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The Maturity and CH_4, N_2O, NH_3 Emissions from Vermicomposting with Agricultural Waste

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ABSTRACT
This study investigated the maturity and gaseous emissions from vermicomposing with agricultural waste. A vermicomposting treatment (inoculated *Eisenia fetida*) was conducted over a 50-day period, taking tomato stems as the processing object and using cow dung as the nutrient substrate. A thermophilic composting treatment without earthworm inoculation was operated as a control treatment. During the experiment, maturity indexes such as temperature, pH, C/N ratio, and germination index (GI) were determined and continuous measurements of earthworm biomass and CH_4, N_2O, and NH_3 emissions were carried out. The results showed that the temperature during vermicomposting was suitable for earthworm survival, and the earthworm biomass increased from 10.0 to 63.1 kg m^{-3}. Vermicomposting took less time on average to reach the compost maturity standard (GI 80%), and reached a higher GI (132%) in the compost product compared with the thermophilic composting treatment. Moreover, the decrease of the C/N ratio in vermicompost indicated stabilization of the waste. The activities of earthworms played a positive role in reducing gaseous emissions in vermicompost, resulting in less emissions of NH_3 (12.3% NH_3-N of initial nitrogen) and total greenhouse gases (8.1 kg CO_2-eq/t DM) than those from thermophilic compost (24.9% NH_3-N of initial nitrogen, 22.8 kg CO_2-eq/t DM). Therefore, it can be concluded that vermicomposting can shorten the period required to reach compost maturity, can obtain better maturity compost, and at the same time reduce gaseous emissions. As an added advantage, the earthworms after processing could have commercial uses.

Introduction

Modern agriculture in China uses chemical fertilizer instead of organic fertilizer, and replaces agricultural waste with artificial diet for the fodder, which breaks the waste recycling in traditional agriculture. This transformation results in a substantial accumulation of agricultural waste, and produces serious resource waste and environmental problems. Vegetable waste and livestock manure are important agricultural wastes in China; about 2.1 $\times$ 10^8 t vegetable waste and 2.7 $\times$ 10^9 t livestock manure were produced annually (Zhang et al. 2014; Zheng et al. 2016). However, a few parts of these wastes could be disposed efficiently, the others are discarded and generate foul odors and leachate, which affect the ambient air and pollute underground water bodies because of the high moisture and organic content in vegetable waste and livestock manure. Furthermore, the disposal of vegetable waste and livestock manure in open dumps also leads to wastage of nutrient substrates, which could be recycled and used as fertilizers, substrates for mushroom cultivation, etc. (Sarkar, Pal, and Chanda 2016). Consequently, a sustainable approach to handling vegetable waste is to reprocess and recycle.

Traditional thermophilic composting is a biological process that can reduce the volume and mass of agricultural waste, as well as produce a safe, stabilized, and nutrient-enriched soil amendment. Previous studies have focused on co-thermophilic composting of agricultural waste (Holman et al. 2016; Pellejero et al. 2015; Scotti et al. 2016). However, thermophilic composting usually needs regular turning and a long period, which consumes fuel and time, and also produces leachate and gaseous emissions, mainly NH_3

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and greenhouse gases (GHG; CH_4, N_2O), owing to the high moisture and organic content in agricultural waste. Published literatures have shown that 9.6%–46% of initial total N is lost in the form of NH_3 during the composting period, which leads to serious N loss in compost. Meanwhile, NH_3 can be neutralized by acidic substances, such as SO_2 and NO_x, to generate ammonium salt and other secondary particles, which is discussed as an important precursor of $PM_{2.5}$; 0.2%–9.9% of initial total N and 0.08%–6% of initial carbon (C) is lost in the form of N_2O and CH_4, respectively (Awasthi et al. 2016; Jiang et al. 2016). According to the report of the International Panel on Climate Change, the global warming potentials of CH_4 and N_2O, in a 100-year time frame, are 25 and 298 times higher than that of CO_2, respectively (IPCC 2014).

