Relationship between gas depth profiles in compost heap and gas emission

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ABSTRACT

The purpose of this study was to quantify the relationship between the emission patterns of ammonia (NH_3) and nitrous oxide (N_2O) during the process of composting swine deep-litter and the movement of gaseous and liquid components inside the compost heap.

Emissions of NH_3 and N_2O during the process of composting swine deep litter were measured using a chamber system. The heap was subdivided into 3 layers: surface, middle and bottom. Within each layer, the concentrations of gaseous (NH_3, N_2O and O_2) and liquid (NH_4^+, NO_2^- and NO_3^-) components were measured during composting, and compared with gas emissions from the heap.

Intensive NH_3 emission was observed during the initial week, N_2O emission was observed during week 4-6 of the composting period. There was a good correlation between NH_3 emission and NH_3 or NH_4 concentration in the surface layer of the heap. N_2O emission also showed a good correlation to N_2O concentration in the surface layer of the heap. On the other hand, no or a less significant correlation was observed between gas emissions and gas concentration in the middle and bottom of the heap. It is considered that NH_3, or NH_4^+ and N_2O concentrations in the surface layer of a compost heap could be good indicators for predicting NH_3 and N_2O emissions, respectively.

Keywords: Ammonia; Nitrous oxide; Swine deep litter; Composting; Chamber method; Stratification

INTRODUCTION

The emission of harmful gases from composting of livestock waste has been the cause of serious environmental problems, such as complaints from residents around farms about odor, and destruction of the natural ecosystem by greenhouse and other harmful gases (Haga, 1998). Because of the low carbon/nitrogen (C/N) ratio, ammonia (NH_3) is one of the principal malodorous compounds emitted during composting of livestock waste. The NH_3 emission from livestock production has been evaluated in a large number of studies (Ryden *et al.*, 1987;

Hartung *et al*., 1994; Sommer *et al*., 1996), and these studies have demonstrated the need for a solution to this problem. Moreover, NH_3 can cause acidification or disturb natural ecosystems through deposition (Pearson & Stewart, 1993). Nitrous oxide (N_2O) released from nitrification or denitrification has a high global warming potential (Houghton *et al*., 1992) and is involved in the depletion of stratospheric ozone (Cicerone, 1987). The loss of gaseous nitrogen from composting of livestock waste causes not only environmental problems, but also leads to decreased nutrient value of manure (Sommer, 2001; Møller *et al*., 2000; Kirchmann, 1985; Eghball *et al*., 1997).

It is important to suppress the emission of harmful gaseous components in composting livestock waste. However, because the generation and emission of these components is still incompletely understood, it is difficult to establish effective countermeasures for suppression of the harmful gases. Therefore, more detailed information about gaseous generation and emission in composting is necessary.

The condition of a compost heap dramatically changes during the composting process. Moreover, the environment inside a compost heap is not uniform. During composting of livestock waste without forced aeration, some stratification is established inside the compost heap depending on the supply of oxygen from the surface of the heap. At the surface layer of a heap, sufficient oxygen is supplied for aerobic degradation of organic material. On the other hand, because there is only a few oxygen at the center of a compost heap, degradation of organic material must progress anaerobically. Haga *et al*. (1998) found that there were remarkable differences in the degradable ratio of biological oxygen demand (BOD) and the accumulation of volatile fatty acids between the anaerobic and aerobic portions in a compost heap. These differences inside a compost heap may affect the generation of gaseous components. However, there are few studies focusing on the movement of gaseous components in each layer inside a compost heap during composting, and the relation of this movement to the emission of those gaseous components. We consider that understanding the relationship between the movement of gaseous components inside a compost heap and gas emissions would be crucial to understanding the mechanism of gas emissions from the composting of livestock waste.

