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RESEARCH ARTICLE

Effect of spent mushroom substrate as a bulking agent on gaseous emissions and compost quality during pig manure composting

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Abstract

The aim of this study was to investigate the gaseous emissions (CH_4, N_2O, and NH_3) and compost quality during the pig manure composting by adding spent mushroom substrate (SMS) as a bulking agent. The control treatment was also studied using corn stalk (CS) as a bulking agent. The experiment was conducted in a pilot scale composting reactor under aerobic condition with the initial C/N ratio of 20. Results showed that bulking agents significantly affected gaseous emissions and compost quality. Using SMS as a bulking agent improved composting efficiency by shortening the time for maturity. SMS increased germination index and humic acid of the final compost (by 13.44 and 41.94%, respectively) compared with CS. Furthermore, composting with SMS as a bulking agent could reduce nitrogen loss, NH_3, and N_2O emissions (by 13.57, 35.56, and 46.48%, respectively) compared with the control. SMS slightly increased CH_4 emission about 1.1 times of the CS. However, a 33.95% decrease in the global warming potential of CH_4 and N_2O was obtained by adding SMS treatment. These results indicate that SMS is a favorable bulking agent for reducing gaseous emissions and increasing compost quality.

Keywords Composting · Ammonia · Greenhouse gas · Spent mushroom substrate · Compost quality · Pig manure

Introduction

Nowadays, livestock feedlots are increasing in size and in animal density with large amounts of solid manure produced on a relatively small land base. Without proper treatment, these wastes can cause a series of problems such as hygiene hazards, odor pollution, and ground and surface water pollution (Santos et al. 2016). Due to the high organic matter and nutrient content, livestock manure is a valuable resource for organic fertilizer. However, fresh manure is unsuitable for direct land application owing to the unstable organic matter (OM), weed seeds, and pathogens (Guo et al. 2012). Analysis in literature indicates that composting is an effective, sustainable, and economically feasible technology for the treatment of livestock manure prior to land application (Awasthi et al. 2016; Lim et al. 2016).

However, mismanagement of the composting process results in emissions of harmful gases (such as NH_3, CH_4, and N_2O) which lead not only to the decline in value of the compost as a fertilizer, but also the malodor problem during composting (Lim et al. 2016; Santos et al. 2016). Due to the degradation of N-containing compounds, NH_3 emission appeared especially in the thermophilic phase (Jiang et al. 2015). CH_4 is formed by the deoxidization of CO_2/H and acetic acid by methanogens under anaerobic conditions (Santos et al. 2016). The formation of N_2O occurs during incomplete nitrification/denitrification processes that normally convert NH_4^+ into N_2. During denitrification; N_2O can be synthesized where there is a lack of O_2 or a nitrate (or nitrite) accumulation (Nigussie et al. 2016; Reino et al. 2017). Besides, N_2O can also be produced in the presence of O_2 or low availability of degradable carbohydrates during nitrification (Nigussie et al. 2016; Reino et al. 2017). Therefore, N_2O can be produced under both aerobic and anaerobic conditions. Moreover, CH_4 and N_2O are both significant greenhouse gases (GHGs) with the global warming potential over a 100-

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year time frame of 34 and 298 times, respectively, compared with CO_2 (IPCC 2013).

C/N ratio is one of the major factors that can affect composting (Guo et al. 2012; Onwosi et al. 2017). Low C/N ratio can lead to a high NH_3 emission, while high C/N ratio might make this process very slow due to the excessive amount of degradable OM (Bernal et al. 2009; Onwosi et al. 2017). The optimum C/N ratio for composting is agreed to be in the range of 15–30, especially 20–25 (Guo et al. 2012). The C/N ratio of pig manure is about 12–14 (Guo et al. 2012; Jiang et al. 2015). Bulking agent, which was found to have a relative high C/N ratio, could be added to balance the C/N ratio of pig manure during composting (Chowdhury et al. 2014). In addition, bulking agent plays an important role in the conditioning of the starting composting mixtures, which are usually used to create inter-particle voids, providing air space, regulating the moisture content of waste, and also providing carbon source for micro-organisms (Santos et al. 2016; Yang et al. 2013). Corn stalk is a common and economical bulking agent (Guo et al. 2012). Previous study has found that using corn stalk as a bulking agent not only improves the maturity of compost but also reduces gaseous emissions during composting and increases the amounts of reusable nutrients that are present in the compost (Yuan et al. 2016).

