Effects of Membrane Covers and Biochar on Compost Quality and Greenhouse Gas Reduction in Aerobic Composting

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The addition of biochar and the use of membrane coverings are two methods used in aerobic composting of agricultural waste. The effectiveness of each of these two methods on compost quality and reduction of greenhouse gas emissions was tested in the laboratory. The results showed that both methods increased the maximum composting temperature and extended the thermophilic period. The germination index of biochar-treated compost and membrane-covered compost reached 70% on the 18th day, which was 12 days earlier than the corresponding value in the control group. The products from the biochar-treated compost had higher pH and lower electrical conductivity, compared with the product of the control group, indicating that these products are more suitable for acidic soils. In terms of greenhouse gas reduction, both methods were found to reduce the emissions of CH_4 and N_2O from composting. The addition of biochar had a better emission reduction effect on N_2O, whereas the membrane covering technique yielded a better effect on CH_4 emission reduction. The results of this study provide technical support for managed aerobic composting to reduce greenhouse gas emissions.

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Keywords: Membrane cover; Biochar; Aerobic composting; Greenhouse gas

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INTRODUCTION

Aerobic composting, a stabilization and humification process of organic matter, is the most economical and effective disposal technology for converting agricultural organic waste into useful resources. The application of compost products to farmlands can increase soil permeability, improve soil water and fertilizer retention capacity and microbial activity, and promote crop yield and quality.

Global warming is a critical issue that requires urgent attention worldwide. On September 22, 2020, at the 75th General Assembly of the United Nations, China officially proposed its goals of achieving a carbon peak by 2030 and carbon neutrality by 2060. As a developing country with a population of 1.4 billion, China's current carbon intensity is much higher than the average level of developed countries; therefore, more measures are needed to reduce carbon emissions from various sectors of society. China's agricultural carbon emissions account for approximately 15% of total emissions and are one of the key areas for targeted emission reduction. The composting of agricultural waste produces three greenhouse gases: CO_2, CH_4, and N_2O. Based on extensive research worldwide, the most used method of composting is to add foreign additives, such as superphosphate (Luo *et al.*

2012), zeolite (Wu *et al.* 2020a), and biochar (Liu *et al.* 2016). Among these, biochar has attracted widespread attention because it is pollutant-free and widely available.

Biochar is a black solid produced from organic matter in agricultural waste under high-temperature anaerobic conditions. It is characterized by a large specific surface area, porous structure, functional groups, and high thermal stability and adsorption capacity. Because of these unique physicochemical properties, the application of biochar as an auxiliary material for composting has attracted the attention of many researchers. According to Wang *et al*. (2020), the addition of biochar promotes the detoxification and maturation of the compost pile, increases the total organic carbon and humic acid contents, and increases the stability of humic acid. Li *et al*. (2023) reported that the application of biochar could enrich the diversity of microbial communities during aerobic composting, ultimately resulting in high diversity. Ottani *et al*. (2023) studied the effect of biochar on reducing greenhouse gas emissions from composting and found that the application of 3% biochar (dry weight) of the initial materials could reduce the production and emission of CH_4 and N_2O during the composting process. Fu *et al*. (2017) found that adding biochar to aerobic composting of pig manure could reduce CH_4 by 16.3 to 23.5%, N_2O by 50.2 to 70.7%, and CO_2 by 8 to 20%. Considering its strong adsorption capacity, theoretically, covering the surface of the compost pile with biochar to absorb greenhouse gases emitted during the composting process should also have a good effect, and this will be studied in detail in my subsequent research.