The purpose of this study was to quantify the relationship between gas emission patterns from the heap and the movements of gaseous and liquid components within it the heap. In this study, we measured NH_3 and N_2O emissions during the process of composting swine deep-litter using a chamber system. Furthermore, we considered the stratification inside the compost heap by subdividing into three layers, and investigated the time course of gaseous NH_3, N_2O and O_2 concentration in each level during composting. We also measured the change in the concentrations of liquid components (NH_4^+, NO_2^-, and NO_3^-) in the deep-litter taken from each level of the heap. Based on these results, we investigated the relationship between the pattern of gas emissions and the movement of gaseous and liquid components inside the compost heap.

MATERIALS AND METHODS

Composting

327 kg of swine deep litter were collected from inside the animal house and piled up inside a chamber (heap height: 80 cm, diameter: 180 cm at the beginning of experiment). The litter consisted of swine manure, urine and barley straw. The composting experiment was carried out from 24th July to 24th September 2001. During composting, the pile was not turned. At the end of the experiment, the total weight of the heap was obtained. When the experiment was finished, the weight of the heap was 154 kg (heap height: 40 cm, diameter: 180 cm).

Nutrient composition

Three samples each of 0.5 l of composting material were taken from the surface, middle and bottom portion of the heap by hand. Sampling was carried out twice a week from start to 5th week, and once a week from the 5th week to the end of the experiment. The samples were stored at $-18\ ^{o}C$. Before chemical analysis, the organic material was thawed at $0\ ^{o}C$, and each sample was ground up. Representative subsamples of about 500 g of chopped material were then cut into small pieces, and from this material 100 g was taken for analysis. All manure samples were analyzed for dry weight, ash content, pH, total N, NH_4^+, NO_3^- and NO_2^-.

NH$_4^+$, NO_2^- and NO_3^- in the litter were extracted in 1 M KCl for 30 min, filtered before analysis on a QuichChem 4200 flow injection analyser (Lachat Instruments, Wisconsin, USA). Dry matter was determined after drying at $103\ ^{o}C$ for 24 h, and ash content at $525\ ^{o}C$ for 6 h. Total N was analysed using the Dumas method (Hansen, 1989; Sweeney, 1989).

Concentration of gaseous components in the compost heap

For determination of NH_3, N_2O and O_2 concentrations inside the heap, air samples were collected from each level of the heap (surface, middle and bottom: shown in Fig. 1.) by air sampling equipment.

To avoid air contamination inside the heap by taking the solid samples, the air samples were taken just before taking the solid samples. The air sampling equipment was an iron pipe (length: 1 m, inner diameter: 1.5 cm) with small holes (diameter: 1.5 mm) at its tip. This air-sampling pipe was inserted at each sampling position inside the heap, and the air was sucked out with a 100 ml-air syringe. The air in the pipe was sucked out several times for flushing before the sampling. About 100 ml of air was sucked from the sampling point and then transferred to 5-ml glass bottles fitted with butyl rubber septa for N_2O and O_2 analysis. N_2O was measured on a Hewlett Packard (5890, series II) gas chromatograph with an electron capture detector (ECD-GC). It was equipped with a 1.8 m x 3 mm column with Porapak Q 80/100 for N_2O, Ar/CH$_4$ (95/5) was used as a carrier at 30 ml/min, and the temperatures of the injection port, oven and detector were 110, 40 and $320\ ^{o}C$, respectively. O_2 was measured on a Varian 3350 gas chromatograph equipped with a thermal conductivity detector as well as with

a 1 m x 1/8" column with Molecular Sieve 5 A 60/80 for isolating O_2. The NH_3 concentration in the heap was monitored with a detection tube and a gas sampler (GASTEC Co., Ltd). The detection tube was directly connected to the air-sampling pile by short rubber tube, enabling the gas sampler to suck 50 or 100 ml air into the air-sampling pipe.
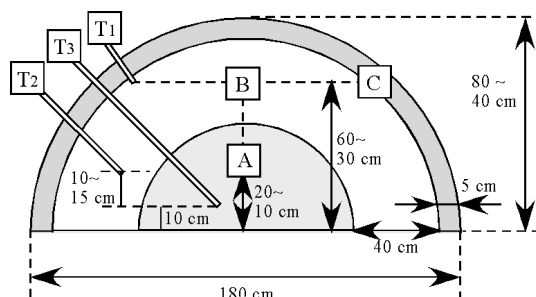

Figure 1. Schematic diagram of cross section of the compost heap. Air sampling point; A: bottom, B: middle, and C: surface. Temperature measuring point; T1: surface, T2: middle, T3: bottom. During the composting, the height of the heap changed from 80 to 40 cm.

