriate adding conditions of biochar to mitigate various GHG were proposed.
- Exploring new application and production methods of biochar can better reduce GHG.

GRAPHICAL ABSTRACT



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ABSTRACT

Biochar possesses a unique porous structure and abundant surface functional groups, which can potentially help mitigate greenhouse gas (GHG) emissions from compost. This review summarizes the properties and functions of biochar, and the effects of biochar on common GHGs (methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O)) and ammonia (NH_3, an indirect GHG) during composting. Studies have shown that it is possible to improve the mitigation of GHG emissions during composting by adjusting the biochar amount, type of raw material, pyrolysis temperature, and particle size. Biochar produced from crop residues and woody biomass has a greater effect on mitigating CH_4, N_2O, and NH_3 emissions during composting, and GHG emissions can be reduced significantly by adding about 10% (w/w) biochar. Biochar produced by high temperature pyrolysis (500–900 °C) has a greater effect on mitigating CH_4 and N_2O emissions, whereas biochar generated by low temperature pyrolysis (200–500 °C) is more effective at reducing NH_3 emissions. Interestingly, adding granular biochar is more beneficial for mitigating CH_4 emissions, whereas adding powdered biochar is better at reducing NH_3 emissions. According to the current research status, developing new methods for producing and using biochar (e.g., modified or combined with other additives) should be the focus of future research into mitigating GHG emissions during composting. The findings summarized in this review may provide a reference to allow the establishment of standards for using biochar to mitigate GHG emissions from compost.

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1. Introduction

The rapid development of modern society and various human activities have generated large volumes of greenhouse gas (GHG) emissions, which have increased the global average temperature and aggravated the global greenhouse effect, thereby potentially leading to increases in the incidence of diseases and insect pests, sea level rises, abnormal climate, and frequent droughts (Zachos et al., 2008; Byers, 2021). Studies have indicated that the global temperature will continue to rise in the coming decades, thereby affecting human life and development (Upadhyay, 2020). The common GHGs include methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and ammonia (NH_3). CO_2 is the main gas produced when microorganisms decompose organic matter and it plays an indispensable role in the heat balance of the Earth, and thus an increase in atmospheric CO_2 will affect climate change (Kweku et al., 2018). CH_4 is produced under anaerobic environments by methanogens and its capacity for absorbing infrared light and exacerbating the greenhouse effect are about 26 times and 22 times higher than those of CO_2, respectively (Cao et al., 2019). In addition, N_2O and NH_3 are inevitably produced in the nitrogen conversion process, and N_2O is an important cause of ozone layer depletion, where its effect is 296 times higher than the single molecule warming potential of CO_2 (Ermolaev et al., 2015). NH_3 does not lead to increases in temperature but it is the substrate for N_2O production, and thus NH_3 is also generally considered an indirect GHG (Akdeniz, 2019).

Agriculture is one of the main sources of GHG emissions and about 13.5% of global anthropogenic GHG emissions come from agricultural production (Havlík et al., 2014). It has been estimated that agricultural activities contribute 80% of N_2O emissions and 40% of CH_4 emissions (Havlík et al., 2014), and the treatment and utilization of manure are important sources of GHGs (Aguirre-Villegas and Larson, 2016). Composting treatment is an effective method for dealing with manure by transforming degradable organic matter into stable humus for use as organic fertilizer (Chadwick et al., 2011). However, composting manure is also a major source of GHGs. Barrington et al. (2002) found that 14–51% of the organic carbon in the raw material may be released into the atmosphere in the forms of CH_4 and CO_2 during composting. Similarly, the initial loss of the total nitrogen content during composting is about 16–74% in the forms of NH_3 and N_2O emissions (Ren et al., 2010). Thus, GHGs emissions will reduce the quality of the compost product and harm the atmospheric environment (Yang et al., 2015).

Many studies have investigated methods for reducing GHG emissions from compost. In particular, physical methods aim to reduce GHG emissions via their adsorption in the pores of materials. For instance, Mao et al. (2019) showed that adding zeolite reduced CH_4 and N_2O emissions by 69% and 67%, respectively, during pig manure composting. Biological additives can affect GHG emissions during composting by changing the structure of the microbial community. For instance, Fukumoto et al. (2006) showed that N_2O emissions can be reduced by adding nitrite-oxidizing bacteria during composting. Moreover, chemicals such as superphosphate can be used as nitrogen fixation agents during composting. In particular, studies have shown that amendment with superphosphate reduced NH_3 emissions by 37.9% (Zhang et al., 2017) and CH_4 emissions by 80.5% (Yang et al., 2015) during composting. Compared with other additives, biochar has a more porous structure and a greater abundance of surface functional groups (Wang and Zeng, 2018), and it is an effective additive for mitigating GHG emissions from composting. In addition, biochar can synergistically reduce the emissions of common GHGs (CH_4, N_2O, and NH_3) (Liu et al., 2017) and the effect of its application is highly stable (Mao et al., 2019).

Biochar has many useful physical and chemical properties, such as numerous pores, a large surface area, and abundant surface functional groups (Cha et al., 2016). These properties have attracted much attention and it has been shown that biochar can mitigate GHG emissions from wetlands (Zhou et al., 2020) and soils (Lehmann et al., 2011).