Functional membrane-covered composting is a static aerobic composting technology that has emerged in recent years. This technology does not require mechanical turning for the treatment of organic waste, and the membrane can be used multiple times. Although the amount of electrical energy needed to pump the air has to be increased, compared to the energy required for traditional mechanical turning, this can still significantly reduce composting costs. This functional membrane originated in the United States and was later used in Germany to reduce odors during the composting process. The core of this functional membrane is a special material with uniformly distributed micropores called expanded polytetrafluoroethylene (e-PTFE), which can be used for its special structure to reduce greenhouse gases. The best-known commercial brand of this functional membrane is Gore-Tex®, manufactured by W. L. Gore & Associates, USA. In China, a functional membrane produced by Zhiteng Technology Co., Ltd. (Qingdao, China) has been shown to be of good quality. Ma *et al*. (2021) conducted research using core membranes and found that they could reduce NH_3 and N_2O emissions by 11.77% and 26.40%, respectively, ultimately reducing GWP by 16.97%. Li *et al*. (2020) found that a functional membrane had a good emission reduction effect on odor gases in compost, which can reduce 58.6% of NH_3 and 38.1% H_2S emissions.

Although extensive research has been conducted on the addition of biochar and the use of membrane-covered technology in aerobic composting, research on membrane-covered technology has mainly focused on reducing odor and nitrogen-containing gases, and there is relatively little research on the reduction of greenhouse gas emissions, namely CH_4 and CO_2. Many researchers have studied the effects of adding biochar to reduce greenhouse gases in compost; however, there are few reports comparing its emission reduction effect with that of membrane-covered technology. In addition, owing to the rapid development of agricultural intensification in China and the enormous pressure for agricultural carbon reduction, the reduction of greenhouse gas emissions during fertilization and utilization of agricultural waste is also becoming more important. In this study, the effects of membrane covering and biochar addition were evaluated relative to the quality of aerobic composting and possible reduction of greenhouse gases. This topic has guiding significance for composting plants to choose suitable greenhouse gas emission reduction technologies for themselves. China's animal husbandry industry has shifted towards large-scale industrial farming, and animal manure has been well treated. Vegetable and mushroom cultivation waste are currently the main agricultural organic waste that needs to be resourcefully utilized. Therefore, tomato straw and mushroom residue were selected as the raw materials for this study, and the mixture of these two wastes can obtain a more suitable carbon nitrogen ratio for aerobic composting. The results of the study will provide technical support for reducing greenhouse gas emissions during the processing and application of agricultural waste.

EXPERIMENTAL

Materials

Tomato stalks were collected from an organic farm in Zhenjiang, Jiangsu Province, China, and crushed to 1 to 3 cm long pieces using a vegetable grinder. The mushroom residue was obtained from a nearby mushroom plant. Biochar, produced by a company in Nanjing, was mainly derived from rice husks. Under anaerobic conditions, the pyrolysis and carbonization temperatures were 450 and 650 °C, respectively, which were maintained for 10 h. The biochar was naturally cooled and sieved with a screen opening size of 0.38 mm. The characteristics of all experimental composting materials are shown in Table 1.

Table 1. Characteristics of the Composting Material

Parameters	TC (%)	TN (%)	C/N	MC (%)	pH value
Tomato stalks	39.31 ± 1.76	1.40 ± 0.05	28.08 ± 1.03	20.7 ± 1.22	8.16 ± 0.48
Mushroom residues	20.42 ± 1.23	1.07 ± 0.02	19.08 ± 0.56	49.4 ± 0.39	7.23 ± 0.33
Mixture	39.61 ± 0.45	1.72 ± 0.04	24.18 ± 0.25	62.8 ± 1.98	7.95± 0.36
Biochar	46.84 ± 0.75	0.59 ± 0.06	79.39 ± 0.25	2.7 ± 0.09	9.62 ± 0.62

TC: Total carbon; TN: Total nitrogen; C/N: the ratio of total carbon to total nitrogen; MC: Moisture content