In China, with the country urbanizes, the standard of living and income level increases which leads to higher consumption of industrial crop such as mushrooms. Moreover, with the development of mushroom industry, large quantities of waste are being produced within concentrated areas. Spent mushroom substrate (SMS) is the remains of the substrate in which mushrooms are produced. Due to the high OM content, SMS has been widely used as energy feedstock and organic fertilizers in recent years (Paredes et al. 2009; Wu et al. 2013). However, the presence of phytotoxic compounds and active OM in SMS may cause hygiene hazard problems during agricultural utilization (Medina et al. 2012). SMS is thought to require a 1–2-year weathering cycle prior to being commercially soil-applied (Chefetz et al. 2000). Thus, using SMS as a bulking agent during composting cannot only condition the initial composting material but also enhance the stabilization degree of SMS. Moreover, previous studies reported that the fungi that existed in SMS could accelerate the degradation of polycyclic aromatic hydrocarbon (PHA) and immobilization of heavy metals (García-Delgado et al. 2013).

However, to our knowledge, the effect of adding SMS as a bulking agent on gas emission coupled with advanced maturity indicators such as humification indices has not yet been systematically studied. In order to address the research gaps, the objectives of this study were to (1) evaluate the effect of SMS as a bulking agent on gas emissions during composting process, including CH_4, N_2O, and NH_3; (2) comprehensively evaluate and compare compost quality using maturity (including humus indices) and stability indices.

Materials and methods

Composting materials and experimental design

Pig manure was collected from Sujiatuo pig farm (Beijing, China). Corn stalk was taken from Shangzhuang Experimental Station and chopped to lengths of 2–3 cm. Spent mushroom substrate was provided by a mushroom farm in Beijing. After three harvesting cycles of mushroom, the SMS was air-dried and crumbed by hand to 2–3 cm prior to use. The physical and chemical properties of these raw materials and the initial compost mixture are all presented in Table 1.

Composting reactors were a series of cement rotting box with the dimension of 1.08 m × 0.8 m × 1.4 m (length × width × height, pilot scale). Detailed descriptions of these reactors are also available elsewhere (Jiang et al. 2015). Continuous aeration rate was set at 0.24 L kg^{-1}DM min^{-1}.

Two treatments with three replicates were carried out, namely, CS: pig manure + corn stalk; SMS: pig manure + spent mushroom substrate. The CS was a control treatment. Pig manure and bulking agent (corn stalk or spent mushroom substrate) were mixed with the C/N ratio of 20. Distilled water was added to adjust the moisture to approximately 60%. On the 14th day, water was added to adjust the moisture content to 60% in order to satisfy microbial needs (Hough et al. 2010).

Table 1 Physical and chemical properties of raw materials and compost mixture

Materials		TOC[a] (g kg^{-1})	TKN[a] (g kg^{-1})	C/N	MC[b] (%)
Pig manure		352 (4.58)	27.4 (0.10)	12.9 (0.10)	74.12 (1.52)
CS		411 (7.81)	10.7 (0.44)	38.4 (0.44)	8.51 (0.09)
SMS		359 (5.68)	16.1 (0.14)	22.3 (0.14)	11.62 (0.17)
Compost mixture	CS	381 (5.17)	19.1 (0.19)	19.9 (0.12)	59.81 (2.13)
	SMS	356 (4.68)	17.9 (0.09)	19.9 (0.14)	60.21 (2.41)

Values in parentheses are standard deviations of mean values

TOC total organic carbon, *TKN* total Kjeldahl nitrogen, *MC* moisture content

[a] Dry weight basis

[b] Wet weight basis

Compost sampling and analytical methods

The treatments were operated for 28 days. Temperature was measured by a thermocouple sensor inserted into the middle of the composting materials and continuously recorded by a computer. Homogeneous samples of compost were taken after totally mixing during the turning on the 0th, 3rd, 7th, 14th, 21st, and 28th days. The solid samples were collected using multipoint sampling method (from more than 5 different locations). A part of samples was air-dried, milled with mixer mill (Retsch MM400, Germany), and passed a 0.15-mm mesh screen while the other was stored at 4 °C for analysis. Fresh samples were prepared for the measurement of moisture content (MC), seed germination index (GI), pH, and E_4/E_6. Air-dried samples were prepared for the determination of total organic carbon (TOC), total Kjeldahl nitrogen (TKN), extractible carbon (C_{Ex}), humic acid carbon (C_{HA}), and fulvic acid carbon (C_{FA}). All indices were replicated three times for each sample.

The moisture content was determined by drying the solid samples in an oven at 105 °C for about 8 h until a constant weight was achieved. The pH, GI, and E_4/E_6 were measured by adding deionized water to the samples at a solid to water ratio of 1:10 (*w*/*v*). Then, pH was measured by a pH probe (PHS-3C, China) and E_4/E_6 was determined by the colorimetric method. GI was determined using the method described by Yang et al. (2013). TOC and TKN of compost samples were measured according to Chinese national standard of organic fertilizer (NY 525-2012). C_{Ex}, C_{FA}, and C_{HA} were extracted and measured following the method described previously by Li et al. (2017).