Biochar can interact with the main nutrient cycles and it is conducive to the growth of microorganisms during composting (López-Cano et al., 2016). Improved environmental conditions can promote changes in microbial communities to affect important microbially mediated biogeochemical cycles (Lehmann et al., 2011), including the degradation of organic matter (Guo et al., 2020a, 2020b), humification, nitrification, and denitrification (Zainudin et al., 2020). Therefore, exploiting the physical and chemical properties of biochar can potentially help to enhance the quality of compost and mitigate GHG emissions.

This review summarizes the preparation methods and functions of biochar, as well as the mechanisms associated with its effects on the emissions of various GHGs during composting. In addition, according to the current research status, the application prospects and future research areas are identified in order to obtain a greater understanding of the effects of biochar on mitigating GHG emissions from compost.

2. Preparation and functions of biochar

2.1. Preparation of biochar

Biochar has attracted much attention in agriculture, environmental applications, and as a new material due to its unique physical and chemical properties, including high porosity, a large specific surface area, and abundant functional groups. Biochar is produced in artificially controlled pyrolysis conditions, where the pyrolysis temperature and residence time are mainly adjusted (Tomczyk et al., 2020). In general, biochar mainly comprises elemental carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S), as well as ash (Xiao et al., 2018). The elements in the raw materials undergo different physical and chemical processes in the biomass pyrolysis process to yield biochar with diverse properties (Das et al., 2021).

The type of raw material employed significantly affects the elemental composition, specific surface area, and pore volume of biochar (Table 1) due to differences in the contents, such as the cellulose/hemicelluloses/lignin (Tomczyk et al., 2020), elements (Xiao et al., 2018), and mineral salts (Guo et al., 2020a, 2020b). In the biomass pyrolysis process, low molecular weight cellulose and hemicellulose are readily decomposed to form pores, whereas the pyrolysis of high molecular weight lignin yields the biochar skeleton (Luo et al., 2015). In addition, differences in the elemental and mineral salt contents of the raw material will lead to the production of diverse functional groups on the surface of biochar after pyrolysis (Tomczyk et al., 2020). As shown in Table 1, the pore volume and specific surface area are significantly lower for biochar produced using sludge, manure, and shell materials compared with those produced from crop residues and wood biomass, mainly due to the higher cellulose and hemicellulose contents of crop residues and woody biomass compared with other materials, as shown by Tomczyk et al. (2020) and Ahmad et al. (2014).

In addition to the type of raw material employed, the pyrolysis temperature significantly affects the physicochemical properties of biochar. The pyrolysis temperature range used for producing biochar in most studies is generally 200–900 °C (Yuan et al., 2019). The biochar pyrolysis process comprises the following three stages according to the temperature applied (Lee et al., 2017). In the first stage from ambient temperature to 200 °C, the internal structure is rearranged due to water evaporation, chemical bond breakage, and the formation of hydroperoxide, –COOH, and –CO groups (Cárdenas-Aguiar et al., 2017). The rapid degradation of cellulose and hemicellulose (Yuan et al., 2019)

Table 1
Characteristics of biochar prepared under different conditions.

Raw material	Pyrolysis		Element content (%)				Pore volume (cm^3/g)	BET surface area (m^2/g)	Pore size(nm)	Reference
	Residence time (h)	Temperature (°C)	C	H	O	N				
Biosolids	1.5	550	39.57	1.17	–	5.67	0.042	3.98	3.95	Stylianou et al. (2020)
Cattle manure			28.46	0.88	–	1.58	0.022	14.03	3.94	
Spent coffee grounds			87.38	2.36	–	4.28	0.008	1.53	60.39	
Rice straw	2	300	36.40	4.06	–	1.36	0.022	5.89	–	Xu et al. (2019)
		500	42.57	3.22	53.09	1.12	0.072	34.03	–	
		700	54.06	1.31	44.33	0.30	0.189	122.63	–	
Phragmites communis		300	37.39	4.28	57.91	0.42	0.008	3.51	–	
		500	55.19	4.17	40.50	0.14	0.106	131.46	–	
		700	59.15	3.51	37.22	0.12	0.415	441.71	–	
Sawdust		300	55.9	4.60	39.48	0.02	0.006	2.95	–	
		500	64.07	3.18	32.74	0.01	0.233	378.72	–	
		700	71.72	2.97	25.31	0.00	0.278	594.92	–	
Egg shell		300	23.59	0.70	75.60	0.11	0.004	2.03	–	
		500	15.93	0.25	83.79	0.03	0.006	3.72	–	
		700	14.83	0.18	84.90	0.09	0.009	5.33	–	
Cow manure	1	300	47.25	4.23	11.23	3.26	0.003	1.55	7.34	Zhang et al. (2019)
		500	43.08	1.60	7.17	2.15	0.003	1.77	5.89	
		700	42.56	0.72	2.73	1.79	0.023	31.23	3.00	
Wheat straw	1	700	55.18	1.33	10.41	–	0.040	44.47	1.65	Shi et al. (2020)
Spent mushroom substrate	2	800	55.20	1.09	10.10	1.32	0.050	64.40	3.30	Sewu et al. (2019)
Pomelo peel	1	300	64.41	5.03	22.03	2.13	0.003	0.88	9.88	Yin et al. (2020)
Rice straw	–	–	–	–	–	–	0.013	9.61	–	He et al. (2019)
Bamboo			–	–	–	–	0.018	25.23	–	
Cow manure	2	500	41.70	1.20	–	1.89	0.021	8.55	11.36	Kiran et al. (2017)
Pine sawdust	1	300	55.30	5.50	39.00	0.07	–	8.20	–	Luo et al. (2015)
Maize straw			57.40	6.64	34.20	1.59	–	2.60	–	
Sugarcane bagasse			58.50	6.73	34.30	0.42	–	12.20	–	
Pine sawdust		500	76.00	3.54	19.80	0.15	–	68.40	–	
Maize straw			80.70	3.23	14.10	1.71	–	33.20	–	
Sugarcane bagasse			77.70	3.96	17.50	0.68	–	97.80	–	
Municipal sewage sludge	1/3	500	17.46	0.70	10.45	1.54	0.051	25.42	3.74	Chen et al. (2014)
		600	18.40	0.34	7.35	1.38	0.053	20.27	3.76	
		700	16.92	0.21	6.86	0.95	0.068	32.17	3.75	
		800	16.20	0.03	3.64	0.50	0.090	48.50	3.71	
		900	15.92	0.11	2.44	0.53	0.099	67.60	3.84	