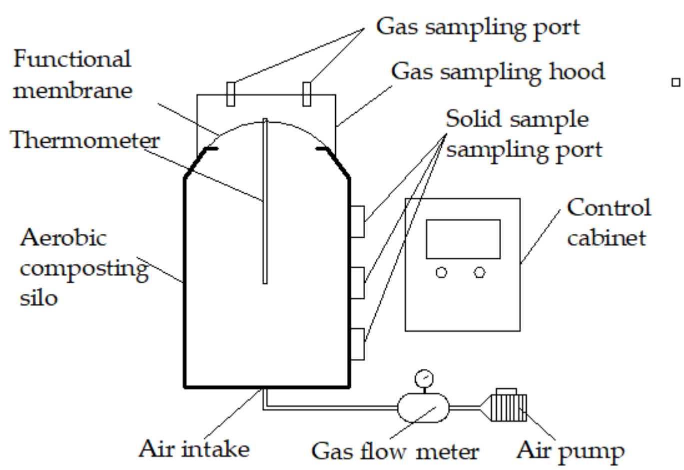

Fig. 1. Structure diagram of aerobic composting device

Experimental Design

The experimental period for aerobic composting was 36 days, and three different treatments were applied to an equal amount of the waste material (mixture of tomato straw and mushroom residue). In the control (CK) group, the top of the aerobic composting device was hollow. In the T1 treatment group, a layer of functional membrane covered the top of the device (Fig. 1). In the T2 group, the fermentation equipment was the same as in the CK group, and 10% biochar (dry weight) was added. The fermentation device used was a 500-L plastic bucket with a diameter of 860 mm and a height of 900 mm, and air was pumped into the bottom of the material through a pipeline at a rate of 0.1 $m^3 \cdot min^{-1} \cdot m^{-3}$. The functional membrane used in the T1 group was purchased from Qingdao Zhiteng Technology Co., Ltd. The main functional material was expanded polytetrafluoroethylene (e-PTFE), and the pore size of the micropores distributed on the membrane was approximately 2 μm.

Sample Collection and Analysis

Temperatures of the three groups were automatically recorded every 24 h using a digital thermometer. On days 0, 6, 12, 18, 24, 30, and 36, solid samples were collected from three different parts of the compost pile and mixed evenly, after which the pH, EC, and germination index (GI) values were immediately measured. Gas samples were collected using a 500-mL aluminum foil gas sampling bag on days 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33 and 36 of the experiment. The concentrations of CH_4, N_2O, and CO_2 in the gas samples were determined through gas chromatography (Agilent Technologies, Santa Clara, CA, USA). The pH, electrical conductivity (EC), and GI were measured using published methods (Cao *et al.* 2022), in which the pH and EC values were measured using a pH meter (model FE28, Mettler Toledo), and the GI of each treatment group was calculated using the following formula:

$$GI = \frac{\text{seed germination (treatment group) (\%)} \times \text{root length (treatment) (mm)}}{\text{seed germination (control group) (\%)} \times \text{root length (control) (mm)}} \times 100$$

Data and Statistical Analyses

Excel 2016 and SPSS 22 were used for data analyses, and plots were generated using OriginPro 9.1.

RESULTS AND DISCUSSION

Changes in Physicochemical Parameters during Composting

Changes in temperature

Temperature is an important indicator reflecting microbial activity, organic matter degradation rate, and harmful bacterial inactivation effect during the composting process (Gao *et al.* 2015; Wu *et al.* 2020b), which affects the composting process and quality (Li *et al.* 2014). The maximum temperature, time to maximum temperature, and length of the thermophilic (heating) period, are all factors associated with effective decomposition.

The treated compost exhibited the typical temperature pattern of aerobic composting (Tiquia *et al.* 1996; Cáceres *et al.* 2015) (Fig. 2). The maximum temperature varied among the three treatment groups, as did the time to maximum temperature. In the CK group, the maximum temperature (65.3 °C) was reached on day 6, after which the temperature declined. In the T1 group, maximum temperature (69.2 °C) was reached on day 4, and in the T2 group, maximum temperature (75.2 °C) was reached on day 3. In other words, the highest temperature was obtained in the biochar-treated compost and the maximum temperature was reached sooner than in the other groups. The heat generated during the composting process is mainly due to the degradation of organic matter by aerobic microorganisms. According to Chen *et al.* (2022a), when the temperature of the compost pile exceeds 55 ℃, the compost enters a thermophilic period that is normally maintained for 5 days at least. In the present study, the thermophilic periods for CK, T1, and T2 were 6, 10, and 8 d, respectively. Temperature changes during the composting process depend on the composting material, microbial activity, and heat dissipation rate (Zhou *et al.* 2018). The longest thermophilic period was observed in the T1 group, indicating that the membrane cover effectively increased and maintained the pile temperature of the compost, which is in line with the conclusion reached by Ma *et al.* (2017).

