



# Influence of Peat and Biochar on Gas Emissions and Microbial Metabolism During Co-composting of Chicken Manure and Maize Straw

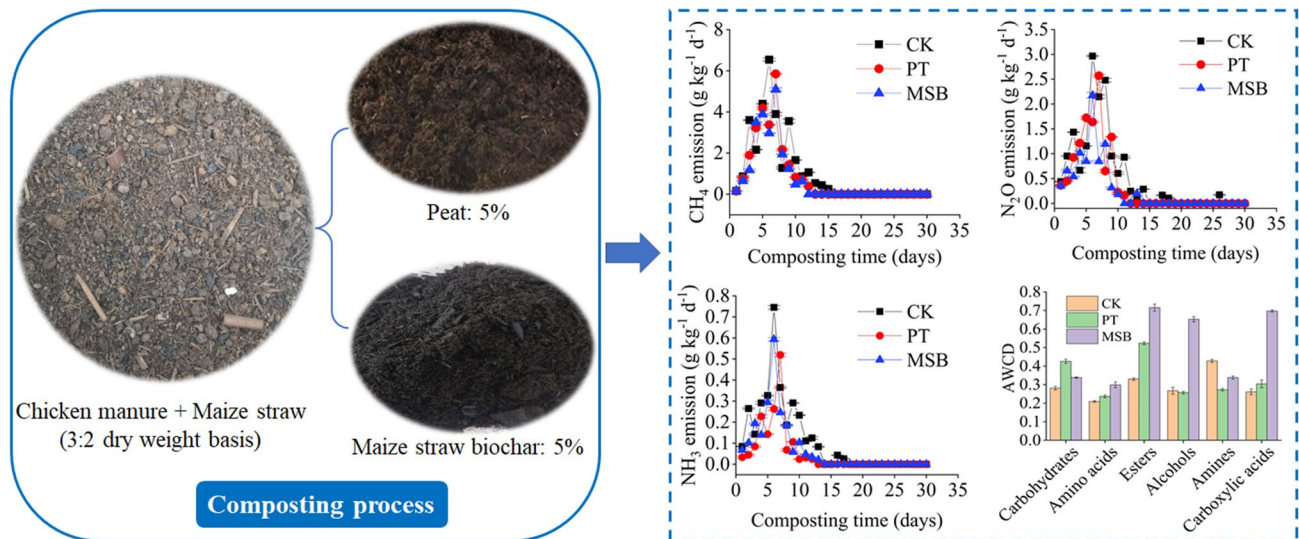
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## Abstract

This study investigated the effects of peat (PT) and maize straw biochar (MSB) on gas emissions and microbial metabolism characteristics during chicken manure (CM) and maize straw (MS) composting. Three treatments with different additives (0%, 5% PT, 5% MSB added on dry weight basis) were designed to conduct 30-day aerobic composting experiments in nine insulated polyvinyl chloride (PVC) reactors. The results showed that PT and MSB addition increased the temperature and nitrate-nitrogen ( $\text{NO}_3^-$ -N) content but decreased the ammonium nitrogen ( $\text{NH}_4^+$ -N) content of compost. Compared with control, the total emissions of methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ) and ammonia ( $\text{NH}_3$ ) in PT and MSB were reduced by 20.13–30.57%, 28.88–47.46% and 37.35–52.71%, respectively. In addition, PT and MSB amendments improved the microbial utilization capacity on carbohydrates, esters and carboxylic acids. Redundancy analysis revealed that temperature,  $\text{NH}_4^+$ -N, pH and microbial metabolism were positively correlated with  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  emissions. Meanwhile, temperature,  $\text{NH}_4^+$ -N and pH also had positive correlations with microbial metabolism. Together these results indicated that PT and MSB amendment improved the metabolism capacity of microbes and reduced  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  emissions, eventually mitigating nitrogen loss and promoting the quality of compost product.

## Graphical Abstract



Mengting Feng and Xiaoyu Wu have contributed equally to this work.

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**Keywords** Chicken manure · Peat · Maize straw biochar · Gas emissions · Microbial metabolism

## Statement of Novelty

This experiment aimed to evaluate the efficiency of peat (PT) and maize straw biochar (MSB) to decrease gas emissions of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  during chicken manure (CM) and maize straw (MS) composting. The carbon sources degradation capacity of microbes at different composting stages was detected. Redundancy analysis revealed the relative contributions of environmental factors and microbial metabolism on gas emissions. Our finding suggested that PT and MSB effectively inhibited the release of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  and promoted the quality of compost, thus reducing the risk of gas emissions during CM and MS composting and improving the agricultural value of compost products.

## Introduction

Chicken manure (CM) has increased rapidly due to the sustained development of the large-scale livestock industry in the past decades. It is estimated that approximately 457 million tons of CM are globally produced each year [1]. CM is a vital fertilizer resource for farming and gardening [2] because it is rich in organic matter and essential plant nutrients such as nitrogen, phosphorous, calcium and potassium [3, 4]. However, CM contains many pathogens, parasite ova, and toxic substances [1], and the direct application of CM into the soil would cause a series of environmental and social problems [5, 6].

Composting has proven to be an eco-friendly and economically feasible technology for recycling organic waste [7]. It is a natural biological process that converts organic matter into stable and sanitary end products [8]. Notably, large amounts of ammonia ( $\text{NH}_3$ ) and greenhouse gas (GHG) are released with the decomposition of organic matter during the composting process, resulting in atmospheric pollution and reduction in the agricultural value of compost products. Numerous studies have demonstrated that additives amendment could effectively alleviate gas emissions during composting. A previous report showed that 10% clay addition reduced methane ( $\text{CH}_4$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ) emissions during pig manure composting [9]. Fukumoto et al. [10] revealed that the addition of nitrite-oxidizing bacteria after the thermophilic phase of composting inhibited  $\text{NO}_2^-$  accumulation and thus decreased the emission rate of  $\text{N}_2\text{O}$ . Awasthi et al. [11] also found that the emissions of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  were effectively reduced during co-composting of dewatered fresh sewage sludge, lime and biochar.