Measurement of the gas emissions

The measurement system consisted of a dynamic/open chamber device to collect the exhaust gas from composting materials, and a measurement device (Fig. 2.).

We used a modification of the chamber system used by Osada & Fukumoto (2001). The differences of the present to the original one are: 1) the system to introduce fresh air into the chamber is changed, and 2) the experiment is conducted inside a building to minimize environmental factors as much as possible.

The cylindrical chamber was made and installed in the laboratory of the Danish Institute of Agricultural Science (DIAS), Research Centre Bygholm. The chamber was made from waterproof transparent material (PE) measuring 3 m in diameter, 2.2 m height, and had a volume of 13 m^3. The chamber was placed on a waterproof floor. The lower edge of the chamber was sealed along the floor with vinyl tape to prevent air leaks. Fresh air is introduced through 6 holes around lower side of the chamber, and exhaust air is vented from the middle of the ceiling. Flaps made of PE sheet were set at each hole inside the chamber to disseminate the airflow. The air pressure inside the chamber was kept slightly higher than that outside (1-2 Pa higher) by regulating the outlet airflow. The airflow rate was measured using an orifice plate (hole diameter: 70 mm), mounted in the inlet duct (O, Fig. 2.). According to the study of Osada & Fukumoto (2001), the airflow rate was set up around 130 m^3 h^{-1} (10 times ventilation in one hour) in this study.

Samples of inlet air (fresh air) were extracted from the pipe going to the chamber behind the ventilation blower inlet (S1, Fig. 2.), and exhaust air was extracted just after exiting the top of the chamber (S2, Fig. 2.). Gas from each sampling point was automatically carried to the analysis apparatus through a Teflon tube (4 mm in diameter). The Fourier Transform

Infrared (FTIR) spectroscopy detector (Infrared Photoacoustic Detector; IPD, INNOVA, Denmark) measured NH_3 and N_2O concentrations in air samples at 15-min intervals during the composting experiment. The detection limits of this equipment typically lie in the 10 ppb to 1 ppm range (200 ppb for NH_3, and 30 ppb for N_2O).
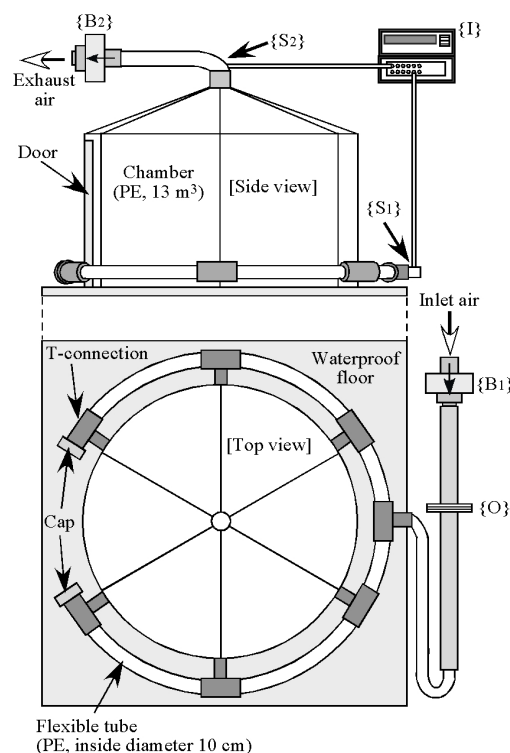

Figure 2. Schematic of the measurement system for emission from composting (Chamber system). B; Ventilation blower for Inlet (B1) and Outlet (B2) air. B2 was connected to a voltage regulator for controlling the airflow rate. S; Sampling point for Inlet (S1) and Outlet (S2) air. I; Infrared Photoacoustic Detector (IPD, INNOVA, DK). O; Orifice; airflow rate measurement equipment.