Vermicomposting is a low-cost biotechnology that enables the recycling of a variety of wastes through the combined action of earthworms and microorganisms. Apart from being excellent bioactive amendments to improve soil fertility, vermicompost is considered to be a useful material for restoring pesticide contaminated soils as it enhances the adsorption of pesticides, thus reducing the environmental risk of pesticide leaching towards groundwater (Alidadi et al. 2016; Mendes et al. 2012). As an added advantage, the application of earthworms in pharmacology and nutriology are currently significant; therefore, the bodies of earthworms after the vermicomposting process can be used for commercial purposes, improving the economic benefits of organic waste treatment. Many researchers have studied the methods and effects of vermicomposting application on the treatment of various organic wastes (Garg and Gupta 2011; Singh et al. 2011; Sudkolai and Nourbakhsh 2017; Taeporamaysamai and Ratanatamskul 2016). Singh et al. (2011) indicated that vermicomposting of municipal solid waste is a sustainable waste management option, as the vermicast obtained at the end of the process is rich in plant nutrients and devoid of pathogenic organisms. Garg and Gupta (2011) found that vermicomposting of cow dung spiked-pre-consumer processing vegetable waste decreased C and organic matter concentration and increased the N, P, and K content in the vermicompost; also, the C/N ratio was decreased by 45%–69%, indicating stabilization of the waste. Taeporamaysamai and Ratanatamskul (2016) showed that vermicomposting is a biotechnological process that converts various organic materials into compost through the combined activities of red worms and microorganisms. Sudkolai and Nourbakhsh (2017) reported that urease activity was an index for assessing the maturity of cow manure and wheat residue vermicomposts.

Table 1. Physical and chemical properties of the raw materials used in the composting processes.

Materials	pH*	TN† (g kg^{-1})	TOC† (%)	GI (%)	Moisture content (%)
Tomato stems	8.87	8.3	44.5	15.7	42.8
Cow dung	7.94	20.1	42.6	47.1	60.5
Mixture	8.54	14.2	43.6	33.6	50.8

*Wet weight basis.
†Dry weight basis.

The aim of this study was to discover the effect of vermicomposting with agricultural waste, using earthworms (*Eisenia fetida*) under laboratory conditions. Cow dung was mixed with vegetable waste, which functioned as the microbial inoculant and food source for the earthworms. The compost maturity, gaseous emissions (CH_4, N_2O, and NH_3), and earthworms' biomass were determined and analyzed systematically in this study.

Methods

Composting Materials

Tomato stems were provided as a vegetable planting base. They were air dried for a few days, in case the moisture content was too high for earthworms, and were cut into 1- to 5-cm pieces before the experiment. Cow dung from a cattle farm in Beijing was mixed into the composting materials to inoculate microorganisms and nutrients into the compost and provide the main food source for earthworms. To obtain the appropriate moisture content and C/N ratio, tomato stems and cow dung were mixed at a ratio of 1:1 (wet weight; Bansal and Kapoor 2000; Garg and Gupta 2011; Guo et al. 2012). Earthworms (*Eisenia fetida*) were bought from an earthworm culturing farm. The physical and chemical properties of the raw materials are presented in table 1.

Experimental Design and Methods

The reactors with 1.5 m^3 (length 1.5 m × width 1 m × height 1 m) volume were used in this study, which were casted by cement. The fronts of the reactors were equipped with wooden boards, which can be easily removed while setting up compost. Plastic boards with holes were installed at the bottom of the reactors for aeration.

Two composting treatments were investigated and each treatment was triplicated. The earthworms were inoculated into vermicomposting treatment at the start of the composting period with a density of 10 kg m^{-3}. The vermicomposting treatment was operated with no turning and supplied with ~2 kg of distilled water per day, for the optimal moisture content for earthworms (~60%). Thermophilic composting without earthworms was operated as a control, which was aerated with an air pump alternated between on and off every 30 min with an air flow rate of 0.2 L·kg^{-1} dry matter (DM)·min^{-1}, and the materials were turned and mixed weekly. In consideration of earthworm production for vermicomposting treatment and heat preservation for thermophilic composting treatment, the height of the two treatments was operated at 1 m. The trial was operated for 50 days and all of the treatments were without any amendment.