Peat (PT) is one of the carbon-based materials produced by the decomposition of the plants under a water-saturated and anoxic condition [12]. It was reported that PT possessed excellent characteristics such as high specific area, high pH range and abundant humic acid [13]. PT could be a potential bulking agent for composting because it can increase cation exchange capacity and regulate the moisture content and density of compost [14]. Chang et al. [15] found that the addition of woody peat could promote the maturity process and significantly decrease the nitrogen loss during vegetable waste composting. As a stable carbon-rich material, biochar can regulate bulk density, water retention and oxygen supply during composting [16, 17]. The high porosity and sorption capacity of biochar can provide suitable habitats for microorganisms and stimulate the activity of microbes in compost, which may effectively control nitrogen loss and gas emissions [18, 19]. Awasthi et al. [20] studied the effects of bamboo biochar on poultry manure composting, and their results suggested that bamboo biochar amendment reduced the emissions of GHG and  $\text{NH}_3$ . Agyarko-Mintah et al. [21] found that green waste and poultry litter biochar addition reduced the total nitrogen (TN) and  $\text{NH}_3$  losses and improved the fertility of final compost products. Wheat straw biochar was demonstrated to play a positive role in organic matter degradation and nitrogen conservation during sewage sludge composting [22, 23]. Compared to wheat straw biochar, maize straw biochar (MSB) performed better in terms of thermophilic temperature and TN concentration during pig manure composting [24]. Although many researches about the influence of biochar as an additive on compost had been reported, no study focused on the contrast effects of PT and MSB on gas emissions and microbial metabolism during CM and MS composting.

In this study, we evaluated the impacts of PT and MSB on  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  emissions during co-composting of CM with MS. Biolog EcoPlate is a low-cost, convenient and rapid technique for detecting the carbon sources utilization ability of microbial populations [25]. Therefore, we used Biolog EcoPlate to investigate the carbon sources metabolism of microbes during composting. The relationships between environmental factors, microbial metabolism and gas emissions were also evaluated to understand the variations of gas emissions during composting. The results obtained from this study would provide new insights into the development of composting technology and better understand important factors responsible for the changes in  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  emissions during the CM and MS composting process.

## Materials and Methods

### Experimental Design

The composting materials in the present study comprised fresh CM, MS, PT and MSB. The fresh CM and MS were collected from a local farm (Jiujiang, Jiangxi Province, China). The MS was cut into 5 mm pieces before use. PT and MSB were purchased from a factory in Jiangsu Province, China. The biochar was prepared from MS by pyrolysis at a temperature of 400 °C in oxygen-poor condition for 8 h. The basic properties of the raw materials are shown in Table 1. Composting was conducted in 9 insulated polyvinyl chloride (PVC) reactors (diameter 45 cm, height 73 cm, active volume 100 L) [20, 26]. The CM and MS were thoroughly mixed with the ratio of 3:2 (dry weight basis), and each treatment contained approximately 75 L of the mixture. PT or MSB was added in different treatments. The treatment contained 5% (w/w) PT was labeled as PT, while that contained 5% (w/w) MSB was labeled as MSB. The control treatment (CK) was conducted by introducing the mixture without additives. Each treatment was repeated three times. The duration of the composting was 30 days. Deionized water was added to composting piles to maintain 60% moisture content throughout the experiment. Intermittent aeration (twice a day for 20 min) was employed with an air pump at a rate of 0.45 L kg<sup>-1</sup> (dry weight) h<sup>-1</sup>. The pile temperature and ambient temperature were monitored daily using digital thermometers located in the middle of each pile and outside the reactors.

### Sampling and Chemical Analysis

Compost samples were collected from each treatment on day 1, 5, 10, 15, 20, 25 and 30. Each sample (about 250 g) was distributed into two parts: one part was immediately stored at 4 °C, and the other was air-dried and preserved in a desiccator. Electricity conductivity (EC) and pH were analyzed using aqueous extracts of compost samples. The aqueous extracts were obtained by mechanically shaking the mixture of samples and deionized water at a ratio of 1:5 (w/v, dry weight basis) for 1 h [27, 28]. TN content was determined by an elemental analyzer (Elementar, Germany) [29]. The concentrations of ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N)

and nitrate-nitrogen (NO<sub>3</sub><sup>-</sup>-N) were measured via sodium hydroxide solution titration and ultraviolet spectrophotometer colorimetry, respectively [30]. The germination index (GI) of samples was analyzed as described previously [31].

### Gas Emissions Measurement

Gas sampling was carried out every 5 days during the composting period. Gas samples were collected with syringes and stored in 1-L gas sampling bags [32]. The concentrations of N<sub>2</sub>O and CH<sub>4</sub> in gas samples were analyzed by gas chromatography (Agilent 6890 N, USA) [33]. The NH<sub>3</sub> concentration was determined by absorbing the exhausted gas with the boric acid solution before titration with 1 mol L<sup>-1</sup> HCl [34].