The method of gas sample collection was according to that of Jiang et al. (2015). The composting reactors were covered by a box, and samples were taken 10 min after covering. Gas samples were collected with the air sampler and analyzed four times per day for the first 2 weeks and two times per day for the remaining days. The CH_4 and N_2O were analyzed using the gas chromatograph (3420A, Beifen, China), and they were examined by a flame and ionization detector and an electron capture detector, respectively. The NH_3 was captured in washing bottle with boric acid and titrated against H_2SO_4. The O_2 was measured by an O_2 detector (BIOGAS-5000, Geotech, UK).

Statistical analysis

The mean value and standard deviation of three replicates of each treatment were reported. The differences between treatments were compared by a *t* test analysis. Statistical Analysis System 8.2 for Windows was used for the variance analysis.

Results and discussion

Temperature and oxygen

The changes in ambient and compost temperatures are shown in Fig. 1a. The composting materials went through three typical degradation phases: mesophilic, thermophilic, and curing. The temperature of CS and SMS treatments increased to over 50 °C (thermophilic phase) both on the 3rd day and remained above this level for 20 and 11 days, respectively. Such quick increases indicate fast biodegradation of the materials due to the presence of easily degradable forms of organic matter in the mixtures (Lim et al. 2016). The thermophilic phase of the two treatments lasted more than 3 days, both met the sanitation standards (Yang et al. 2013). However, the temperature in SMS treatment was lower than that in CS treatment during composting. Temperature variations during composting are the result of the thermal balance between the heat generated by the microorganisms and the heat loss through convection, conduction, evaporation, and radiation (Santos et al. 2016). Thus, the energy generated by microorganisms and its effect on the temperature during composting depend on the thermal

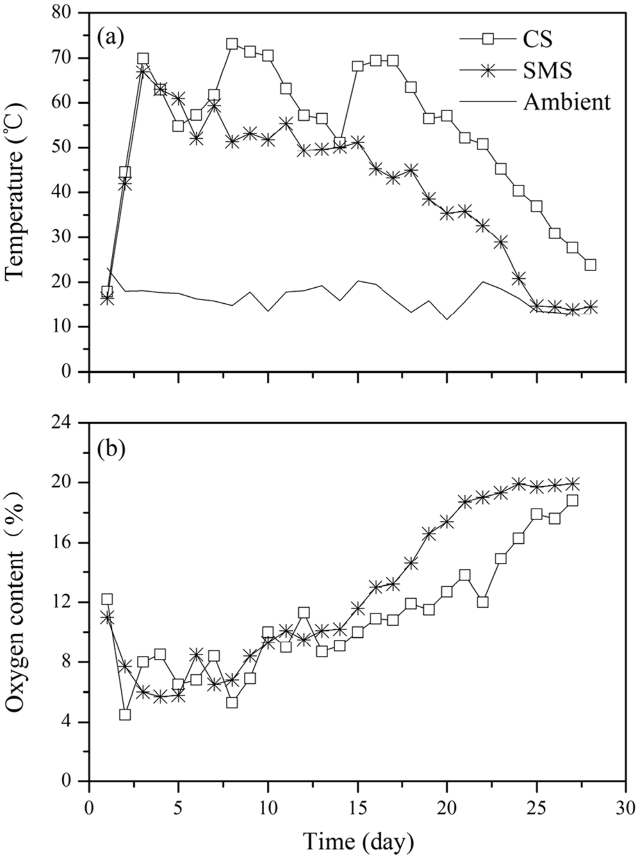

Fig. 1 Profiles of temperature (**a**) and oxygen content (**b**) during composting. Standard deviations of mean values of temperature (**a**) and oxygen content (**b**) were in the range of 0.1–12.3 °C and 0–4.8%, respectively

properties of the bulking agent and its proportion (Pandey et al. 2016; Santos et al. 2016). Moreover, the thermophilic phase was shorter in SMS treatment than CS treatment ($p < 0.0001$), which may be due to the higher hydrolysable characteristic of SMS after the growth of mushroom (Zhu et al. 2012) and the more extracellular enzymes secreted by the fungi in SMS (Chatterjee et al. 2017; García-Delgado et al. 2013). Thus, using SMS as a bulking agent improved composting efficiency by shortening the time for maturity.

Due to oxygen consumption by aerobic microorganisms for biodegrading organic matters,oxygen contents of the two treatments decreased rapidly when composting started (Fig. 1b). Following this sharp decrease, a slowly fluctuating increasing trend of oxygen concentrations was observed. The oxygen content in SMS treatments returned to ambient level with the exhausting of organic matter after 21 days, while oxygen content in CS treatments became close to ambient level at the end of composting, indicating the slower OM degradation in CS treatment. Previous study showed that cellulose and lignin in the substrate decreased by 50 and 30% after mushroom growth, respectively, while the contents of crude protein and fat were doubled (Zhu et al. 2012). In contrast, the higher amount of recalcitrant compounds (data not shown), such as cellulose and lignin, in CS treatment might explain the prolonged oxygen consumption (Yamada and Kawase 2006).