Compost Sampling and Analysis

The temperature was monitored by a sensor inserted into the middle of the piles, and recorded continuously by a computer connected to the reactor. The homogeneous solid samples weighing ~0.4 kg were taken in duplicate on the 0, 5th, 10th, 15th, 20th, 30th, 40th, and 50th day using the multipoint sampling method, and were mixed thoroughly. The earthworms were manually collected immediately from the solid samples and cleaned by deionized water. The biomass of earthworms was obtained by weighing them. The solid samples without earthworms were divided into two parts, one was stored at 4°C for the measurement of moisture content, pH value, and germination index (GI). The other part was air dried, then ground and sieved to 0.5 mm, for the determination of total nitrogen (TN) and total organic carbon (TOC) content.

The moisture content was determined by drying the fresh solid samples at 105°C for ~6 h, until a constant weight was achieved. The fresh compost samples ($n = 3$) were mixed with distilled water (1:10 w/w ratio) and shaken for 0.5 h. The pH value of the compost was determined from the mixture using a pH meter (PHSJ-4F). The extract was centrifuged and the supernatant was removed and filtered through a 0.45-μm filter membrane to determine the GI. Twenty *pakchoi* seeds were distributed on filter paper in petri dishes (10 cm in diameter) and moistened with 10 mL of the compost water extract. Three replicate dishes for each sample were incubated at 20°C for 3 days. The number of germinating seeds and root length was measured, with distilled water used as a control. The GI was calculated by the following formula:

$$GI\,(\%) = \frac{[Seed\,germination\ of\ treatment(\%)]\ [Rootlenght\ of\ treatment]}{[Seed\,germination\ of\ control(\%)]\ [Rootlenght\ of\ control]}\,(\%)$$

The TN and TOC were analyzed in accordance with the Chinese national standard (NY 525–2012) using the air-dried samples. The CH_4, N_2O, and NH_3 samples were collected and analyzed daily during the composting period. The Emission Isolation Flux Chamber technique (Klenbusch 1986) was used for the collection of surface emissions of vermicomposting, which was approved by the Environmental Protection Agency (EPA). A stainless-steel chamber with a volume of 30 L and diameter of 16 inches was used for collecting gas samples from the compost surface, with gas inlet and outlet on its dome. Clean dry sweep air was added to the chamber at a fixed, controlled rate (5 L/min). The volumetric flow rate of sweep air through the chamber was recorded by a gas flowmeter.

For the forced aerated thermophilic composting, the USEPA chamber design was modified by using a 2″ diameter exhaust stack, in order to eliminate a "back pressure" in the chamber, or a "skirting" of source gas away from or around the chamber. A diffuser-type sweep air/tracer introduction system was used, and an internal impeller at about three rotations per second was operated. The advective flow into the chamber was measured by the recovery of the tracer and then used in the calculation of flux from the test source.

The emission rate was calculated as:

$$E_i = (Y_i)\,(Q_{sw} + Q_{ad})\ /\ A$$

where:

E_i = emission rate of component i (mass/area – time);

Y_i = concentration of component i in the air flowing from the chamber (mass/volume);

Q_{sw} = flow rate of sweep air into the chamber (volume/time);

Q_{ad} = flow rate from the area source determined by tracer (volume/time);

A = surface area enclosed by the chamber (area).

The CH_4 and N_2O concentrations were analyzed by a gas chromatograph (3420A; Beifen, China), equipped with both electron capture and flame ionization detectors. The NH_3 was analyzed using Nessler's reagents spectrophotometer (photoLab 6600, Germany).

Statistical Analysis

Data were analyzed by a one-way analysis of variance. The least significant difference test was used to determine the significance of the difference in the mean values. All data were analyzed using SAS (Statistical Analysis System) 8.2 for Windows.

Results and Discussion

Maturity Indexes

The changes in ambient and compost temperature are shown in figure 1. The ambient temperature of Beijing was in the range of 20°C–30°C in July–August (2015). The temperature of the vermicompost was in the range of 25°C–35°C, which was obviously lower than that of the thermophilic compost in the first 30 days. After that, the microbial reactions in the two treatments had almost stopped, as the degradable C was exhausted, and they approached ambient temperature gradually. The statistical analysis showed that there were significant differences in temperature between