### Biolog EcoPlate Analysis

Biolog EcoPlate analysis was conducted to investigate the capacity of microorganisms to oxidize different carbon sources during composting [35]. The analyses were performed from fresh compost samples collected on day 1, 10 and 30. A fresh compost sample (1 g) was shaken in 100 mL of sterile NaCl solution (0.85%, w/v) for 20 min at 20 °C. The obtained suspension was diluted to 1:1000 and then inoculated onto a Biolog EcoPlate with a pipettor. Each well of the EcoPlate was added with 150 µL of the diluted suspension. The plates were subsequently incubated at 25 °C in the dark for 6 days. The absorbances of the plates were measured at 590 nm and 750 nm every 24 h using an automatic microorganism identification instrument (Biolog, USA). The absorbance data were used to calculate average well color development (AWCD), which could reflect the metabolic capacity of microorganisms in compost. The well absorbance values were corrected by subtracting the absorbance of the control well before the data analysis. The AWCD was calculated as follows: AWCD =  $\sum OD_i/n$ , where OD<sub>i</sub> represents the mean optical density value from each well, n is the number of carbon substrates (31 for EcoPlate) [36].

### Statistical Analysis

Statistical analysis was conducted using SPSS 16.0 (SPSS for Windows, version 16.0, USA) with the significance level  $p < 0.05$ . Redundancy analysis was performed using the R

**Table 1** Basic characteristics of the raw composting materials

Parameters	Chicken manure	Maize straw	Peat	Maize straw biochar
Moisture content (%)	79.39 ± 0.27	9.78 ± 0.26	19.63 ± 0.26	1.74 ± 0.03
pH	7.61 ± 0.05	7.14 ± 0.03	5.25 ± 0.04	9.12 ± 0.05
TC (g kg <sup>-1</sup> )	379.28 ± 7.52	437.25 ± 18.64	453.48 ± 14.09	381.36 ± 22.54
TN (g kg <sup>-1</sup> )	29.52 ± 0.77	6.32 ± 0.24	5.64 ± 0.19	7.28 ± 0.29

Cluster package (version 3.5.0 for Windows) to identify the correlation between gas emissions, environmental factors and microbial metabolism.

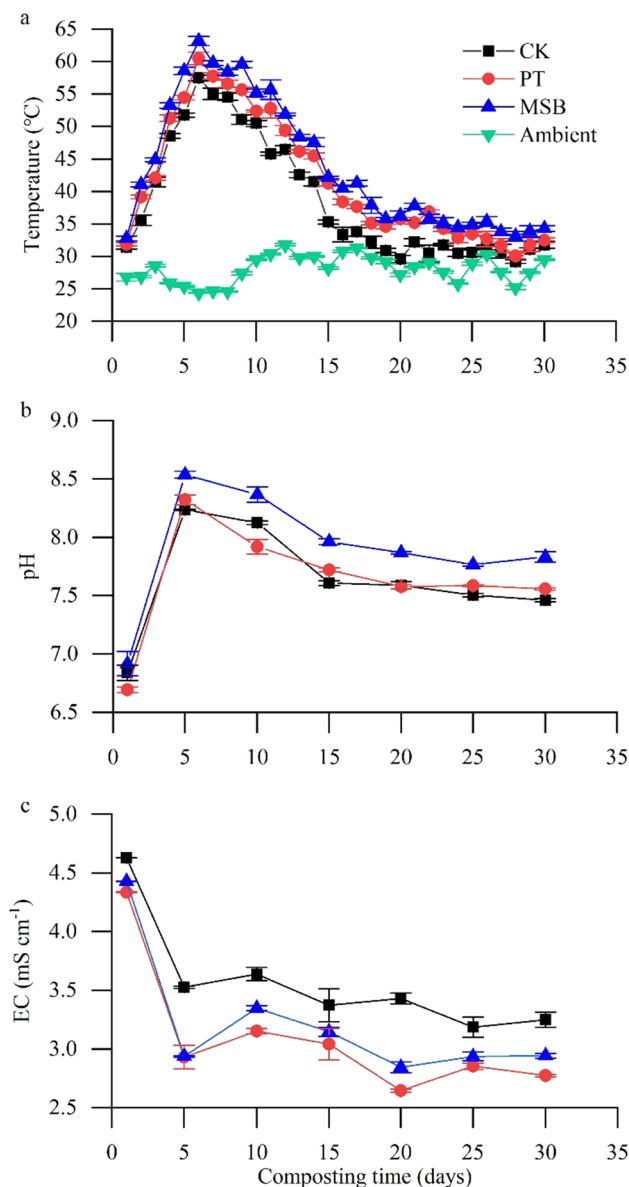
## Results and Discussion

### Variation in Physicochemical Properties of the Compost

Temperature is considered a principal parameter that determines the evolution of microbial communities and the degradation of organic materials during the composting process [37]. In the present study, the temperature of all piles elevated rapidly during the initial stage of composting (Fig. 1a). It took 5 days for CK to exceed 50 °C, and the following thermophilic phase lasted 6 days. Both PT and MSB exceeded 50 °C on day 4 and maintained the thermophilic phase for 8 days and 9 days, respectively. The peak temperatures of PT (60.5 °C) and MSB (63.2 °C) were higher than that of CK (57.5 °C). As the composting progressed, the temperatures in all groups gradually decreased to close to the ambient level. These results indicated that the addition of PT and MSB increased the temperature and prolonged the thermophilic period of composting. As described in previous studies, the high surface area of PT and MSB could provide more suitable conditions for microbial reproduction and metabolism [13, 38, 39], thus accelerating the degradation of organic matter and increasing the pile temperature. It was reported that temperature above 50 °C could accelerate the rate of composting and kill pathogenic microorganisms [40, 41]. Consequently, the addition of PT and MSB could promote composting maturity and improve the quality of matured compost.