Compost quality

Compost quality is a primary concern for soil application. According to previous research, compost quality could be evaluated by pH, EC, GI, humification, and some other stability and/or maturity indices (Bernal et al. 2009).

Table 2 Variation of composting performance with composting time

Sample[a]	MC[a] (%)	pH	GI (%)	C_{Ex}[b] (g kg^{-1})	C_{HA}[b] (g kg^{-1})	C_{FA}[b] (g kg^{-1})	C_{HA}/C_{FA}	E_4/E_6
CS-0	59.81 (2.13)	7.30 (0.08)	48.12 (1.07)	92.41 (2.07)	11.63(0.85)	80.78(0.72)	0.14(0.01)	2.18(0.06)
CS-3	58.15 (1.06)	7.01 (0.20)	46.08 (3.36)	88.03 (1.22)	12.90(1.23)	75.13(1.19)	0.17(0.02)	2.52(0.12)
CS-7	53.13 (2.87)	7.56 (0.17)	68.42 (3.21)	78.45 (1.51)	19.32(0.95)	59.13(0.67)	0.33(0.01)	2.64(0.14)
CS-14	45.58[c] (1.28) /60.12[d] (2.15)	7.99 (0.10)	84.16 (0.95)	53.32 (1.06)	23.80(1.33)	29.52(0.27)	0.81(0.04)	2.11(0.08)
CS-21	50.59 (3.24)	7.91 (0.04)	89.51 (4.32)	41.52 (0.98)	25.91(1.23)	15.61(0.98)	1.66(0.08)	2.31(0.11)
CS-28	42.18 (1.83)	7.86 (0.06)	93.25 (1.56)	37.56 (0.91)	26.42(0.88)	11.14(0.82)	2.37(0.09)	2.15(0.12)
SMS-0	60.21 (2.41)	7.86 (0.09)	52.34 (2.13)	101.61 (1.48)	13.73(0.73)	87.88(1.14)	0.16(0.01)	2.05(0.03)
SMS-3	58.76 (3.01)	7.52 (0.15)	50.89 (0.68)	94.59 (1.14)	15.76(0.52)	78.82(0.81)	0.20(0.01)	2.43(0.07)
SMS-7	52.43 (1.89)	7.85 (0.11)	78.29 (3.24)	88.66 (1.44)	29.68(0.93)	58.98(0.59)	0.50(0.01)	2.32(0.15)
SMS-14	46.87[c] (1.02) /59.82[d] (2.45)	8.26 (0.09)	89.12 (2.92)	64.24 (1.06)	32.76(0.55)	31.48(0.67)	1.04(0.01)	1.98(0.08)
SMS-21	53.28 (1.19)	8.18 (0.05)	95.16 (3.29)	58.11 (0.58)	35.87(0.56)	22.24(0.29)	1.61(0.03)	1.76(0.09)
SMS-28	48.19 (1.56)	8.11 (0.11)	105.78 (2.07)	48.39 (0.83)	37.50(0.75)	10.89(0.29)	3.44(0.07)	1.34(0.07)

Values in parentheses are standard deviations of mean values

MC moisture content, *GI* germination index, C_{Ex} extractible carbon, C_{HA} humic acid carbon, C_{FA} fulvic acid carbon, E_4/E_6 absorbance ratio of wavelength 465 and 665 nm

[a] The sample nomenclature follows the X-Y pattern. "X" shows the composting treatment, while "Y" the age (days) after the installation day (day 0) of composting

[a] Wet weight basis; [b] Dry weight basis; [c] Before water addition; [d] After water addition

The optimum moisture content for composting varies with the waste to be composted, but generally the mixture should be at 50–60% (Gajalakshmi and Abbasi 2008; Onwosi et al. 2017). During composting, large quantity of water can evaporate in order to control excessive temperature, and as water content diminishes the rate of decomposition decreases, then rewetting should be required in order to maintain the optimum moisture content for the microbial activity (Bernal et al. 2009). As shown in Table 2, the moisture contents in the two treatments were both dropped below 50%; then, water was added to adjust the moisture content to 60% (Hough et al. 2010).

A pH at the range of 6.7–9.0 can support a better microbial activity during composting (Miller 1992). The pH of the composts in CS and SMS treatments was 7.01–7.99 and 7.52–8.26, respectively (Table 2), which indicated good microbial activity in both treatments. The pH decreased at the beginning of the composting due to the rapid degradation of readily available OM and accumulation of organic acids (Pandey et al. 2016), while later on, gradually increased pH might be ascribed to the degradation of proteinaceous materials and the accumulation ammonium (Zhang and Sun 2016). Then, with the ammonia volatilization and humification process after thermophilic phase pH decreased. The pH values in SMS treatments are slightly higher than those found in CS treatments during all composting phases, possibly due to a greater OM stabilization and humification degree in the SMS than CS (Bernal et al. 2009; Paredes et al. 2009).