Note: "–" denotes no data available.

yields more aggregated organic compounds in the second stage at 200–500 °C (Ding et al., 2014). The degradation of refractory organic compounds and lignin occurs in the third stage at temperatures above 500 °C (Cárdenas-Aguiar et al., 2017). According to Table 1, the specific surface area and pore volume of biochar increase as the pyrolysis temperature increases, whereas the H/C and O/C atomic ratios decrease as the pyrolysis temperature increases. These changes occur because increasing the pyrolysis temperature promotes the formation of aromatic carbon in biochar and the release of hydrogen-containing and oxygen-containing groups (Weber and Quicker, 2018), thereby decreasing the H/C and O/C atomic ratios (Xiao et al., 2016), and reducing the number of oxygen-containing functional groups (Tomczyk et al., 2020). Therefore, increasing the pyrolysis temperature enhances the degree of aromatization and reduces the number of oxygen-containing functional groups on biochar. In summary, biochar produced by pyrolysis in the range from 200 to 500 °C contains more oxygen-containing functional groups, whereas biochar produced by pyrolysis in the range from 500 to 900 °C has a larger pore volume and specific surface area as well as a higher degree of aromatization.

Thus, the properties of biochar can be adjusted by controlling the pyrolysis temperature and the type of raw material.

2.2. Functions of biochar

Biochar can be used as an additive to improve the activities of microbes as well as the humification process and composting performance, and mitigate GHG emissions (Fig. 1). These capabilities are mainly attributed to the unique physicochemical properties of biochar, as follows. (1) The abundant pores in biochar provide a high capacity for water holding and they can prevent the production of anaerobic zones by absorbing excess water from the composting pile (Sanchez-Monedero et al., 2018), thereby improving the aerobic environment during composting (Wu et al., 2017). He et al. (2018) found that compost with granular biochar increased the porosity by 4.02% and reduced CH_4 emissions by 22.15%. (2) The large specific surface area of biochar can provide suitable habitats for microorganisms to enhance their activity (Xiao et al., 2017). Yin et al. (2021) found that biochar changed the microbial community structure of compost and enhanced the activities of cellulase and urease by 56% and 96%, respectively, by enhancing the activities of related microorganisms. (3) The abundant functional groups (e.g., carboxyl, hydroxyl, epoxy, carbonyl, acyl, ester, sulfonic, ether, amido, and azyl groups) on the surfaces of biochar can serve as adsorption sites to enhance the adsorption capacity during composting (Iqbal et al., 2015; Xiao et al., 2018). In addition, the functional groups on the surface of biochar can enhance the activities of microbes to facilitate the degradation of organic compounds during composting (Zhang et al., 2014). López-Cano et al. (2016) found that biochar reduced nitrogen losses in the composting process by adsorbing NH_4^+ and promoting nitrification to enhance the efficiency of the composting product when applied as fertilizer. (4) The alkaline pH of biochar can affect the activities of microorganisms by providing a suitable pH for their growth in the composting pile (Xiao et al., 2017). Mao et al. (2018) found that biochar inhibited CH_4 emissions by affecting the pH of the compost pile.

3. Effects of biochar on the transformation of materials during composting

3.1. Effects of biochar on the degradation of organic matter

The composting process involves the conversion of organic matter into stable humus through the actions of microorganisms (Wu et al., 2017). Unstable organic compounds such as simple carbohydrates, amino acids, and fats degrade rapidly in the initial stage of composting (Akdeniz, 2019). The slow degradation and transformation of other forms of stable organic matter, such as cellulose, hemicellulose, and lignin, can limit the efficiency of composting as well as affecting the quality of the compost product (Bernal et al., 2009; Yin et al., 2019a). Many studies have shown that the addition of exogenous additives (e.g., zeolite (Wang et al., 2017), wood vinegar (Guo et al., 2020a, 2020b), superphosphate (Zhang et al., 2017), and biochar (Akdeniz, 2019) can enhance the decomposition of organic matter and increase the effectiveness of the compost product when used as fertilizer.