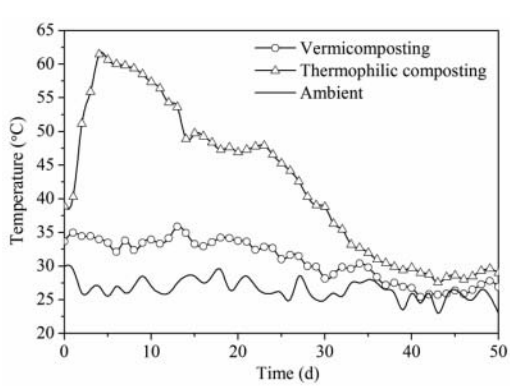

Figure 1. Changes in temperature during the composting period.

the two treatments during the composting period ($P = 0.01$). The composting materials of the thermophilic composting went through three typical degradation phases: mesophilic, thermophilic, and curing; the temperature was from 28 to 61°C, and reached its maximum temperature (61°C) on day 4. The thermophilic compost entered the thermophilic phase (>50°C) on day 2, and maintained a temperature of >50°C for more than 7 days, meeting the compost sanitation requirements specified in the Chinese national standard (NY525–2012). The vermicompost did not enter a thermophilic phase over the whole composting period, although heat was produced along with the easily degradable C, which decomposed rapidly in the initial days. This could be attributed to the activities of earthworms fragmenting the large particles, decreasing particle sizes and increasing porosity in the composting materials, which contributed to heat dissipation. In addition, the pile was watered every day to maintain the moisture content and the evaporation took away significant quantities of heat. The relatively low temperature during vermicomposting was suitable for earthworm survival and breeding but not sufficient for pathogen elimination. To solve the problem of pathogens in vermicompost, it is suggested that pre-composting of the raw materials is necessary, in accordance with conclusions from previous studies (Kumar et al. 2012; Suthar 2009).

The pH values of the two treatments showed a similar trend (table 2). Statistical analysis showed that the pH values were significantly different between them ($P = 0.04$). The low pH values obtained in the first few days could be attributed to the production of organic acids, such as acetic acid and butyric acid, produced by micro-organic reactions (Eklind and Kirchmann 2000). After the first 10 days, the organic acids began to volatilize as the temperature increased rapidly. Concurrently, organic N was mineralized by microbial activity, thus the pH values increased and reached the peak values on day 25. After this stage, because of the declining temperature, the effect of volatilization and mineralization reduced and the pH values decreased. At the end of composting, the pH values of the two treatments were in the range of satisfactory pH values (7–8.5; Shen et al. 2016). The pH values in the range of 6–9 are suitable for earthworm survival and 8–9 is best for breeding, as they are sensitive to acidity and alkalinity because of the chemical perceptive organs on their body surface. The pH

Table 2. Chemical characteristics and earthworms biomass of the composts at different composting times.

Composting time (d)	pH	TN ($g\ kg^{-1}$)	TOC (%)	C/N ratio	NO_x^- ($g\ kg^{-1}$)	NH_4^+ ($g\ kg^{-1}$)	GI (%)	Earthworms biomass ($kg\ m^{-3}$)
Vermi-composting								
0	8.54	14.2	43.6	30.7	0.16	0.27	33.6	10
5	8.32	14.5	42.8	29.5	0.18	0.18	22.3	12.8
10	8.18	15.0	39.9	26.6	0.21	0.20	62.8	14.9
15	8.49	14.9	35.2	23.6	0.26	0.15	89.2	17.2
20	8.78	15.7	34.1	22.7	0.33	0.09	96.3	22.8
30	8.67	16.2	34.2	21.1	0.39	0.08	113.0	29.6
40	8.57	16.5	33.7	20.4	0.46	0.06	124.5	47.3
50	8.48	17.2	31.9	18.6	0.53	0.03	132.3	63.1
Thermophilic composting								
0	8.54	14.2	43.6	30.7	0.16	0.27	33.6	—
5	8.12	14.0	43.4	31.0	0.33	0.35	28.9	—
10	7.92	14.6	43.9	30.1	0.38	0.30	54.8	—
15	8.26	14.5	41.6	28.5	0.42	0.18	72.5	—
20	8.91	14.9	40.9	27.5	0.48	0.13	80.3	—
30	8.46	13.8	33.6	24.4	0.53	0.10	102.3	—
40	8.40	14.2	32.9	23.2	0.65	0.08	100.3	—
50	8.33	15.0	32.1	21.3	0.72	0.07	105.7	—

values of vermicompost in this study were in the range of 8.2–8.8 during the composting process, which was suitable for earthworm survival, and this result was consistent with the research of Suthar (2009) in a vermicomposting experiment with cow dung, vegetable waste, and cornstalks.