From Table 2, the GI decreased slowly during the early phase. Previous studies attributed this drop to the production of low molecular weight short chain volatile fatty acids (mainly acetic acid) and ammonia (Guo et al. 2012). The GI increased with the decomposition of these toxic materials and the stabilization of the compost. After 14 days, GI reached more than 80% in both of the two treatments, indicating phytotoxic-free and mature of compost (Zhang and Sun 2016). Compared to CS treatments, SMS treatments could increase the final GI by 13.44%. Similar to the lower temperature in SMS treatments, this also implied the high degree of maturity. The statistical analysis showed that the bulking agent had a significant influence on GI ($p = 0.0096$).

The humified fraction of OM is the most important one responsible for organic fertility functions as it is the fraction most resistant to microbial degradation (Bernal et al. 2009). As shown in Table 2, the contents of humic substances (C_{Ex}, including HA and FA) decreased from 92.41 to 37.56 g kg^{-1} and 101.61 to 48.39 g kg^{-1} in the CS and SMS treatments, respectively. Contents of C_{Ex} declined possibly due to the dramatic decrease of FA (from 80.78 to 11.14 g kg^{-1} and 87.88 to 10.89 g kg^{-1} in the CS and SMS treatments, respectively, Table 2). The noticeable reduction in FA could be explained by the feature of FA containing easily degradable compounds which were firstly exposed to microbial attack (Sellami et al. 2008). The degradation of the readily available organic substances, including the FA, provided energy to the microorganism (Zhou et al. 2014). The bio-oxidation of these compounds led to the production of substances with more stable structures like HA in mature composts. Hue and Liu (1995) proposed $C_{FA} \leq 12.5$ g kg^{-1} for the maturity of different origin composts. Compost in these two treatments both attained this maturity standard at the end of the composting.

On the contrary, HA contents increased from 11.63 to 26.42 g kg^{-1} and 13.73 to 37.50 g kg^{-1} in the CS and SMS treatments, respectively. Similar results were found by Awasthi et al. (2016) and Zhou et al. (2014). The increase of HA may be ascribed to the high content of readily available OM decomposed, leading to a higher rate of HA generation than decomposition. Alternatively, parts of the HA may be transformed from other forms of humic substances, such as FA (Li et al. 2017; Zhou et al. 2014). SMS treatments could significantly increase the final HA by 41.94% compared to CS treatments ($p = 0.0057$). The higher contents of HA in SMS treatments indicated a higher level of humification in SMS.

The HA-to-FA (HA/FA) ratio is widely used to reflect the stability and maturity of the final compost (Li et al. 2017). From Table 2, the HA/FA ratio increased with the higher change in the SMS treatments (from 0.16 to 3.44) than the CS treatments (from 0.14 to 2.37). The increase in the HA/FA ratio, also known as the "degree of polymerization," reflected the formation of complex molecules (HA) from more simple molecules (FA) and a diminution in the non-humic components of other organic acid fraction which are the most easily degraded by microorganisms (Sellami et al. 2008). During the humification process, SMS provided rich substrates for aromatization and oxidation with more fiber-structure components (Wu et al. 2013), leading to a higher HA/FA ratio in SMS treatment than CS treatment. Indeed, for CS and SMS treatments, the ratios of C_{HA}/C_{FA} were both higher than 1.6, which would indicate an extended degree of maturity achieved by organic matter in both mixtures (Sellami et al. 2008). Their evolution during composting reveals the humification process of the OM, but a limit value cannot be fixed for expressing compost maturity.

Usually, the E_4/E_6 decreases with the increasing of molecular weight and degree of HA condensation but it is not related to the molecular quantity of HA (Yuan et al. 2016). In the beginning of composting, large values of E_4/E_6 ratio (Table 2) have been connected with the presence of smaller size organic molecules or more aliphatic structures and usually with a higher content of functional groups (Li et al. 2017). With the increase in composting time, E_4/E_6 ratio decreased significantly indicating that the easily degradable organic matters were mineralized and phenolic compounds were oxidized and bound to methoxyl groups and/or aliphatic side chains in humic substances (Sellami et al. 2008). At the end of composting, a sufficient level of stability and maturity was achieved by a lower E_4/E_6 ratio. Moreover, SMS treatments showed smaller E_4/E_6 as compared to CS treatments, indicating that HA in SMS had the larger molecular weight and the higher humification degree than HA in CS treatments.

In short, temperature data combined with other maturity and stability properties clearly indicates that SMS-amended compost has higher humic substances and maturity degree.