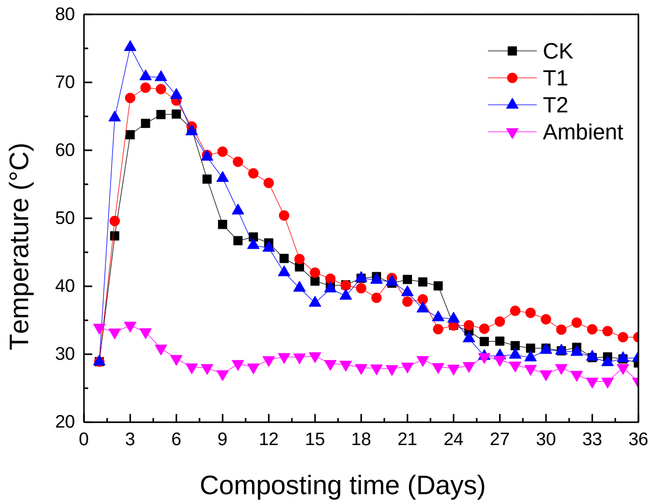

Fig. 2. Temperature changes of the three treatment groups and ambient temperature during composting. CK, control; T1, membrane-covered; T2, biochar addition

With respect to the T2 treatment, the superior performance compared to that of the control group can be attributed to the physical properties of the biochar. The rich pore structure and a large specific surface area not only provide a suitable area for growth of the microorganisms (Jindo *et al.* 2012) but also help to increase the oxygen content of the compost pile, thus enhancing the metabolic activity of microorganisms, resulting in greater heat production (Zhang and Sun 2014). As expected, the T2 group exhibited the highest reactor temperature, and the thermophilic period was longer than that of the CK group (but shorter than that of the T1 group). Similar findings were reported in studies in which livestock manure was mixed with biochar for composting (Janczaka *et al.* 2017).

Changes in pH value

The pH is an important indicator of compost maturity, as it affects the growth and reproduction of microorganisms in the pile. According to Awasthi *et al.* (2016), the most suitable pH range for composting is 6 to 9. As shown in Fig. 3, the pH of the three treatments did not exceed the optimal range throughout the experiment. The pH of the CK and T1 groups showed a trend of initially ascending and subsequently descending. It is probable that the catabolism of acids and the generation of ammonia were the main reasons for the increase in the pH of the CK and T1 groups after the start of the experiment (Jia *et al.* 2016). However, the biochar treatment group showed a different trend. The initial pH of T2 was 8.34, which was significantly higher than that of the other two treatment groups. A significant downward trend was observed during the early stages of the experiment. As shown in Table 1, the pH of the biochar was 9.62, which was the main reason for the high initial pH of the T2 group. The addition of biochar may lead to the degradation of some large-molecule organic matter into small-molecule organic acids (Li *et al.* 2018), which may be attributed to a decrease in pH in the early stages of the experiment. As the experiment progressed, with the volatilization of ammonia, degradation of acid, and release of H^+ by microbial nitrification (Awasthi *et al.* 2018), the pH of the compost pile gradually decreased and stabilized.

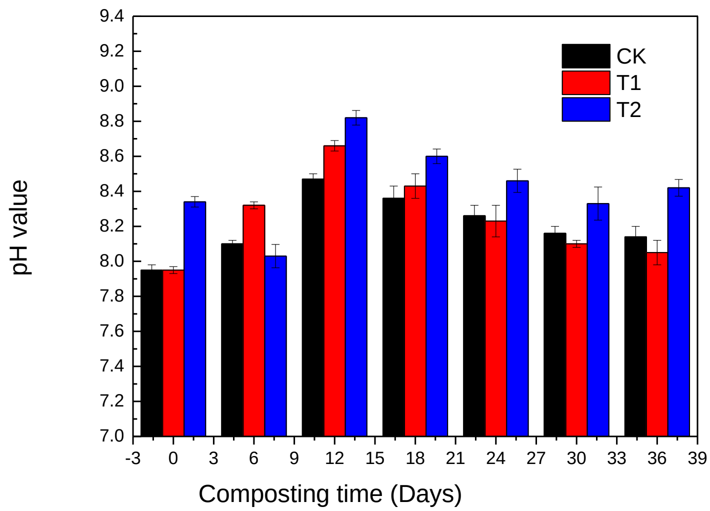

Fig. 3. pH value changes of three treatment groups during composting

Changes in electrical conductivity (EC)