Biochar has unique physical and chemical properties, and it can accelerate the mineralization of organic matter, shorten the composting time (Wang et al., 2017), and improve the compost product (Sánchez-García et al., 2015), mainly because biochar can enhance the aeration of compost (Godlewska et al., 2017), stimulate microorganisms and their enzyme activity levels (Yin et al., 2021), and promote the degradation of organic matter (Khan et al., 2016). For example, Yang et al. (2020) found that adding biochar increased the abundance and diversity of bacteria during composting. Yin et al. (2021) showed that bamboo charcoal enhanced the activities of cellulase and urease by 56% and 96%, respectively, during chicken manure composting. In addition, biochar can accelerate the degradation of organic matter by adsorbing

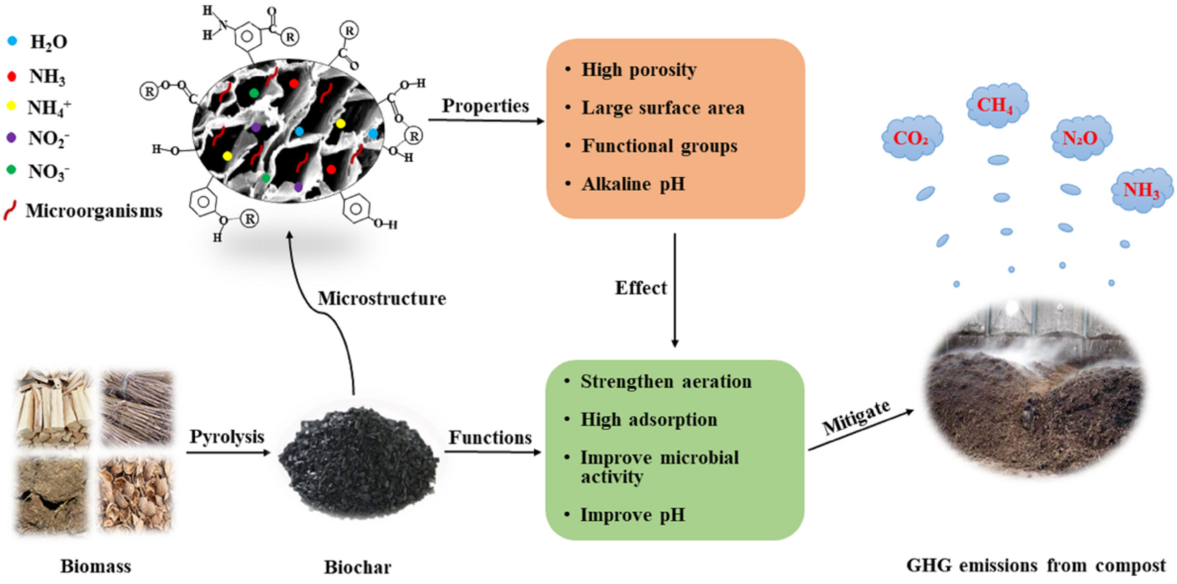

Fig. 1. Schematic illustrating the relationships between biochar and GHG emissions during composting.

refractory compounds, e.g., H_2S, NH_3, NH_4^+, and SO_4^{2-} (Akdeniz, 2019; Zhang et al., 2016). Li et al. (2015) found that the organic matter degradation rate increased by 14.8–29.6% after adding biochar to pig manure composting. However, some studies have shown that adding biochar to compost can accelerate the degradation of organic matter but also lead to increased CO_2 emissions (Czekala et al., 2016). For example, adding 10% (dry weight) biochar increased the CO_2 emissions by 7.4% compared with composting without biochar (Awasthi et al., 2020).

3.2. Effects of biochar on the transformation of nitrogen

In the initial stage of composting, nitrogen mainly exists in forms of organic nitrogen, such as in proteins, urea, and amino acids (Sanchez-Monedero et al., 2018). Organic nitrogen is ammoniated to NH_4^+ (Yin et al., 2019a), which is transformed into NO_3^- by nitrifying bacteria and NO_3^- can then be transformed into N_2 by denitrifying bacteria (Maeda et al., 2011). Some nitrogen can be lost from the composting pile in the forms of N_2O and NH_3, and large amounts of nitrogen volatilizing in the form of gas may have adverse effects on the environment, as well as reducing the effectiveness of the compost product when used as fertilizer (Yang et al., 2015).