The C/N ratio is an important index for evaluating if the compost product has been thoroughly stabilized. During the composting period, biodegradable components are decomposed and transformed to CO_2, H_2O, and other small molecules by the actions of microorganisms. However, the rate of loss on organic N is lower than that on organic C, causing the C/N ratio to decrease during the composting process. In general, the C/N ratio of completely decomposed compost should be 15–20 (Moharana and Biswas 2016). In this study, the C/N ratio of all mixtures followed the same trend, with statistically significant differences between the two treatments ($P = 0.04$; table 2). The C/N ratio of vermicompost was decreased by 41.9% (changed from 31 to 19) indicating stabilization of the composting materials, and it showed a greater reduction than thermophilic compost. That was because the earthworms fragmented the large compost particles; they improved the ventilation and oxygen content inside the pile, which accelerated decomposition of C. Moreover, the final TN content in vermicompost was obviously higher than the initial value (table 2), which contributed to the decline of the C/N ratio as well. This was reported in previous publications. Wang et al. (2016) attributed this phenomenon to the degradation of nitrogenous organic compounds and related concentration effect. Fernández-Gómez et al. (2010) considered that this increase may be due to the high mineralization of N from decaying earthworm tissues along with the release of other nutrients by the oxidation of organic matter. However, Bansal and Kapoor (2000) attributed this phenomenon to the high activity of dehydrogenase in vermicompost. At the end of the composting period, the C/N ratio of vermicompost (18.6) was lower than that of thermophilic compost (21.3), meeting the completely decomposed standard.

The GI is a significant parameter for evaluating compost phytotoxicity and maturity, and is known to increase with the decomposition of toxic materials in compost, such as short chain volatile fatty acids (mainly acetic acid; Guo et al. 2012). Yuan et al. (2016) reported that a GI of more than 80% indicates that a compost was free of phytotoxic substance and mature. Table 2 shows the GI changes during the composting process and statistical results showed significant differences between the two treatments ($P = 0.05$). The GIs of the two treatments decreased slowly during the early phase. Guo et al. (2012) attributed this drop to the production of short chain volatile fatty acids (mainly acetic acid) and ammonia. After that, the GIs of the two compost treatments increased and reached 80% by the end of the experiment. The GI of the vermicompost had an apparent advantage, rising from 33 to 132% and the time taken for vermicompost to reach 80% was shorter than that of thermophilic compost, similar to the results of Fernández-Gómez, Romero, and Nogales (2010). This was caused by the metabolism of earthworms transforming the organic matter to absorbable forms for microorganisms, consequently enhancing the activities of microorganisms and accelerating the speed of toxicant decomposition. The measured GI results indicated that vermicomposting reduced the phytotoxicity and hastened the maturation of compost.

Biomass of Earthworms

Earthworms with a density of 10.0 kg m^{-3} were inoculated into the composting materials at the beginning of the experiment; their behavior was observed and noted. The changes in earthworm biomass during the composting period are shown in table 2. The biomass increased along with the composting process. On days 0–30, the growth rate of the biomass was lower than that in days 30–50. The reasons can be summarized as follows: first of all, the temperature during days 0–30 was in the range of 30°C–35°C, which was unsuitable for earthworm survival, as the optimal temperature range for them is 0°C–30°C. Second, the raw materials were not completely degraded in the prophase of the composting period and so were insufficient as nutrients for earthworms. From day 30, the temperature decreased to 5°C–30°C, and the raw materials were degraded gradually and could be absorbed by earthworms. Therefore, the biomass increased with a greater degree. At the end of the composting period, the biomass increased to 63.1 kg m^{-3}. The biomass data indicated that the physical and chemical changes of composting materials were relevant to earthworms. In addition, the applications of earthworms in pharmacy and other fields are drawing more and more attention, and earthworms after processing could be used for commercial purposes as well.