As shown in Fig. 1b, the pH in three treatments rose rapidly in the first 5 days of composting. The mineralization of organic matters such as proteins and amino acids led to the accumulation of  $\text{NH}_3$  [42], which contributed to the increase of pH during this stage. The peak pH in MSB (8.5), PT (8.3) and CK (8.2) was recorded on day 5, and then the pH gradually decreased in the later stage of composting. The highest pH value in MSB was likely due to the absorption capability of biochar to nitrogen-containing substances during composting [43]. The formation of lower molecular weight fatty acids and  $\text{CO}_2$  may be responsible for the subsequent decline in pH [44]. At the end of composting, the pH in three treatments was relatively stable, and the pH values were 7.5, 7.6 and 7.8 for CK, PT and MSB, respectively.

EC can reflect the compost salinity and determine the effects of matured compost on seed germination [45]. The initial EC values in three treatments ranged from 4.3 to 4.6  $\text{mS cm}^{-1}$  (Fig. 1c). The EC value of each treatment decreased sharply in the early stage of composting. From day 5 onward,



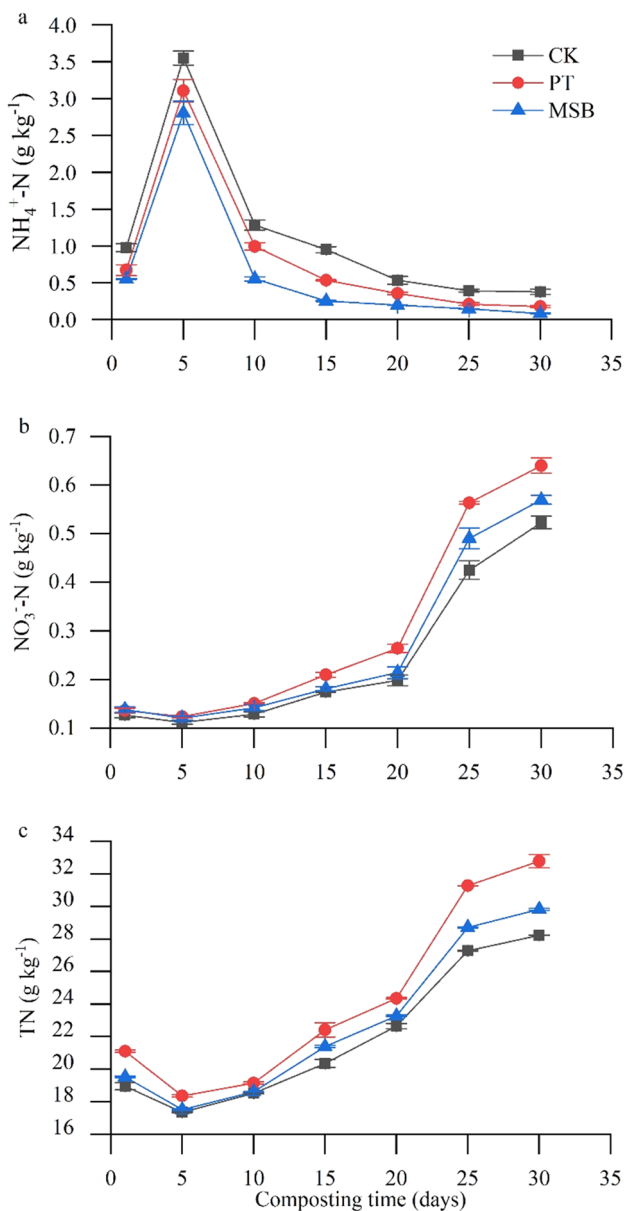
**Fig. 1** Changes in temperature (a), pH (b) and EC (c) from different composting treatments. Error bars represent  $\pm$  standard deviation

the EC values in three treatments gradually increased and then fluctuated until the end of composting. The final EC values in CK, PT and MSB were 3.3, 2.8 and 2.9  $\text{mS cm}^{-1}$ , respectively. In general, composting products could be safely applied into farmland only when the EC values of products were lower than 4.0  $\text{mS cm}^{-1}$  [46]. Hence, the end-products in all treatments met the safety standards of application.

### Evolution of $\text{NH}_4^+\text{-N}$ , $\text{NO}_3^-\text{-N}$ and TN During Composting

As shown in Fig. 2a, the  $\text{NH}_4^+\text{-N}$  content of three treatments increased rapidly during the first 5 days. The increase

in  $\text{NH}_4^+\text{-N}$  was likely due to the rapid decomposition of organic nitrogenous compounds in the early stage of composting [47]. Fang et al. [48] pointed out that the low pH in compost promoted the conversion of  $\text{NH}_3$  into  $\text{NH}_4^+\text{-N}$ , which could explain the higher  $\text{NH}_4^+\text{-N}$  content in CK compared to PT and MSB during this period. The peak  $\text{NH}_4^+\text{-N}$  contents were 3.55, 3.11 and 2.81  $\text{g kg}^{-1}$  in CK, PT, and MSB treatments, respectively. Afterward, the  $\text{NH}_4^+\text{-N}$  content in three treatments sharply declined from day 5 to day 10 and then gradually stabilized. Raj and Antil [49] reported that the decrease of the  $\text{NH}_4^+$  might enhance nitrification



**Fig. 2** Variation in the content of  $\text{NH}_4^+\text{-N}$  (a),  $\text{NO}_3^-\text{-N}$  (b) and TN (c) during composting of all treatments. Error bars represent  $\pm$  standard deviation

and immobilization by microorganisms. After 30 days of composting, the  $\text{NH}_4^+\text{-N}$  contents for CK, PT and MSB were 0.38, 0.18 and 0.08  $\text{g kg}^{-1}$ , respectively. As described previously, the  $\text{NH}_4^+\text{-N}$  content lower than 0.20  $\text{g kg}^{-1}$  was regarded as a maturity and stability index for compost [8]. Our data indicated that the addition of PT and MSB could improve the maturity and stability of final composting products.