Biochar can significantly affect the total nitrogen content of the compost product because the acidic functional groups on biochar can adsorb NH_4^+ and NH_3 (López-Cano et al., 2016), and aromatic compounds in biochar may also interact with NO_3^- (Zhang et al., 2018). Furthermore, biochar can affect the transformation of nitrogen by changing the microbial community structure during composting (Godlewska et al., 2017). Vandecasteele et al. (2016) found that the NH_4^+ content was 29% higher in the final compost product obtained with 10% biochar compared with that without added biochar. Awasthi et al. (2020) found that the addition of 2–10% (dry weight) bamboo biochar to pig manure compost increased the NO_3^- content of the final product by 38.8–152.6%. Similarly, Li et al. (2017) and López-Cano et al. (2016) showed that the NO_3^- content was significantly higher in the compost product obtained with added biochar compared with that produced without biochar.

4. Mitigation of GHG emissions from compost by adding biochar

4.1. GHG production during composting

Composting is a complex biochemical process where organic matter is degraded by microorganisms and stable humus is finally obtained (Cáceres et al., 2018). However, many unfavorable by-products are generated during the composting process, including GHGs produced by the metabolic activities of microorganisms, which have received widespread attention in recent years.

Organic carbon can serve as an energy and carbon source for microorganisms, and microorganisms can directly convert organic carbon into CO_2 under aerobic conditions (Awasthi et al., 2016). However, CH_4 emissions are mainly due to methanogens and methanotrophs, where methanogens convert organic carbon into CH_4 in an anaerobic environment, and CH_4 is converted into CO_2 in an aerobic environment via the actions of methanotrophs (Tong et al., 2019) (Fig. 2). Therefore, the emission of CH_4 depends on the production of CH_4 under the action of methanogens, but also on the oxidation of CH_4 by methanotrophs during composting.

Organic nitrogen is used as a nutrient source by microorganisms, and NH_3 and N_2O are inevitably produced during the transformation process (Maeda et al., 2011). Organic nitrogen is converted into NH_4^+ via ammonification, which is then converted into NO_3^- by nitrifying bacteria (Sanchez-Monedero et al., 2018), but some NH_4^+ can be volatilized in the forms of N_2O and NH_3 during composting (Cáceres et al., 2018). Furthermore, NO_3^- is converted into N_2 under the actions of denitrifying bacteria, where N_2O is also produced during this process (Ermolaev et al., 2015) (Fig. 2). The N_2O emission pathways during denitrification can be divided into two processes comprising N_2O production (NO_3^- into N_2O) and N_2O consumption (N_2O into N_2), and the net N_2O emissions depend on the interactions between these two processes (Li et al., 2016).

4.2. Mechanisms that allow biochar to reduce GHG emissions during composting

4.2.1. CO_2

Studies have shown that biochar significantly affects CO_2 emissions during composting, but the effects are inconsistent among different studies. In particular, a study found that adding biochar during pig manure composting reduced CO_2 emissions by 26.1% (Wang et al., 2018), whereas another study showed that adding biochar increased CO_2 emissions by 53.2% during pig manure composting (Mao et al., 2018). These different effects of biochar on CO_2 emissions can be explained by biochar increasing the sequestration of exogenous organic matter when applied during composting to reduce CO_2 emissions (Liu et al., 2017), or by biochar providing a better habitat for microorganisms to enhance

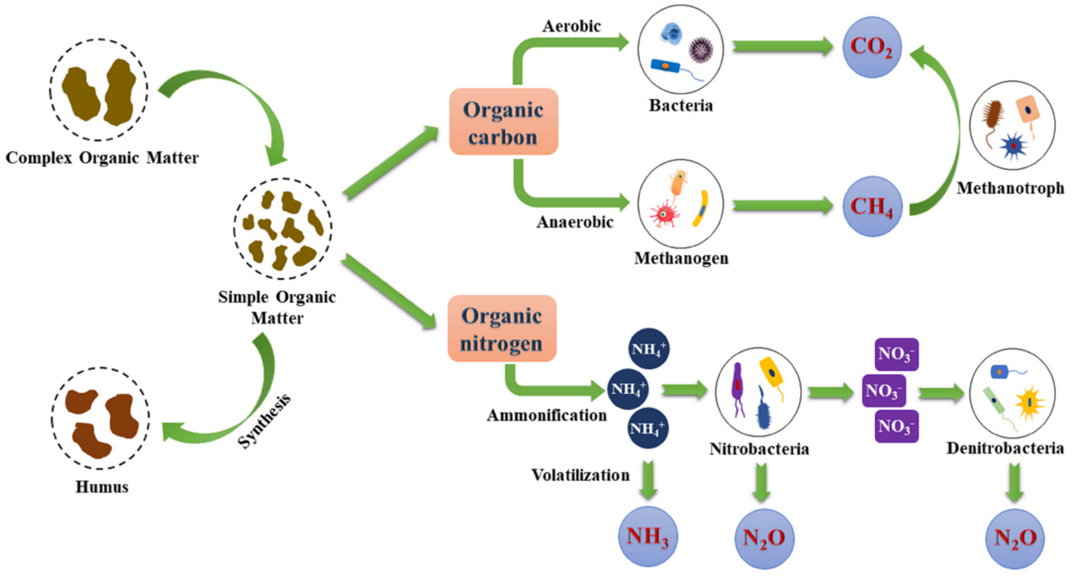

Fig. 2. Schematic illustrating the microbial mechanisms associated with GHG emissions during composting.