Gaseous Emissions

CH_4 is formed by deoxidization of carbon CO_2/H and acetic acid by methanogens under anaerobic conditions (Huang et al. 2016). Concentrations of CH_4 monitored at the outlet of the reactors are shown in figure 2*A*. Statistical analysis showed a highly significant difference in CH_4 emissions between the two treatments ($P < 0.01$). The CH_4 of the thermophilic compost was discharged mainly during the thermophilic phase as has been found in other research (Manios et al. 2007; Sánchez-Monedero et al. 2010). This was because, during the thermophilic phase, the oxygen consumption rate was much higher than the supplement rate, and CO_2 was produced during the intensive organics degradation, hence an anaerobic

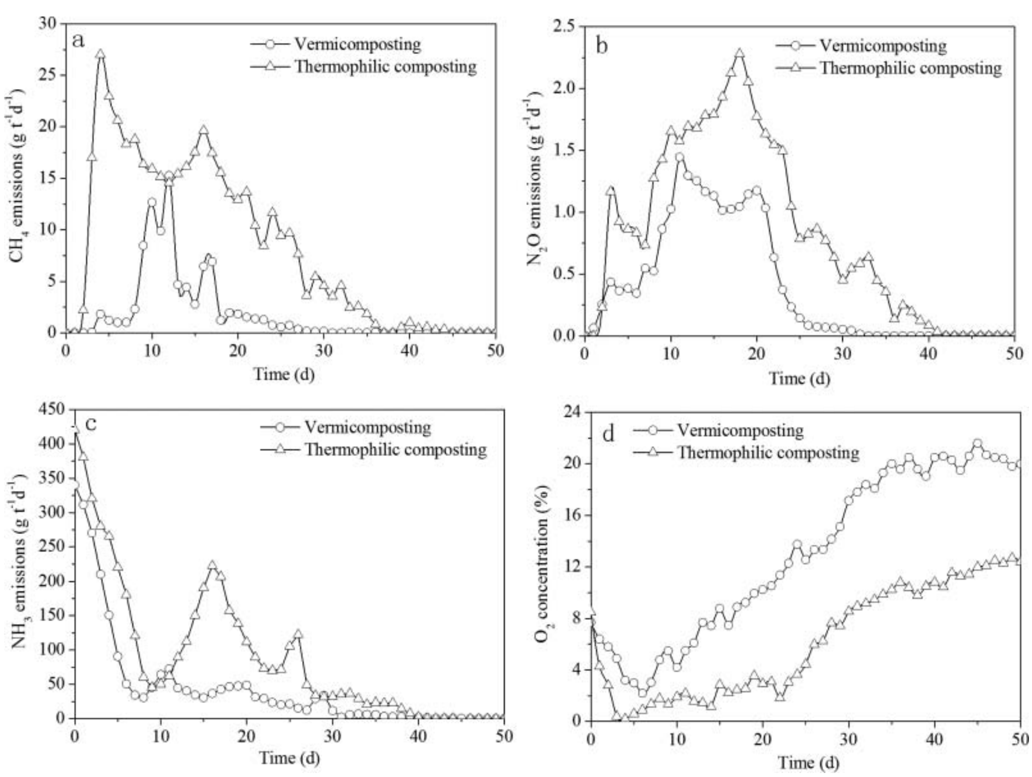

Figure 2. Gaseous emissions and oxygen concentration during the composting period.