The emission rate of each substance was computed from the amount of ventilation and the concentration differences of each substance between the inlet and outlet air samples.

$$E_{15\ min} = (C_O - C_I) \times 15/60 \times q \qquad (1)$$

where: $E_{15\ min}$ is the emission rate of each substance in mg 15 min^{-1}; C_O is the gas concentration in the outlet air in mg m^{-3}; C_I is the gas concentration in the inlet air in mg m^{-3}; and q is the airflow rate in m^3 h^{-1}.

Temperature
Thermocouple wires fixed to a support were inserted into the heap at surface, middle and deep layers (Fig. 1.), and the data were collected using a data logger. Air temperature at the outlet tube and inside the chamber was also measured. Temperatures were measured hourly.

RESULTS AND DISCUSSION

Composting condition

During the composting experiment, the airflow rate was steady and measured as 123 m^3 h^{-1}. The average temperature and humidity inside the chamber were 21.8 ^{o}C (S.D. 1.6) and 67.8% (S.D. 8.9), respectively. The continuous records of gaseous emission were initiated 24 hours after the establishment of the heap.

Temperature

Courses of the temperature of the heap and air inside the chamber are shown in Figure 3. The temperature of the heap rose quickly after building the heap. Especially, on the surface and in the middle of the heap, it took only a very short time to reach maximum temperature (60-67°C). However, it took longer for the temperature at the bottom of the heap to rise. After reaching the peak, the temperature began to decline gradually. Around 28th day, the strong decrease of the heap temperature was occurred, which would be due to the compaction of compost heap as composting progressed. The temperature curve grew flatter and closer to ambient temperature as composting progressed. After 40 days had passed, the temperature at the surface and in the middle layers was very close to ambient temperature, and only a little higher at the bottom of the heap.
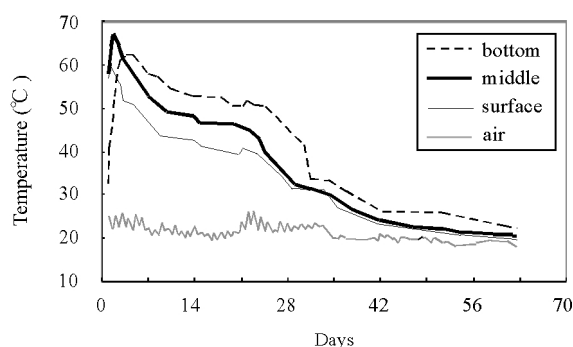

Figure 3. Change in the temperature of the compost material and air inside the chamber during composting swine deep-litter.

Gas emissions

The courses of NH_3 and N_2O concentrations ($C_O - C_I$) during composting are shown in Figure 4. The peak of NH_3 emission from the heap was observed 2 days after the start of the experiment. The highest concentration was 105 mg m^{-3}, and it quickly declined after the peak. Two weeks after the start, the NH_3 concentration was around 3 mg m^{-3}, and one month after the start, NH_3 emission was barely detectable.

N_2O emission from the heap was not detected for 2 weeks after the start of the experiment, and was first observed on day 16, and then N_2O concentration ($C_O - C_I$) was