Table 2
Studies of the impact of biochar on GHG emissions.

Composting materials	Biochar characteristics				GHG emissions reduction effect (% compared with control)				Reference
	Feedstock	Dose (%)	Pyrolysis temperature (°C)	Particle size (mm)	CO_2	CH_4	NH_3	N_2O	
Hen manure +Sawdust	Straw	10 fw	450–500	≤2	–	–	12.4	–	Zhang et al. (2020)
Poultry manure +Wheat straw	Bamboo	2–10 dw	–	–	5.5–72.6	12.5–72.9	19.0–77.4	12.4–81.6	Awasthi et al. (2020)
Pig manure +Wheat straw	Tobacco stalk	10 dw	500–600	2–5	26.1	41.7	35.9	64.9	Wang et al. (2018)
Chicken manure +Wheat straw	Chicken manure	2–10 dw	550–600	–	–	20.5–61.5	19.2–48.1	4.7–15.1	Chen et al. (2019)
Pig manure +Sawdust	Bamboo	5 dw	–	2–3	–	54.4	12.4	36.1	Mao et al. (2018)
Layer manure +Sawdust	Cornstalk Bamboo Woody Layer manure Coir	10 fw	450–500	≤2	–	15.5–26.1	9.2–24.8	–	Chen et al. (2017)
Sewage sludge +Wheat straw	Wheat straw	2–18 dw	500–600	2–5	–	92.8–95.3	58.0–65.2	95.1–97.3	Awasthi et al. (2017)
Poultry litter + Sugarcane straw	Green waste Poultry litter	10 dw	550	–	–	77.8–83.3	54.9–60.2	68.2–74.9	Agyarko-Mintah et al. (2017)
Green waste + Municipal solid waste	Holm oak	10 dw	650	–	52.9	95.1	–	14.2	Vandecasteele et al. (2016)
Cattle manure +Rice-chaff	wheat straw	3 dw	450	–	–	–	–	54.1	Li et al. (2016)
Hen manure +Barley straw	Hardwood + Softwood (4:1)	27.4 dw	500–700	≤16	21.5–22.9	77.9–83.6	35.3–43.0	16.1–35.3	Chowdhury et al. (2014)
Pig manure +Wood chips +Sawdust.	Bamboo	3 dw	600	–	–	–	–	25.9	Wang et al. (2013)

Note: "–" denotes no data available.
dw: dry weight.
fw: fresh weight.

their activity and intensify the degradation of organic matter to allow the production of more CO_2 (Mao et al., 2018). Although biochar may increase the CO_2 emissions but the enhanced oxygen environment in compost piles will inhibit the activity of anaerobic bacteria such as methanogens and denitrifying bacteria (He et al., 2019) to reduce CH_4 and N_2O emissions.

4.2.2. CH_4

CH_4 production requires a strict anaerobic environment and a low oxidation-reduction potential (Eh < −150 mV) (Liu et al., 2017). The addition of biochar improves the structure of the compost pile by reducing the number of anaerobic spots, and biochar can change the oxidation–reduction potential by improving the permeability, which decreases the activity of methanogens and enhances that of methanotrophs to reduce CH_4 emissions (Sonoki et al., 2013). In addition, the adsorption of NH_4^+ by biochar will reduce the nitrogen utilization efficiency by methanogens, thereby inhibiting the activity of methanogens and reducing CH_4 emissions (Karhu et al., 2011). Furthermore, adsorption by biochar weakens the competitive inhibitory effect of NH_4^+-N on the methane monooxygenase activity and enhances the oxidation of methanotrophs, with further reductions in CH_4 emission (Liu et al., 2017).

4.2.3. N_2O

The emission of N_2O during composting is a complex process and biochar can affect it as follows. (1) Biochar reduces the amount of inorganic nitrogen that can be utilized by nitrifying bacteria and denitrifying bacteria by capturing NH_4^+ and NO_3^-, thereby decreasing N_2O emissions (He et al., 2019; Xiao et al., 2017). (2) The surface of biochar can absorb N_2O and reduce it to N_2 through biological or abiotic reactions (Harter et al., 2016). (3) The enzymes that catalyze N_2O production and N_2O consumption during denitrification are encoded by the *nirK/nirS* (Yin et al., 2019b) and *nosZ* genes (Xiao et al., 2017), respectively. The addition of biochar during the composting process can suppress the expression of *nirK* and enhance the expression of *nosZ*, thereby leading to reduced N_2O emissions during composting (Li et al., 2016; Wang et al., 2013).

4.2.4. NH_3

Adding biochar to compost can mitigate NH_3 emissions as follows. (1) NH_3 and NH_4^+ are absorbed by the acidic functional groups on the surface of biochar (Godlewska et al., 2017). (2) Biochar enhances the composting environment and the activities of nitrifying bacteria that convert ammonia into nitrate, thereby retaining nitrogen within the compost (Akdeniz, 2019). (3) Biochar treatment increases the cellulase activity in the compost (Yin et al., 2021), and thus more dissolved organic carbon is produced via the decomposition of cellulose, which enhances the microbial utilization of NH_4^+ and ultimately reduces NH_3 emissions (Agyarko-Mintah et al., 2017).