environment formed and CH_4 was emitted (Awasthi et al. 2016). Moreover, the high moisture content, initial composition of the mixtures (C/N ratio), and insufficient porosity between composting mass or improper aeration were also responsible for excessive CH_4 generation (Santos et al. 2016). CH_4 was emitted from vermicompost mainly in the first 20 days, when the temperature was higher (figure 1) and O_2 concentration was lower (figure 2*D*) than the other phases. After that, the organic C, especially the easily available C compounds, were exhausted in the composting process, reducing the activities of methanogens in the composting materials and, therefore, gradually decreasing the CH_4 emissions. It can be easily observed that the CH_4 emission load of vermicompost (0.13% CH_4-C of initial organic C) was lower than thermophilic compost (0.60% CH_4-C of initial organic C) cumulatively (table 3). This was because the activities of earthworms not only homogenized the materials and improved the ventilation, but also fragmented large particles and so removed anaerobic conditions (figure 2*D*), which resulted in a reduction of CH_4 production. To the contrary, the anaerobic environment in the thermophilic compost was responsible for the high CH_4 emissions because of the oxygen depletion during degradation of raw materials. The analysis showed that the oxidation redox potential values in the bottom layer of the thermophilic compost were −185 mV, −211 mV, −227 mV, −168 mV, and −151 mV on the 0, 5th, 10th, 30th, and 50th days, respectively, which was quite suitable for CH_4 production; and the heat created by the degradation made the bottom of the pile warm and suitable for CH_4 production. Similar differences can be found in turning composting and static composting as the activities of earthworms function as turning activity. The research of Majumdar et al. (2006) indicated that the CH_4 emissions of vermicompost were lower than other compost forms. They considered this result to be relevant to the different moisture contents of composts, because in dry environments, very little CO_2 generation is expected because of low bioactivity while methane generation might virtually be absent, as anaerobic conditions are not favored. In this experiment, in line with this inference of Majumdar et al. (2006), the moisture content in thermophilic compost was in the range of 58%–70%, higher than that in vermicompost (~60%) by manual controlling, resulting in an unfavorable anaerobic environment in the vermicomposting process.

The formation of N_2O occurs during incomplete nitrification/denitrification processes. During denitrification, N_2O can be synthesized where there is a lack of O_2 and/or a nitrite accumulation (Philippe et al. 2012). During nitrification, N_2O is produced in the presence of O_2 and/or low availability of degradable carbohydrates (Li et al. 2016). Therefore, N_2O can generate under both aerobic and anaerobic conditions. In this study, there was a small emission peak of N_2O in the two treatments on the 3rd day. This was caused by the high concentration of nitrate and nitrite (table 2) in raw materials; N_2O might be synthesized from denitrification in the storage and discharged at the start of composting because of the increased temperature. This inference is in line with the results from previous studies. El Kader et al. (2007) considered that a high concentration of N_2O at the start of composting may actually have been produced before the composting process started. Maeda et al. (2010) found that the denitrification occurred immediately after composting started. After that, there was a low N_2O emission in days 4–7, the high temperature and high free ammonia might have inhibited the nitrifiers, and the absence of available C might have resulted in inactivity of the heterotrophic denitrifiers (Jiang et al. 2013). Contrary to the assumption of Fukumoto et al. (2003) and Thompson, Wagner-Riddle, and Fleming (2004) that the activity of nitrifiers would be inhibited by high temperatures (>40°C), most of the N_2O from the two treatments was emitted during days 10–20 (figure 2*B*). Szanto et al. (2007) reported that methanotrophs were capable of ammonium oxidation under thermophilic

Table 3. C, N balance, and total GHG emissions in the two composting processes.

	Carbon balance (%)*		Nitrogen balance(%)†			GHG emissions(kg CO_2-eq t^{-1} DM)		
Treatments	CH_4-C	Total C loss	N_2O-N	NH_3-N	Total N loss	CH_4	N_2O	Total GHG
Vermi-composting	0.13	53.2	0.92	12.3	15.5	2.28	5.76	8.1
Thermophilic composting	0.6	48.9	1.96	24.9	27.8	10.52	12.29	22.8

*Percentage of initial total carbon, dry weight basis.
†Percentage of initial total nitrogen, dry weight basis.

conditions; Sømmer and Møller (2000) suggested that nitrification could occur at the surface of the compost pile, where the temperature and O_2 content were suitable for nitrosomonas; and Jiang et al. (2016) considered that turning makes the transportation of NO_3^- from aerobic regions to anaerobic regions, and the denitrification of NO_3^- produces N_2O. In this study, the increased NO_x^- concentration (table 2) in the composting materials indicated nitrification during the thermophilic phase. From day 20 of the composting process, the temperature dropped and the amount of O_2 (figure 2*D*) increased gradually, which was appropriate for nitrification. Nonetheless, the nitrification decreased because of the reduction of NH_4^+ (table 2) produced from organic matter degradation. Denitrification also decreased because there was less nitrification, thus reducing the N_2O emissions from both nitrification and denitrification. N_2O emissions from vermicompost (0.92% N_2O-N of initial N) were apparently lower than that from thermophilic compost (1.96% N_2O-N of initial N) cumulatively (table 2). Statistical results showed that there was a highly significant difference in N_2O emissions between the two treatments ($P < 0.01$). Similar results can be found in the research of Rodriguez et al. (2011) who attributed this phenomenon to low activity of denitrifying bacteria in vermicompost. Conversely, the high N_2O emissions from the thermophilic compost might result from stratification of the piles. The NH_3 generated in the bottom layers was oxidized incompletely by methanotrophs through the middle layer where the O_2 content was sufficient. The activities of earthworms in the vermicompost homogenized the materials, and thus destroyed the stratification and decreased the N_2O emissions by 53% (based on initial N). It is also inferred that part of the denitrification might occur in the intestinal tract of earthworms, which decreased the N_2O emissions to some extent.