$\text{NO}_3^-\text{-N}$  is an essential nitrogen source for plant metabolism and growth [50]. In the present study, a similar trend of  $\text{NO}_3^-\text{-N}$  content was observed in all treatments (Fig. 2b). The  $\text{NO}_3^-\text{-N}$  content in three treatments slightly decreased during the initial stage and then gradually increased. Previous studies have demonstrated that the nitrifying bacteria could transform  $\text{NH}_3$  into  $\text{NO}_3^-\text{-N}$  during composting, and high temperature strongly inhibited the growth and activity of nitrifying bacteria [51, 52]. Therefore, the increase of  $\text{NO}_3^-\text{-N}$  content mainly occurred during the mature stage of composting. At the end of composting, the  $\text{NO}_3^-\text{-N}$  contents were 0.52, 0.64 and 0.57  $\text{g kg}^{-1}$  for CK, PT and MSB treatments, respectively. It was noted that PT exhibited higher content of  $\text{NO}_3^-\text{-N}$  than CK and MSB. As the first step of nitrification, oxidization of  $\text{NH}_3$  needed a suitable amount of alkali [53], and the decrease of pH would be favorable for the nitrification process. We inferred that the acidity of wood peat might provide a more suitable pH condition for nitrification and therefore increase the  $\text{NO}_3^-\text{-N}$  content during composting.

TN is one of the primary parameters to evaluate the quality of compost products [8]. The TN content of all treatments slightly decreased in the first 5 days and then gradually increased over time. The variation of TN content was possibly related to the continuous degradation of nitrogenous compounds during composting [54]. The TN content in end-products of CK, PT and MSB were 28.23, 32.77 and 29.83  $\text{g kg}^{-1}$ , respectively. This finding suggested that the addition of PT and MSB could increase the nutrient contents of compost products. Awasthi et al. [27, 28] reported that the additives amendment facilitated the growth and activity of aerobic bacteria associated with organic nitrogen mineralization and therefore increased the nutrient contents of compost, which was consistent with our results.

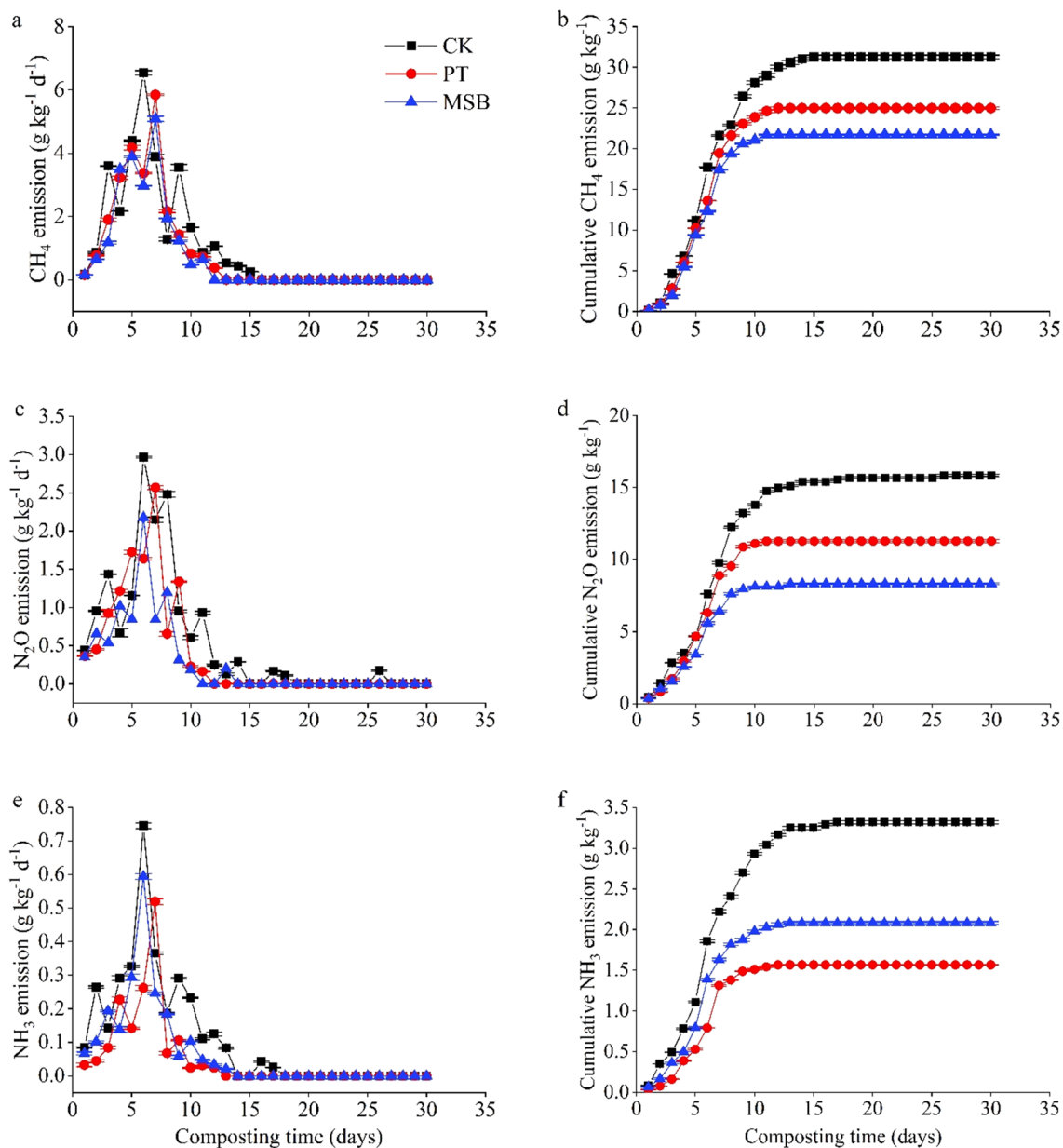
### Changes in Greenhouse Gases and Ammonia Emissions