4.3. *Different effects of biochar on mitigating GHG emissions during composting*

Many studies have explored the effects of adding biochar on the emission of various GHGs during composting. Table 2 shows that adding biochar can mitigate the emissions of various GHGs during composting but the effects varied greatly among studies because of the different types of biochar employed and treatment conditions (dosage, pyrolysis temperature, and particle size). Thus, the effects of biochar on GHG emissions during composting have been investigated under different conditions, such as various dosages (Awasthi et al., 2020), biochar types (Chen et al., 2017), pyrolysis temperatures (Li et al., 2015), and particle sizes (He et al., 2019). Moreover, it has been shown that combining biochar with other additives can be more effective at mitigating GHG emissions (Mao et al., 2018; Wang et al., 2018; Wang et al., 2017).

4.3.1. Effects of biochar dosage

Several studies have shown that the effect of biochar on mitigating GHG emissions is significantly related to the amount of biochar added (Awasthi et al., 2017; Liu et al., 2017). In most studies, the amount of biochar added ranged from 0 to 20% (w/w), and about 10% was the most effective. For example, Awasthi et al. (2017) found that the addition of 2–18% biochar had a significant difference in GHG emissions mitigation effect from compost, where adding 12% biochar had the greatest effect. Similarly, comparisons based on the addition of different amounts of biochar ranging from 2 to 10% showed that adding 10% biochar had the greatest effect on reducing GHG emissions from compost (Awasthi et al., 2020).

In general, a low amount of biochar does not have a significant effect on reducing GHG emissions from compost. Thus, a study showed that compared with adding no biochar, the addition of 8–18% biochar (dry weight) reduced the CH_4, N_2O, and NH_3 emissions by 92.85–95.34%, 95.14–97.28%, and 58.03–65.17%, respectively, whereas the addition of 2–6% biochar had little effect on the emission of these GHGs (Awasthi et al., 2017). Similarly, another study found that compared with adding no biochar, there were no notable differences in the CO_2, CH_4, and N_2O emissions from compost with 3% added biochar (dry weight) because insufficient biochar was added (Sánchez-García et al., 2015). In addition, adding an excessive amount of biochar will have an adverse effect on the composting process. A study of the effects of biochar added at different rates (5%, 10%, or 20%; wet weight) to chicken manure compost found that adding more than 10% biochar led to severe water loss and heat dissipation in the composting pile, with negative impacts on the composting process (Liu et al., 2017).

4.3.2. Effects of raw materials used to produce biochar

The raw materials used for biochar production can significantly affect the GHG emissions during composting because they influence the physicochemical properties of biochar (Akdeniz, 2019). As mentioned in Sections 4.2.1–4.2.4, the abundant pores in the structure of biochar can improve the aeration of the compost pile, enhance the activity of aerobic bacteria, such as nitrifying bacteria and methanotrophs, and inhibit the activity of anaerobic bacteria, such as methanogens and denitrifying bacteria. The surface of biochar can adsorb NH_4^+, NH_3, and N_2O. These factors all contribute to reducing the emission of CH_4, N_2O, and NH_3 from compost. Therefore, in combination with the influence of the type of raw material on the properties of biochar in Section 2.1, biochar produced from crop residues and woody biomass is better at mitigating CH_4, N_2O, and NH_3 emissions from compost.

Several studies support this conclusion. In particular, Chen et al. (2017) investigated the effects of adding bamboo biochar, corn straw biochar, coir biochar, woody biochar, and layer manure biochar on the CH_4 and NH_3 emissions from compost. Adding corn straw biochar resulted in the lowest CH_4 and NH_3 emissions because this biochar had a high pore volume, surface area, and total acidic functional groups (Chen et al., 2017). Similarly, the CH_4 and N_2O emissions were 19.79% and 42.01% lower, respectively, when bamboo biochar was added compared with adding rice straw biochar (He et al., 2019) because the pore volume and specific surface area were larger for bamboo biochar and the degree of aromatization was higher (He et al., 2019).

4.3.3. Effects of pyrolysis temperature used for biochar production

As mentioned in Section 2.1, the temperature used to prepare biochar can affect the porosity, specific surface area, and aromaticity, which increase as the pyrolysis temperature increases, whereas the abundance of acid oxygen-containing functional groups decreases on the surface of the biochar. Therefore, the effects of biochar prepared from the same material at different temperatures will vary on the GHG emissions during composting.

The addition of porous biochar will improve the oxygen environment in the composting pile and reduce CH_4 emissions (Sonoki et al., 2013). Adding biochar with a higher pore volume, specific surface area (Agyarko-Mintah et al., 2017), and degree of aromatization will have a greater effect on mitigating N_2O emissions during composting (He et al., 2019). The abundant acidic functional groups present on the surface of biochar can effectively mitigate NH_3 emissions during composting (Wang and Zeng, 2018). Therefore, in combination with studies of the influence of the pyrolysis temperature on the properties of biochar in Section 2.1, biochar produced by pyrolysis at high temperatures (500–900 °C) is better at reducing CH_4 and N_2O emissions, whereas biochar produced by pyrolysis at low temperatures (200–500 °C) is more effective at decreasing NH_3 emissions.