rising to 3mg m^{-3} within 3 days. It was remaining around 2-3 mg m^{-3} for one week, and then began to decline, approaching the atmosphere level 50 days after the start.
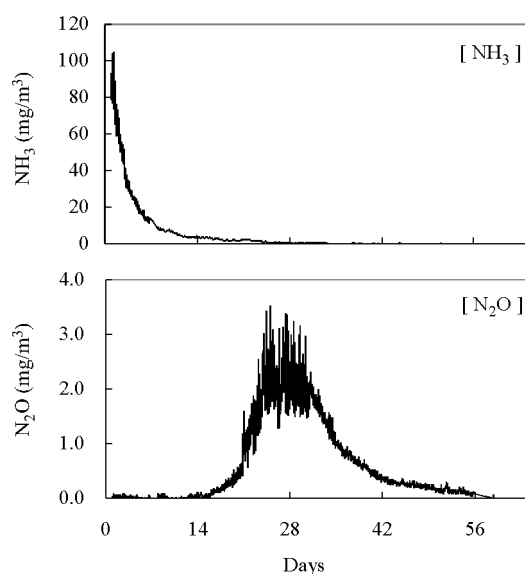

Figure 4. The emission pattern of NH_3 and N_2O during composting swine deep-litter.

Gas concentration inside the heap

The changes in NH_3, N_2O and O_2 concentration inside the heap are shown in Figure 5. When the deep litter was first piled up, NH_3 concentration was around 500 ppm at every measuring point. After three days, it rose to 1600 and 1200 ppm, respectively in the surface and middle layer of the heap. Subsequently NH_3 concentration in the surface layer quickly dropped down. However, when the NH_3 concentration in the surface layer had dropped down to its lower(est) level, in the middle and the bottom of the heap, it remained around 400 ppm until the 28th day, after which it declined rapidly.

The first increase in N_2O concentration was observed in the surface layer. Then also in the middle and bottom levels, the N_2O concentration began to increase nearly 1 week after the increase in O_2 concentration inside the heap. The peak of N_2O concentration in the surface layer was observed on the 25th day, after which it began to decline. On the other hand, the N_2O concentration in the middle and bottom layers continued to increase after peaking in the surface layer.

O_2 concentration in the middle and bottom of the heap was low early in the composting process. When 2 weeks had passed, the first increase in O_2 concentration in the middle and bottom layers was observed. After that, it rose around 16-18% in 1-2 weeks.
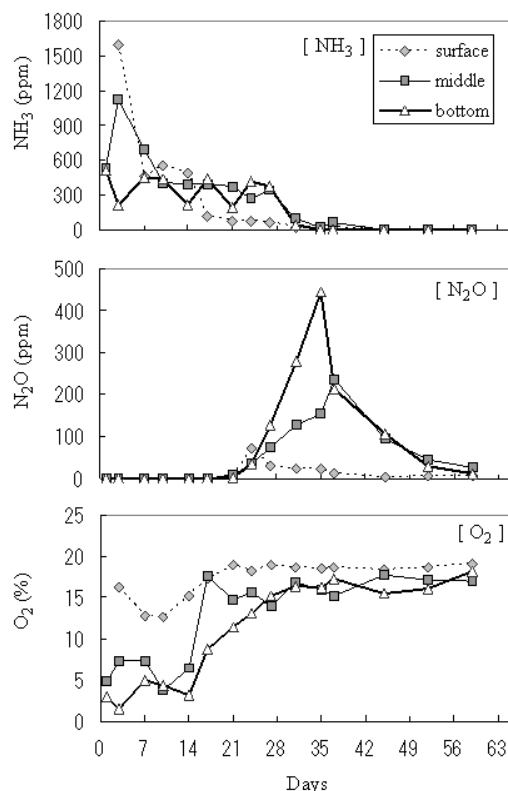
Figure 5. Change in the gaseous NH_3, N_2O, and O_2 concentration inside the compost heap during composting swine deep-litter.

Nutrient composition

The nutrient compositions at the beginning and end of the experiment are shown in Table 1. The changes in NH_4^+-N, NO_2^--N and NO_3^--N concentrations during the composting period are shown in Figure 6.

The swine deep litter contained 3.5% T-N (DM base) at the start of the experiment at which time it consisted of 45.1% NH_4^+-N, 0% NO_2^--N, 0% NO_3^--N and 54.9% other N compounds. During the experiment, 46% of that at initial T-N was lost, being finally reduced to 4.4% NH_4^+-N, 0% NO_2^--N, 6.5% NO_3^--N, and 89.1% other N compounds.