Electrical conductivity (EC) is used to characterize the content of soluble salts in compost and is an important indicator for evaluating the toxic effects of compost products on crops. A high soluble salt content may have an inhibitory effect on seed germination and crop growth. When the EC value is less than 4.0 $mS \cdot cm^{-1}$, the compost products can be defined as safe for soil and plants (Qu *et al.* 2022). As shown in Fig. 4, the EC values of the three treatment groups increased in the first nine days after the start of the experiment, then gradually decreased and stabilized. Ammonium ions and phosphates derived from the rapid mineralization of organic matter may be the reason for the increase in the EC value in the early stages of the experiment. Subsequently, owing to the precipitation of mineral salts and generation of ammonia, the EC value decreased and stabilized during composting. As mentioned in Fig. 1, membrane-covered technology can increase the pile temperature and accelerate the degradation and mineralization of organic matter. The rates of both increase and decrease of EC were greater in the T1 group compared to the corresponding rates in the CK group. The EC value of the T2 group was significantly lower than that of the other two treatments, which was mainly attributed to the adsorption and fixation effect of biochar on free salt ions (Yang *et al.* 2022). The final EC values of the CK, T1, and T2 treatments were 3.33, 3.42, and 3.02 $mS \cdot cm^{-1}$, respectively, all within the safety thresholds for plants and soil.

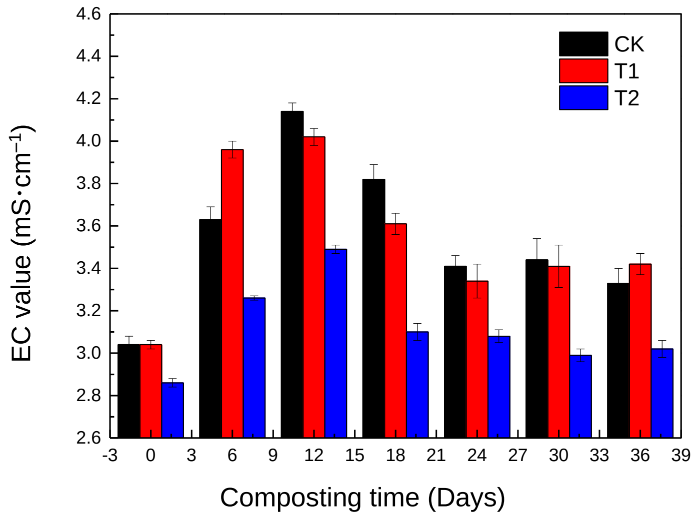

Fig. 4. Electrical conductivity (EC) changes of three treatment groups during composting

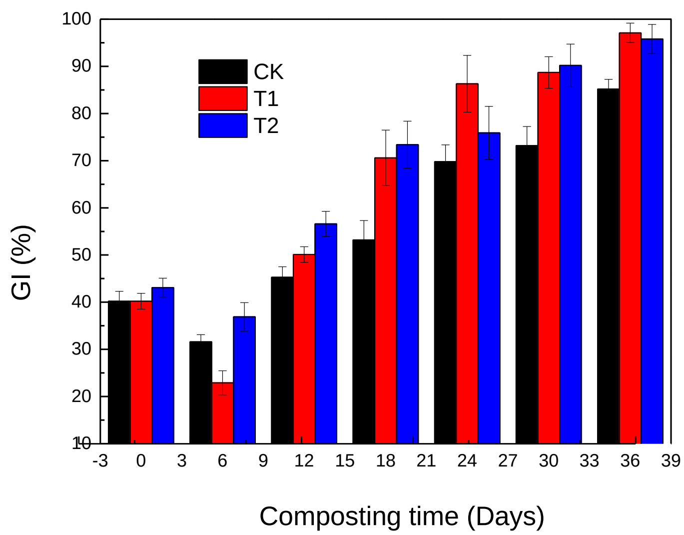

Fig. 5. GI changes of three treatment groups during composting

Changes in Seed Germination Index (GI)