$\text{CH}_4$  is produced by methanogens under anaerobic conditions [34]. The  $\text{CH}_4$  emissions of all treatments primarily occurred in the thermophilic stage and then gradually decreased (Fig. 3a). With the increase of temperature, large amounts of organic matter were rapidly decomposed by microorganisms and caused inadequate oxygen supply during the thermophilic stage of composting [55, 56]. As a result, the partially

anaerobic area in compost was developed in this stage to produce  $\text{CH}_4$ . Besides, Gilroyed et al. [57] pointed out that methanotrophic community was not established in the initial phase of composting and thus, the oxidation of  $\text{CH}_4$  was not completely efficient. The cumulative  $\text{CH}_4$  emission in three treatments showed an increase in the early stage and then tended to be stable (Fig. 3b). After 30 days of composting, the addition of PT and MSB reduced the total  $\text{CH}_4$  emission by 20.13% and 30.57% compared with CK, respectively. It was possible because the high specific area of PT and MSB could partially improve the aeration condition, thereby

accelerating the growth and activity of methanotrophs and enhancing  $\text{CH}_4$  oxidation [13, 58]. In addition, the high pore volume of biochar had been demonstrated to increase  $\text{CH}_4$  sorption [59], which may account for the highest removal rate in compost with PT addition.

Many researchers have studied the  $\text{N}_2\text{O}$  emission profile for its profound impacts on nitrogen conservation and global warming [47, 60]. In the present study, all treatments exhibited a relatively high  $\text{N}_2\text{O}$  emission rate in the early stage of composting and reached the highest  $\text{N}_2\text{O}$  emission in the first week (Fig. 3c). The peak values of  $\text{N}_2\text{O}$  emission in CK,



**Fig. 3** Emissions and accumulations of methane (a and b), nitrous oxide (c and d) and ammonia (e and f) in different composting piles. Error bars represent  $\pm$  standard deviation

PT and MSB were 2.97, 2.57 and 2.18 g kg<sup>-1</sup> day<sup>-1</sup>, respectively. As reported by previous studies, the N<sub>2</sub>O emission during composting is a complex process influenced by many factors, and N<sub>2</sub>O can be produced under both nitrification and denitrification processes [61–63]. Notably, the activity of nitrifiers was generally considered to be inhibited when the temperature was above 40 °C [64]. Meanwhile, Philippe et al. [65] reported that rapid depletion of oxygen and low nitrate concentration promoted the formation of N<sub>2</sub>O in the denitrification process. These findings suggested that the large amount of N<sub>2</sub>O in the first week might be produced mainly through the denitrification of nitrate. The high CH<sub>4</sub> emission in the first week (Fig. 3a) further demonstrated the inadequate oxygen supply during this period, supporting the possibility of N<sub>2</sub>O as a by-product of denitrification. As shown in Fig. 3d, the cumulative emissions of N<sub>2</sub>O in PT and MSB remained constant after day 17, while that in CK reached a stale value until day 26. Compared with CK, the cumulative emissions of N<sub>2</sub>O on day 30 were reduced by 28.88% and 47.46% in PT and MSB, respectively. These results indicated that PT and MSB, especially MSB, efficiently decreased the N<sub>2</sub>O emission during CM and MS composting. The significant difference between MSB and CK was supported by Cornelissen et al. [66], who found direct sorption of N<sub>2</sub>O into biochar. Joseph et al. [67] also reported that biochar had redox activity and might act as the reducing agent in soil. Given the possibility of N<sub>2</sub>O emission via denitrification, we supposed that the redox activity of MSB might facilitate the transformation of NO<sub>3</sub><sup>-</sup>-N to N<sub>2</sub>, thus decreasing the N<sub>2</sub>O emission during composting.

The NH<sub>3</sub> emission during composting causes nitrogen loss of compost products [6]. The variations of NH<sub>3</sub> emission in our experiment are shown in Fig. 3e. Initially, the NH<sub>3</sub> emissions in the three treatments increased sharply and reached their maximum values in the thermophilic stage. The peak values were 0.75, 0.52 and 0.59 g kg<sup>-1</sup> day<sup>-1</sup> for CK, PT and MSB, respectively. The emission of NH<sub>3</sub> in animal manure was affected by pH and NH<sub>4</sub><sup>+</sup>-N H<sub>3</sub> transformation equilibrium [54]. In the initial stage, nutrient degradation was accompanied by increased pH and temperature in compost (Fig. 1). Meanwhile, the mineralization and ammoniation of organic nitrogen rapidly increased the production of NH<sub>4</sub><sup>+</sup>-N, which could volatilize in the form of NH<sub>3</sub> due to high temperature and pH [68]. After 7 days of composting, the NH<sub>3</sub> emission gradually decreased and eventually approached zero. This was attributable to the decrease of pH, which increased the content of acid radical ions and shifted the NH<sub>4</sub><sup>+</sup>-N H<sub>3</sub> equilibrium [69]. The total cumulative NH<sub>3</sub> emissions were 1.57 and 2.08 g kg<sup>-1</sup> for PT and MSB, respectively, which were lower than CK (3.32 g kg<sup>-1</sup>). The results showed that the addition of PT and MSB could efficiently reduce the volatilization of NH<sub>3</sub> during composting, which might be associated with the large surface area