Gaseous emissions

Methane emission

The CH_4 emissions of both treatments mainly occurred during thermophilic phase of the composting (Fig. 2a). In the thermophilic phase, microorganisms could degrade organics rapidly, and then partially, anaerobic conditions occurred in composting piles and leading to CH_4 production in this period (Awasthi et al. 2016; Chowdhury et al. 2014). Subsequently, with the turning activities breaking the big particles, destroying the anaerobic regions, and with the biodegradation of OMs, CH_4 emissions in the two treatments experienced a gradual decline (Santos et al. 2016) whereas oxygen contents increased simultaneously (Fig. 1b). These results were similar to the study by Yang et al. (2013) during kitchen waste composting and Luo et al. (2014) during pig manure composting. CH_4 emission pattern in SMS treatments was similar with that in CS treatments. Statistical analysis of CH_4 emission showed no significant difference between the two treatments ($p = 0.4849$). However, from Fig. 2b, the cumulative CH_4 emission in SMS treatments (1509 g $CH_4\text{-}C{\cdot}t^{-1}DM$) was about 1.1 times of the CS treatments (1370 g $CH_4\text{-}C{\cdot}t^{-1}DM$). The inconsistency should be explained by the characteristics of the materials that SMS contains more easily decomposable materials after mushroom cultivation (Zhu et al. 2012). Similar result was found by Nigussie et al. (2016) during composting of vegetable waste

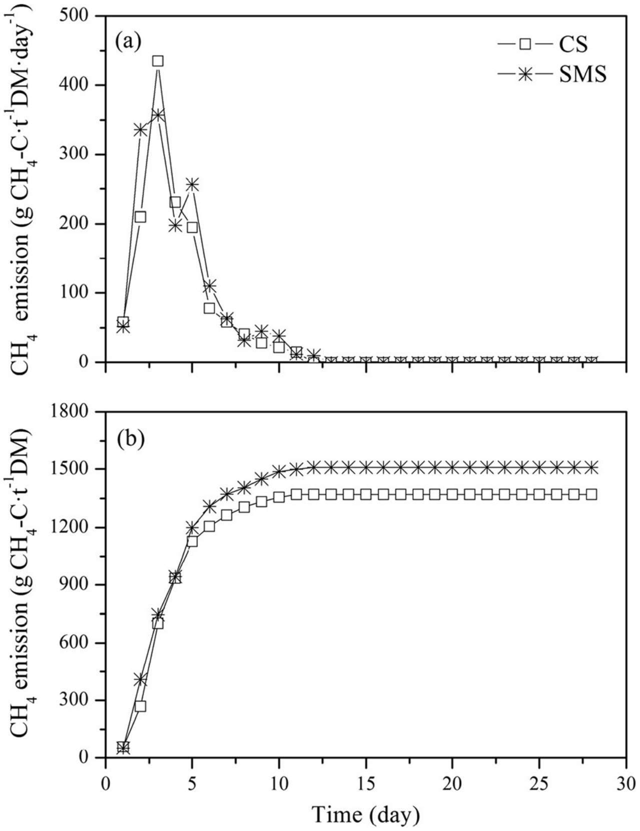

Fig. 2 Changes in emission (**a**) and cumulative emission (**b**) of CH_4 during composting. Standard deviations of mean values of emission (**a**) and cumulative emission (**b**) of CH_4 were in the range of 19–102 g CH_4-C·t^{-1}·DM^{-1}·day^{-1} and 35–437 g CH_4-C·t^{-1}·DM^{-1}, respectively

that a high proportion of easily decomposable materials increase CH_4 production.

Nitrous oxide emission

The dominant emissions of N_2O for the two treatments occurred in the first 2 weeks and peaked at the beginning of composting (Fig. 3a), which was consistent with previous study by Awasthi et al. (2016). This finding clearly indicated the presence of anaerobic pockets during the beginning of the composting and may be the result of composting feedstock settlement reducing the oxygen availability (Santos et al. 2016). According to previous studies, there are two possible mechanisms for this phenomenon: nitrification or denitrification could occur in raw materials before the start of composting (Nigussie et al. 2016); the initial temperature and oxygen concentration are favorable to nitrifies on the surface of composting piles (Hao et al. 2004). In this study, the N_2O emissions at the beginning could be created by the nitrification of ammonia (Fig. 4a). However, N_2O emission in CS treatments was also detected during the maturation phase. This can be attributed to the nitrification of NH_4^+-N, which might accumulate in the thermophilic phase, and thus nitrifying bacteria activity increased during the curing phase (Yuan et al. 2016). Statistical analysis shows that there was a significant difference in N_2O emissions between the two treatments ($p = 0.0024$). Compared to the CS treatments, SMS treatments reduced N_2O emission by 46.48% during composting (Fig. 3b), possibly due to the blockage of gaseous permeation by the CS (Fig. 1b).