The seed germination index is the most sensitive and effective indicator of compost quality. Researchers have found that the GI gradually increased with the degradation of toxic substances in the compost pile. When the GI of compost products reaches 50%, they can be considered phytotoxicity-free; if the GI is greater than 70%, then the product is considered mature compost (Saidi *et al.* 2009). As shown in Fig. 5, the GI values of the three groups showed a decreasing trend during the first six days and then they gradually increased. The rapid degradation of organic matter produces substances that are not conducive to seed germination, which might be the reason for the decrease in the GI value. As the composting reaction progressed, toxic and harmful substances in the compost pile were gradually degraded by the microorganisms, and the GI values of the three treatment groups steadily increased until the end of composting. The final GI values of the three treatments were 85.2%, 97.1%, and 95.8%, respectively, all of which met the maturity requirements. Compared to the CK group, the T1 and T2 required a shorter time to reach 50% and 70% GI, respectively, indicating that either biochar addition or membrane covering can accelerate the composting process and shorten the composting cycle.

Greenhouse Gas Emissions during Composting

The greenhouse gases emitted during composting mainly included CO_2, N_2O, and CH_4. The contribution rates of N_2O and CH_4 to the greenhouse effect are 298 and 25 times that of CO_2, respectively. According to the guidelines of the Intergovernmental Panel on Climate Change (IPCC) on greenhouse gas emissions from agriculture, CO_2 emissions from composting originate from biological processes and should not be counted as a contributing factor to global warming. In this study, three greenhouse gases, including CO_2, were measured to investigate the effects of these two methods on reducing greenhouse gas emissions from composting.

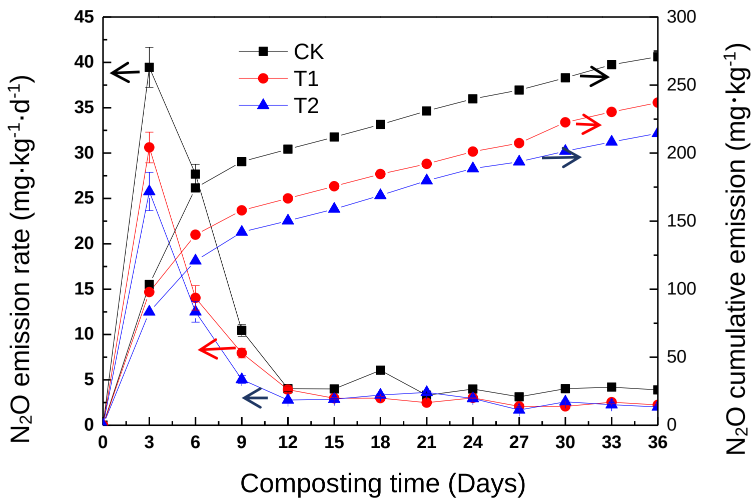

Fig. 6. N_2O emission rate and cumulative emission changes of three treatment groups during composting