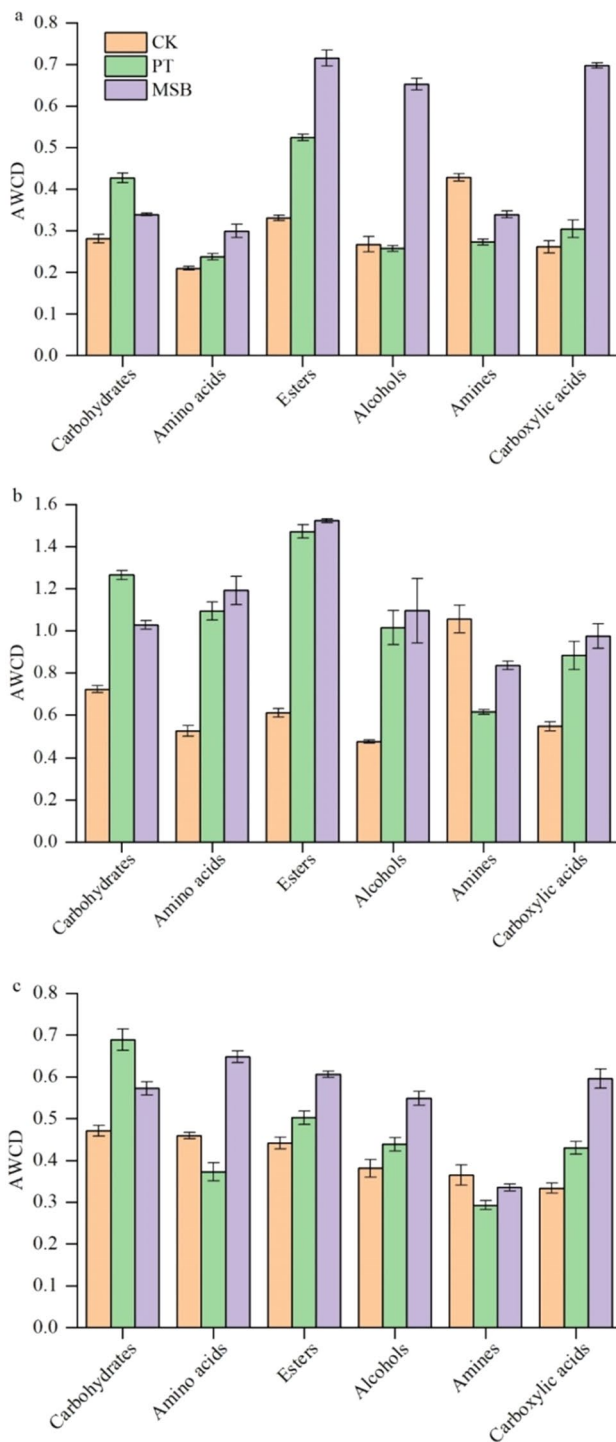
and small particle size of PT and MSB. Previous research demonstrated that bulking agent with a large specific surface area could absorb NH<sub>4</sub><sup>+</sup>-N and NH<sub>3</sub> [32]. Besides, PT and MSB with small particle sizes could result in high bulk density of mixed compost materials, thereby reducing the NH<sub>3</sub> emission [62].

### Carbon Sources Utilization Capacity of Microbial Community

Biolog EcoPlate analysis was conducted to evaluate the carbon sources utilization capacity of microbial community at different stages of composting. The 31 carbon sources in the Biolog EcoPlate were classified into six categories according to the biochemical properties. The AWCD of six carbon sources in three treatments is shown in Fig. 4. The AWCDs of carbohydrates, amino acids, esters and carboxylic acids increased in PT and MSB compared to CK on day 1, indicating that the addition of PT and MSB improved the carbon sources utilization ability of microbes. The peak values of six carbon sources for three treatments were observed on day 10, which meant that the microbial community had the highest metabolic activity in the thermophilic phase among the three composting stages. On day 30, the AWCDs of most carbon sources were still higher in PT and MSB than those in CK. PT and MSB provided more nutrients and suitable habitats for microorganisms and consequently increased the metabolic activity of microbial community. As reported in a previous study, microbial activity of compost exerted a certain role in controlling soil-borne pathogens [70]. Therefore, compost with the addition of PT or MSB might be more efficient at maintaining soil health.

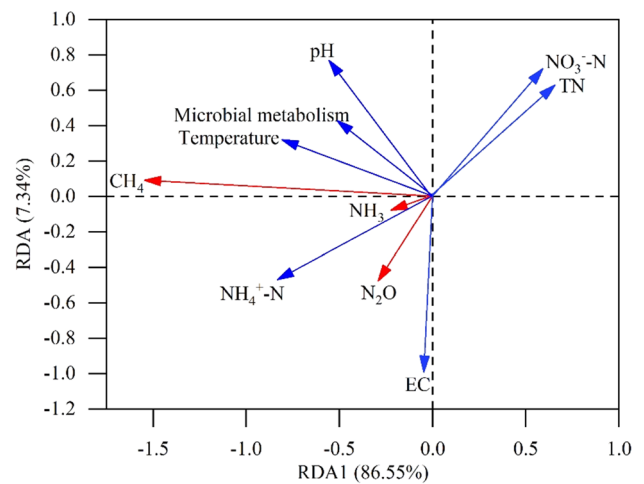
### Relationships Among Environmental Factors, Microbial Metabolism and Gas Emissions