The NH_3 emissions across the two treatments peaked at the start of the composting period and then decreased sharply (figure 2*C*). This initial peak may be the result of high NH_4^+ (table 2) concentrations in the raw materials, which was transformed to NH_3 by ammonifying bacteria in the first few days. The NH_3 emission trend of the vermicomposting process was quite similar to the thermophilic composting process during days 0–10, but there was an obvious increase after day 10 that persisted for ~20 days in the thermophilic compost as a result of the increased temperature and enhanced ammonization, and then declined after the easily degradable materials were exhausted and the degradation rate decreased. Afterwards, with the exhaustion of easily degradable materials, the degradation rate decreased and consequently the NH_3 emissions declined. The NH_3 emissions pattern from this study is in line with previous research (Awasthi et al. 2016; Chan, Selvam, and Wong 2016; Szanto et al. 2007). As a result of the stable temperature in vermicompost, the NH_3 did not have a high emission period. After the composting period was completed, 12.3% of the initial N had been lost in the form of NH_3 in the vermicomposting process, which was lower than that in thermophilic compost (24.9% of initial N) cumulatively (table 3). The low temperature of vermicompost may contribute to this decrease, and the good ventilation in vermicompost caused by the activities of earthworms let the gas escape from the pile. Statistical results showed that there was a significant difference between the two treatments ($P = 0.05$). The NH_3 emission level in this study was in line with the research of Jiang et al. (2016), but was higher than results of Szanto et al. (2007), in which only 2.5%–3.9% of initial N was lost in the form of NH_3. Different materials and high bulk density of the raw materials was likely to be responsible for their low emission level.

C and N Balance and GHG Emissions

Data of the C and N balance and GHG emissions are shown in table 3. In this work, the CH_4-C loss in vermicompost was much lower than that in thermophilic compost, caused by the small particles and increased void ratio formed by the earthworm activities, which destroyed the anoxic conditions for CH_4 production. Other C could be lost in the form of CO_2 released to air, or used by microorganisms to compound cell tissues. A considerable part of N in compost was lost in the form of N_2O, but most N was lost in the form of NH_3. The research of Fukumoto et al. (2003) and Szanto et al. (2007) showed a similar N_2O-N and NH_3-N loss level in thermophilic compost, slightly higher than that of vermicompost. Different temperature, moisture content, and activities of earthworms could be the reasons for this decrease. The total GHG emissions in this study were 8.1 and 22.8 kg CO_2-eq per ton of dry matter in vermicompost and thermophilic compost, respectively, indicating that vermicompost is an effective compost method to reduce GHG emissions.

Conclusions

Results showed that vermicomposting did not have a thermophilic phase during the whole composting period so the temperature was suitable for earthworm survival (5°C–35°C). To solve the problem of pathogens in vermicompost, it is suggested that pre-composting of the raw materials is necessary. According to maturity indexes, vermicompost with tomato stems and cow dung could reach the compost maturity standard, showed a better maturity degree (lower C/N ratio and higher GI), and reduced the time taken to reach compost maturity. Meanwhile, the activities of earthworms homogenized the materials and enhanced ventilation of the composting piles, thus vermicompost released much less GHG (CH_4 and N_2O) and NH_3 than traditional thermophilic compost, demonstrating that vermicomposting of vegetable waste is an effective method to reduce gaseous emissions. As an added advantage, the earthworms after processing could be used for commercial purposes, which could improve the economic benefit of composting.

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