The NH_4^+-N concentration was around 1.6% at the start of the experimental period in every portion/each layer of the heap, and then it began to decline. At the surface layer, NH_4^+-N decreased quickly, while a comparatively higher NH_4-N concentration persisted at the bottom. Finally, it dropped to 0.14%.

NO_2^--N and NO_3^--N concentrations were close to 0% in the early period of the composting process. When 2 weeks had passed, an increase in the NO_2^--N concentration was first observed. Then, NO_3^--N concentration began to increase. The highest concentration of NO_2^--N was observed in the middle layer of the heap (0.39%). Both NO_2^--N and NO_3^--N concentrations in the bottom remained considerable lower than at the surface and in the

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middle layer during the entire experimental period.

Table 1. Characteristics of initial and final material in swine deep-litter composting

	Total fresh weight (kg)	Moisture content (%)	Ash (%DM)	Nitrogen content (%DM)				pH
				T-N	NH$_4$-N	NO$_2$-N	NO$_3$-N	
Initial	327	78.5	17.0	3.5	1.6	0.0	0.0	8.0
Final	154	73.1	28.3	3.2	0.1	0.0	0.2	8.3
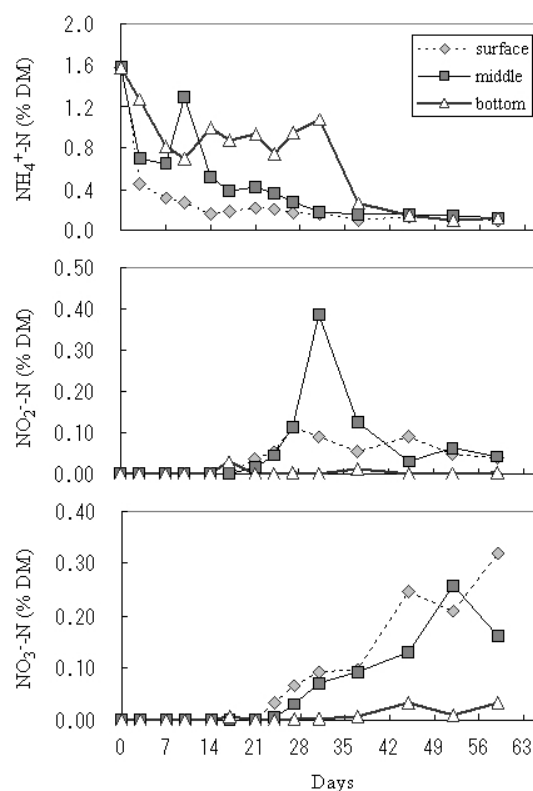
Figure 6. Change in the NH$_4$-N, NO$_2$-N, and NO$_3$-N concentration in the compost material during composting swine deep-litter.

Nitrogen mass balance

The nitrogen mass balance of the investigated swine deep-litter during composting is shown in Figure 7. Total amount of NH$_3$ and N$_2$O emissions during the experimental period were calculated as 685 g NH$_3$-N and 61 g N$_2$O-N, respectively. The bulk of the NH$_3$ emission occurred in the first 2 weeks, and N$_2$O was mainly emitted during days 21-42 days of composting. The loss of T-N from the deep litter during the experimental period was 1059 g (down 46 % of the initial T-N). Therefore, NH$_3$ and N$_2$O emission caused 64.7% and 5.8% of the T-N loss, respectively. The unknown part of T-N loss, which consisted of N$_2$ and other

non-measured NH_3 and N_2O emissions, was 29.5% of its total loss. In this composting process, the major part of N loss from the heap was caused by NH_3 emission.