Redundancy analysis was performed to determine the relationships among environmental factors, microbial metabolism and gas emissions. The results showed that the selected variables accounted for 93.89% of the total variations in gas emissions (Fig. 5). Among the selected factors, environmental factors and microbial metabolism explained 51.10% and 47.46% of the variations, respectively. Environmental factors such as pH, NH<sub>4</sub><sup>+</sup>-N and temperature had positive correlations with CH<sub>4</sub> emission. NH<sub>4</sub><sup>+</sup>-N was negatively correlated with NH<sub>3</sub> emission, because NH<sub>4</sub><sup>+</sup>-N and NH<sub>3</sub> would be transformed to each other under suitable condition [6]. Similarly, Yang et al. [71] indicated a negative correlation between NH<sub>4</sub><sup>+</sup>-N and NH<sub>3</sub> during pig manure composting. Apart from NH<sub>3</sub>, NH<sub>4</sub><sup>+</sup>-N also showed a negative correlation with N<sub>2</sub>O emission. The reason for this may be that the higher NH<sub>4</sub><sup>+</sup>-N concentration restricted the activity of nitrifying bacteria and therefore caused insufficient NO<sub>3</sub><sup>-</sup>-N



**Fig. 4** Average well color development (AWCD) of carbon sources in the Biolog EcoPlate on day 1 (a), day 10 (b) and day 30 (c), respectively. Error bars represent  $\pm$  standard deviation

to produce  $N_2O$ . Moreover, EC exhibited negative correlations with the emissions of  $N_2O$  and  $NH_3$ . Previous studies demonstrated that the increase of soluble salts concentration in compost could lead to the increase of EC [23, 72]. The



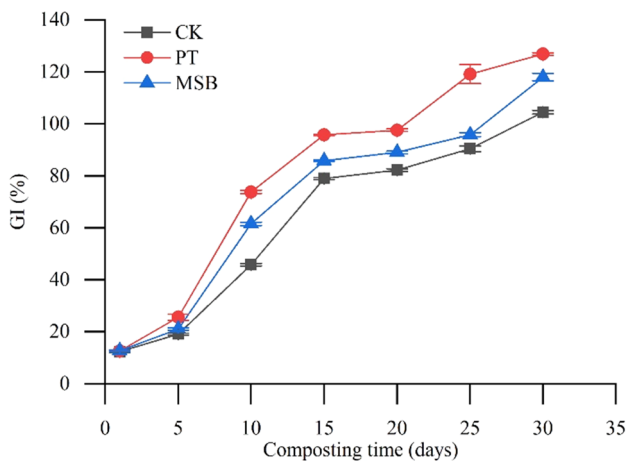
**Fig. 5** Redundancy analysis based on the relationships between environmental factors, microbial metabolism and gas emissions. (Color figure online)

emissions of  $N_2O$  and  $NH_3$  reduced the concentration of soluble nitrogen salts and consequently resulted in the decrease of EC in this experiment. Interestingly, our data showed that pH was negatively correlated with the  $N_2O$  emission. Many reports have confirmed that pH could directly affect  $N_2O$  production by regulating nitrification and denitrification processes [73, 74]. The  $N_2O$ -reductase has been recognized as the key enzyme for reducing  $N_2O$  production in denitrification [75]. It is noteworthy that the decrease of pH would inhibit the activity of  $N_2O$ -reductase [73], thus leading to higher  $N_2O$  emissions. Microbial metabolism exhibited an essential role in the emissions of  $CH_4$ ,  $N_2O$  and  $NH_3$ . The relationships between microbial metabolism and gas emissions were previously demonstrated. For example, Zhang et al. [76] reported that the reduction in  $CH_4$  emission was closely associated with the metabolism of methanogens and methanotrophs. Getahun et al. [77] also pointed out that microbial metabolism could convert some proteins to  $NH_3$ . In addition, microbial metabolism was positively correlated with pH,  $NH_4^+-N$  and temperature. Overall, the addition of PT and MSB changed environmental factors of compost and further influenced the metabolism of microbial, eventually resulting in the variations of  $CH_4$ ,  $N_2O$  and  $NH_3$  emissions.

### Evaluation of Compost Maturity

The GI is considered one of the most sensitive indicators for evaluating changes in product toxicity and the degree of compost maturity [8]. The GI values among all treatments increased gradually throughout the composting period (Fig. 6). At the end of composting, the GI values in CK, PT and MSB were 104.5%, 118.0% and 126.9%, respectively.





**Fig. 6** Germination index (GI) in different treatments during composting. Error bars represent  $\pm$  standard deviation

These results demonstrated that the addition of PT and MSB improved the quality of compost products. According to the standard of U.S. Composting Council, the GI value of compost product should exceed 90%. Therefore, the addition of MSB promoted the quality of compost product better than PT. Guo et al. [78] found that  $\text{NH}_4^+$ -N content had negative correlations with GI during composting. The higher GI values in PT and MSB might be due to the reduction of  $\text{NH}_4^+$ -N content during the composting period.

## Conclusions

This study indicated that PT and MSB amendment increased the pile temperature and prolonged the thermophilic stage of compost. PT and MSB could facilitate the degradation of organic matter and nitrogen conservation during compost. The addition of PT and MSB increased the GI value and promoted the quality of compost. PT and MSB effectively inhibited the release of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  during co-composting of CM and MS. Biolog EcoPlate analysis revealed that PT and MSB enhanced the microbial metabolism involved in carbohydrates, esters and carboxylic acids throughout the composting period. The emissions of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_3$  were significantly associated with microbial metabolism, which was influenced by temperature,  $\text{NH}_4^+$ -N and pH of compost.

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**Data Availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of 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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