N_2O emission

The N_2O emission rates and cumulative emissions of the three groups are shown in Fig. 6. The main sources of N_2O in composting are nitrification of NH_4^+-N and incomplete denitrification of NO_X^--N. The N_2O emission of three treatments were concentrated in the first 12 days after the start of the experiment, and all reached their maximum values on day 3: CK, 39.45; T1, 30.48, and T2, 25.77 mg·kg^{-1}·d^{-1}. The rapid production of N_2O may have originated from the autotrophic oxidation of NH_4^+ to NO_2^-, which is an intermediate stage of N_2O production. Similar conclusions have been reported in previous studies (Sun *et al.* 2014; Zhu *et al.* 2014; Agyarko-Mintah *et al.* 2017). However, N_2O emissions are mainly concentrated in the middle and late stages of composting, which is the cooling stage (Mao *et al*. 2018; Li *et al.* 2020). Investigators have suggested that both nitrification and denitrification may have an inhibitory effect on N_2O when the temperature exceeds 40 °C. The accumulation of NO_2^- and differences in the composting materials may be the main reasons for these differences. In the present study, the total N_2O emissions of the T1 and T2 groups were 14.18% and 21.42% less than those of the CK group, respectively, indicating that either biochar addition or membrane-covered technology can reduce N_2O emissions from composting, with biochar addition having a somewhat better emission reduction effect. The pore structure of biochar can adsorb NH4+- N and NO_3^-- N in the compost pile, and the high pH of biochar can change the abundance of denitrifying bacteria during composting, leading to a decrease in N_2O emissions in the T2 group.

CH_4 emission

The CH_4 emission rates and cumulative emissions of the three groups are shown in Fig. 7. The main source of CH_4 during composting was the anaerobic zone in the compost pile. The peak values of CH_4 emissions from the three treatment groups all appeared on day 6 after the start of the experiment and were 145.11, 34.55, and 107.26 mg·kg^{-1}·d^{-1}, respectively. The rapid production of CH_4 was mainly due to the rapid degradation rate of organic matter during this stage and the high demand for oxygen by aerobic microorganisms, which leads to anaerobic fermentation reactions in some areas of the compost pile. Similar conclusions have been reached in previous studies (Tao *et al.* 2014; Chen *et al*. 2022b). The highest methane emission reduction effect was achieved with the membrane-covered technology (T1), with cumulative methane emissions being 70.8% lower than that of the CK group. This result is attributed to the micro-positive pressure air environment created by the membrane cover; such an environment promotes the uniform distribution of oxygen inside the pile, thereby greatly reducing the anaerobic area in the pile and reducing the production of methane. As for the biochar-treated compost (T2), the methane emission reduction effect can be attributed to the increased porosity of the amended compost, thus improving its oxygen supply capacity and reducing anaerobic zone. Fu *et al*. (2017) reported similar conclusions; however, the authors posited that that biochar adsorbs a large amount of soluble organic carbon, thereby reducing the available activated carbon for anaerobic microorganisms, leading to the main reason for a decrease in methane production. The total CH_4 emissions of the T1 and T2 groups were 70.8% and 23.9% less, respectively, than the corresponding values measured in the CK group. The membrane-covered technology exhibited better methane emission reduction than did biochar addition.

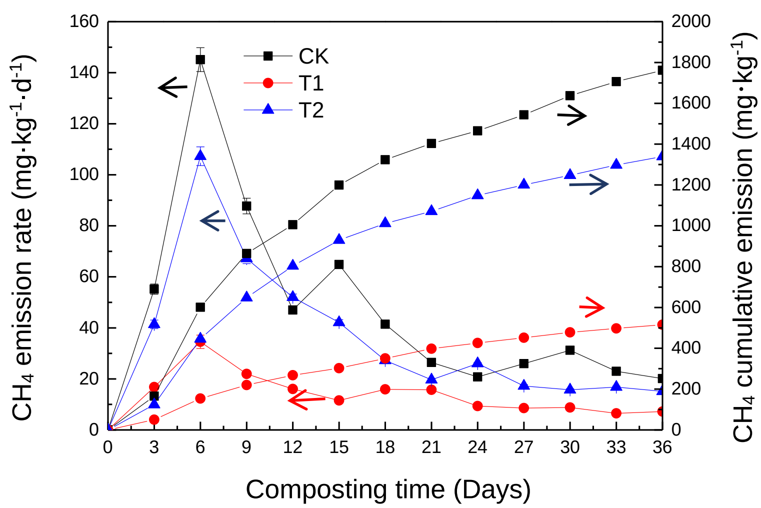

Fig. 7. CH_4 emission rate and cumulative emission changes of three treatment groups during composting