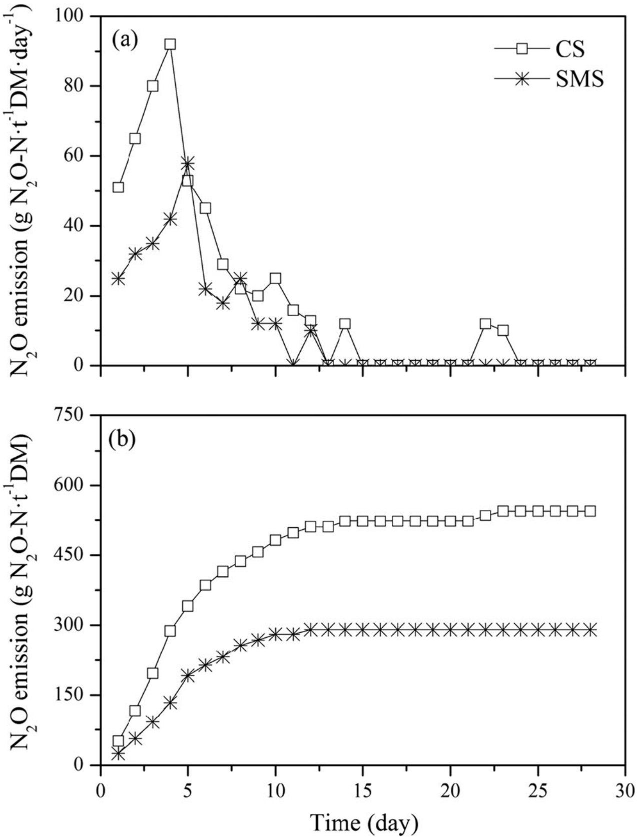

Fig. 3 Changes in emission (**a**) and cumulative emission (**b**) of N_2O during composting. Standard deviations of mean values ($n = 9$) of emission (**a**) and cumulative emission (**b**) of N_2O were in the range of 8–39 g N_2O-N·t^{-1}·DM^{-1}·day^{-1} and 14–156 g N_2O-N·t^{-1}·DM^{-1}, respectively

Ammonia emission

The emissions of NH_3 mainly occurred in the thermophilic phase for the two treatments (Fig. 4a); this could be attributed to the biodegradation of organic nitrogen to inorganic nitrogen such as NH_4^+ which could volatilize in form of NH_3 under high temperature and pH (pH = 7–9 in this study) (Pagans et al. 2006; Santos et al. 2016). The decomposition of organic matter was also accompanied by a rise in pH of the composting pile (Table 2), which in turn accelerated the volatilization of NH_3. The NH_3 emission profile from our study was generally consistent with several previous studies (Awasthi et al. 2016; Pagans et al. 2006; Yuan et al. 2016). The NH_3 emission of CS and SMS treatments reached their

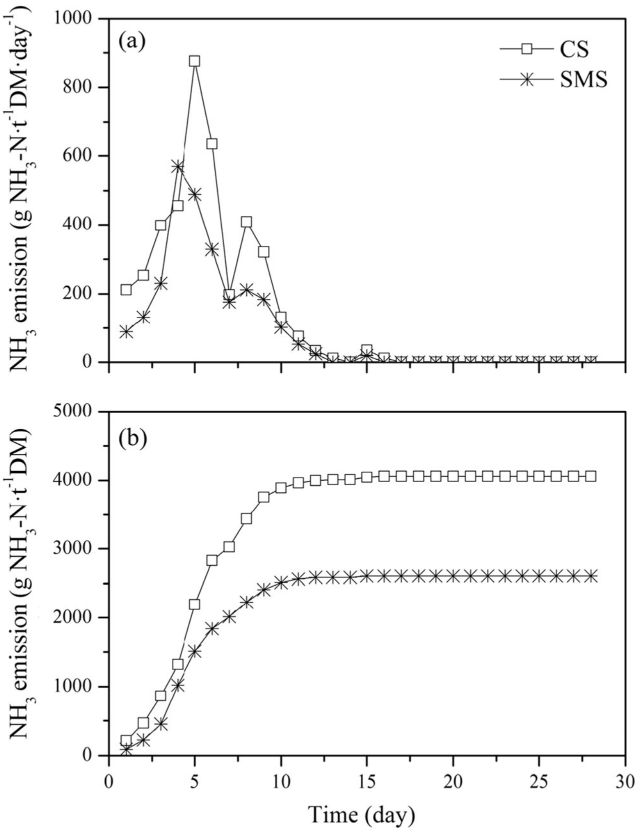

Fig. 4 Changes in emission (**a**) and cumulative emission (**b**) of NH_3 during composting. Standard deviations of mean values of emission (**a**) and cumulative emission (**b**) of NH_3 were in the range of 41–232 g NH_3-$N·t^{-1}·DM^{-1}·day^{-1}$ and 67–357 g NH_3-$N·t^{-1}·DM^{-1}$, respectively