Previous studies have not investigated the effect of the pyrolysis temperature used for biochar production on reducing CH_4 and N_2O emissions during composting. However, a study compared the effects of adding biochar produced at different pyrolysis temperatures (300 °C, 450 °C, and 600 °C) on N_2O emissions from soil, where biochar produced at 600 °C was most effective at decreasing N_2O emissions (Deng et al., 2021). In addition, Li et al. (2015) compared the effects of adding biochar prepared at different pyrolysis temperatures (300 °C, 500 °C, 700 °C, and 900 °C) on the NH_3 emissions during composting, and found that they were significantly lower with biochar prepared at 300 °C and 500 °C compared with biochar prepared at 700 °C and 900 °C.

4.3.4. Effects of biochar particle size

The importance of particle size cannot be ignored when using biochar. The particle size significantly affects the pore characteristics and specific surface area of biochar.

A study showed that adding powdered biochar (4 mm to 1 cm) increased the CH_4 emissions from compost by 56.84%, whereas adding granular biochar (<1 mm) decreased the CH_4 emissions by 22.15% (He et al., 2018). This difference can be explained by the granular biochar destroying the aggregates of pig manure particles to make the compost pile looser, whereas the pig manure was readily mixed with the powdered biochar, and thus it was more difficult to form connections between the pores (He et al., 2018). Thus, adding granular biochar increased the porosity of the composting pile to reduce CH_4 emissions. Another study compared the effects of adding granular (4 mm to 1 cm) and powdered (<1 mm) biochar on the N_2O and NH_3 emissions during pig manure composting, and showed that adding powdered biochar was more effective at mitigating NH_3 emissions because more functional groups were exposed on the surface of the powdered biochar, but the size of the biochar had little effect on the N_2O emissions (He et al., 2019).

4.3.5. Effects of combining biochar with other additives

In addition to biochar, many other additives are effective at mitigating GHG emissions during composting, and combining biochar with other additives can have a greater effect on reducing GHG emissions. In particular, compared with adding no biochar during pig manure composting, adding biochar together with zeolite reduced the N_2O and NH_3 emissions by 78.13% and 63.40%, respectively, whereas adding biochar alone reduced the N_2O and NH_3 emissions by 64.91% and 35.88% (Wang et al., 2017). Similarly, compared with adding no biochar during the pig manure composting process, the combined application of biochar, zeolite, and wood vinegar reduced the CO_2, CH_4, N_2O, and NH_3 emissions by 46.98%, 61.15%, 81.10%, and 74.32%, respectively, whereas they only decreased by 26.06%, 41.73%, 64.91%, and 35.88% with biochar alone (Wang et al., 2018). Moreover, compared with adding no biochar during pig manure composting, the combined application of bacterial powder and biochar reduced the CH_4, N_2O, and NH_3 emissions by 69%, 45%, and 26%, respectively, whereas they only decreased by 54%, 37%, and 13% with biochar alone (Mao et al., 2018).

5. Recommendations for future research

5.1. Combined use of biochar with other additives

Studies have shown that applying biochar and other additives can effectively mitigate GHG emissions, and combining biochar with other additives may have a synergistic effect. Thus, future studies should investigate the effects of combining biochar with other additives to reduce GHG emissions from compost.

5.2. Modified biochar

Modification can enhance the properties of biochar, which has been applied widely in sewage treatment and soil improvement research, and thus modified biochar might more effectively mitigate GHG emissions during composting.

5.3. Biochar particle size

The particle size significantly affects the specific surface area and number of surface functional groups on biochar, as well as the aeration of the compost pile. However, few studies have explored the effects of the size of biochar particles on GHG emissions during composting, and thus further investigations are required.

5.4. Establish standards for the use of biochar

Establishing a standard for the production and use of biochar will facilitate the more efficient mitigation of GHG emissions during composting.

6. Conclusion

Adding about 10% (w/w) biochar is a suitable option for mitigating GHG emissions during composting. Biochar produced via the pyrolysis of crop residues and woody biomass at temperatures of 500–900 °C is more effective at mitigating CH_4 and N_2O emissions, whereas biochar produced via the pyrolysis of crop residues and woody biomass at temperatures of 200–500 °C is better at reducing NH_3 emissions. The addition of granular biochar can better reduce CH_4 emissions whereas powdered biochar can better mitigate NH_3 emissions. In addition, modifying biochar or combining it with other additives is potentially more effective at mitigating GHG emissions. Finally, a set of standards for the production and use of biochar should be developed to reduce GHG emissions during composting.

CRediT authorship contribution statement

Yanan Yin: Conceptualization, Data curation, Methodology, Writing - review & editing, Funding acquisition.
Chao Yang: Validation, Methodology, Investigation.
Mengtong Li: Data curation, Investigation.
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Jie Gu: Review & editing.
Haichao Li: Visualization, Review & editing.
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Xiaochang Wang: Supervision, Writing - review & editing.
Rong Chen: Funding acquisition, Supervision, Project administration, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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