CO_2 emissions

The CO_2 emission rates and cumulative emissions of the three groups are shown in Fig. 8. The main source of CO_2 in the composting process is oxidative degradation of organic matter. Similar to the trend of N_2O emissions, the CO_2 emissions from composting were mainly concentrated in the first 12 days after the start of the experiment, and maximum values of 32.1 (CK), 41.1 (T1), and 44.8 (T2) $g \cdot kg^{-1} \cdot d^{-1}$ occurred on day 3. Organic matter is mineralized and degraded by aerobic microorganisms, which generate large amounts of CO_2. As the easily biodegradable organic matter gradually decreases, microbial metabolism becomes limited, and the amount of CO_2 produced gradually decreases. Cumulative CO_2 emissions of the T1 and T2 groups were 514 and 486 $g \cdot kg^{-1}$, respectively, which were 41.2% and 38.0% higher than that of the CK group. Unlike the role played in reducing CH_4 and N_2O emissions, neither membrane-covered technology nor the addition of biochar reduced the generation and emission of CO_2. Composting is a process in which aerobic microorganisms convert organic matter into humus through oxidative degradation, which is inevitably accompanied by the production and emission of CO_2. As mentioned previously, adding biochar can improve the porosity of the stack, increase the oxygen supply capacity of the pile, and promote the degradation of organic matter, thus increasing CO_2 emissions. Membrane-covered technology creates a micro-positive pressure environment, thereby promoting the uniform transfer of oxygen and degradation of organic matter, thus increasing CO_2 emissions. In recent years, some researchers have studied technological methods to convert organic matter more into humus rather than mineralize it into CO_2 during composting, thereby reducing greenhouse gas emissions.

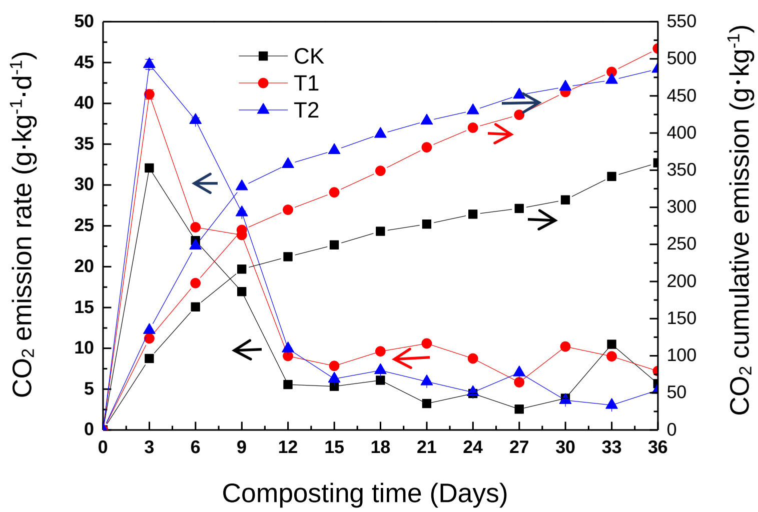

Fig. 8. CO_2 emission rate and cumulative emission changes of three treatment groups during composting

CONCLUSIONS

1. In terms of the impact of bioreactor temperature, both biochar addition and membrane-covered technology can increase the temperature and duration of the thermophilic period, which is more conducive to killing harmful pathogenic bacteria in the pile. Compared to these two methods, the membrane-covered technology resulted in longer

thermophilic period, and the addition of biochar resulted in higher maximum temperature. The highest temperature in the membrane-covered compost was 6.0 ℃ lower than the maximum temperature obtained in the biochar-treated compost, and the thermophilic period was 2 days longer in the membrane-covered group.

2. In terms of material maturity, both biochar addition and membrane-covered technology can accelerate the decomposition of compost piles, and the two methods have similar effects on improving GI values.
3. In terms of greenhouse gas reduction, both biochar addition and membrane-covered technology can reduce N_2O and CH_4 emissions from the compost; however, CO_2 emissions were found to increase. Adding biochar reduced N_2O emissions by 21.4% and CH_4 emissions by 23.9%, but increased CO_2 emissions by 38.0%. The covering of the compost reactor with a membrane reduced N_2O emissions by 14.2% and CH_4 emissions by 70.8% but increased CO_2 emissions by 41.2%.

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