peak values at day 4 (876 g NH_3-$N·t^{-1}$DM) and day 5 (571 g NH_3-$N·t^{-1}$DM), which was attributed to the degradation of partially decomposed materials after turning (Jiang et al. 2015). During the curing phase (after day 14), the NH_3 emissions of the two treatments decreased gradually with the decrease of easily degradable materials and composting temperature (Yang et al. 2013). Statistical analysis shows that there was a significant difference in NH_3 emissions between the two treatments ($p = 0.0150$). At the end of the compost, the cumulative NH_3 (Fig. 4b) losses from the CS treatments were 13.57% higher than those from the SMS treatments, which was caused by higher humus content in SMS treatment fixed more nitrogen in the compost (Table 2).

Carbon and nitrogen balances and the global warming potential of CH_4 and N_2O

Table 3 presents the carbon and nitrogen balances and the global warming potential of CH_4 and N_2O at the end of the composting. After composting, more than 44% of the initial TOC content had been lost. The major pathway for the loss of initial TOC was in the form of CO_2 (43.43–48.22%), whereas 0.38–0.43% of initial TOC was lost due to CH_4 emission under partially anaerobic conditions in composting piles (Santos et al. 2016). This result was similar to that of Yang et al. (2013) in kitchen waste composting and Yuan et al. (2016) in sewage sludge composting.

The TN losses ranged from 29.84 to 34.32% of initial TN in raw materials (Table 3). Most nitrogen was lost in the form of NH_3, while 1.24–2.30% of nitrogen was lost in the form of N_2O. These results were similar to the previous study by Jiang et al. (2015) in pig manure composting and Nigussie et al. (2016) in food waste vermicomposting. Composting with SMS as a bulking agent could significantly reduce nitrogen loss, NH_3, and N_2O emissions (by 13.57, 35.56, and 46.48%, respectively) compared with the CS.

While CO_2, CH_4, and N_2O are all important GHGs, the contribution of CO_2 to greenhouse effect should be excluded during composting as it derives from microbial respiration (IPCC 2013). Therefore, only CH_4 and N_2O were taken into consideration when calculated the total GHG emissions in this study. The global warming potential of CH_4 and N_2O ranged from 124.44 to 196.66 $kgCO_2$-$eq·t^{-1}$DM, with the SMS treatments having the lower GHG emissions. The lower GHG budget from SMS-amended composting may be explained by the lower N_2O production. Moreover, in terms of environmental benefits, using SMS as a bulking agent could significantly reduce the total GHG emission by 33.95% (about 70.96 kg CO2-

Table 3 Carbon and nitrogen balances and the global warming potential of CH_4 and N_2O

Treatment	Carbon balance (%)[a]			Nitrogen balance (%)[b]			The global warming potential of CH_4 and N_2O ($kgCO_2$-$eq·t^{-1}$DM)[c]		
	CH_4-C[d]	CO_2-C	TOC loss	N_2O-N	NH_3-N	TN loss	CH_4	N_2O	Total
CS	0.38 a	48.02 b	49.20 a	2.30a	17.13 a	34.32 a	46.58 a	162.41 a	208.99 a
SMS	0.43 a	43.43 a	44.46 a	1.24 b	11.11 b	29.84 b	51.31 a	86.72 b	138.03 b

[a, b] Percentages of initial total organic carbon and total nitrogen of raw materials, respectively, dry weight basis

[c] The global warming potential of CH_4 and N_2O calculation based on the following: 1 mol CH_4 = 34 mol CO_2-eq, 1 mol N_2O = 298 mol CO_2-eq (eq = equivalent) (IPCC 2013)

[d] Values followed by different letters within a column differ significantly at 0.05 probability level

eq·t^{-1}DM) than that of using CS as a bulking agent. In summary, composting with SMS as a bulking agent is considered as a sustainable and cleaner process as it could significantly reduce the global warming potential of CH_4 and N_2O.

Conclusion

Bulking agents could significantly affect gaseous emissions and compost quality. Using SMS as a bulking agent improved composting efficiency by shortening the time for maturity. Moreover, adding SMS increased germination index and the humic acid of the final compost (by 13.44 and 41.94%, respectively) compared with CS treatment. Furthermore, composting with SMS as a bulking agent could reduce nitrogen loss, NH_3, and N_2O emissions (by 13.57, 35.56, and 46.48%, respectively). Although using SMS as a bulking agent could slightly increase CH_4 emission, it reduced the global warming potential of CH_4 and N_2O by 33.95% compared with the CS treatment.

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