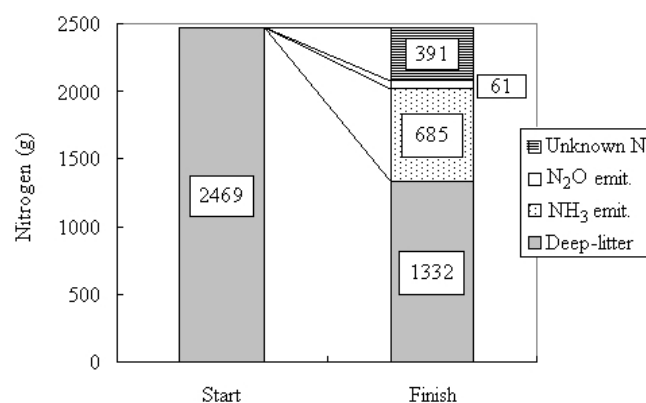Figure 7. Nitrogen mass balance in swine deep-litter during composting.

Comparison between gas emission, gas composition and nutrient composition
To recognize the influence of gas concentration and/or nutrient composition on the gas emissions, we calculated correlation coefficients between these results (Table 2).

Table 2.
The coefficient of correlation between gas emission and gas concentration/nutrient composition in the surface, middle, and bottom of the compost heap

	NH_3 emission		N_2O emission		
	NH_3 conc.	NH_4-N conc.	N_2O conc.	NO_2-N conc.	NO_3-N conc.
surface	0.928	0.909	0.756	0.534	0.007
middle	0.796	0.605	0.152	0.360	0.017
bottom	0.058	0.459	0.202	0.007	0.052

There was a good correlation between NH_3 emission and NH_3 concentration in the surface layer of the heap. On the other hand, the correlation coefficients for the middle and deep layers were lower than that for the surface layer. There was also a good correlation between NH_3 emission and NH_4^+-N concentration in the surface layer. These results mean that the NH_3 emission from a compost heap depends more on the NH_3 and/or NH_4^+-N concentration in the surface layer than that in the middle or bottom of the heap.

There was a better correlation between N_2O emission and N_2O concentration in the surface layer compared with that of the middle or bottom layer. Some correlation between N_2O emission and NO_2^--N concentration in the surface layer was observed in this study. On

the other hand, N_2O emission showed no significant correlation with NO_2^--N in the middle or bottom layers or with NO_3^--N in any layer of the heap. Therefore, it was considered that N_2O concentration in the surface layer of the heap could be one important factor, which affects N_2O emission from the heap.

N_2O is generated as a byproduct during the oxidation process from NH_4^+ to NO_2^- (nitrification), and from the reduction process of NO_2^- and NO_3^- (denitrification) (Bock *et al*., 1995; Abeliovich & Vonshak, 1992). The NO_3^--N concentration rose higher in the surface than in the middle layer and much more than at the bottom of the heap by the end of the experiment. On the other hand, NO_2^- and NO_3^- concentration were very low at the bottom of the heap. Moreover, N_2O concentration in the bottom and also in the middle layer continued to increase even when it had already decreased in the surface layer. From these results, it was thought that the possibility that most of the N_2O in the surface layer was generated from the nitrification process was high. On the other hand, N_2O would be generated from both nitrification and denitrification in the bottom layer of the heap. Furthermore, because N_2O in the middle and bottom layers did not contribute very much to emission from the heap, nitrification in the surface layer could be an important factor in N_2O emission during the composting.

Relational equation

We obtained the relational equations for gas concentration and nutrient content in the heap, and gas emission in this system, and then compared the theoretical results with experimental values. Each equation (NH_3 emission & NH_3 concentration in the surface, NH_3 emission & NH_4^+-N concentration in the surface and N_2O emission & N_2O concentration in the surface) was calculated as follows:

I) NH_3 emission & NH_3 concentration in the surface layer of the heap.

$$Y_1 = 0.0252\, X_1 \tag{2}$$

II) NH_3 emission & NH_4^+-N concentration in the surface layer of the heap.

$$Y_1 = 50.596\, X_2 \tag{3}$$

III) N_2O emission & N_2O concentration in the surface layer of the heap.

$$Y_2 = 0.0411\, X_3 \tag{4}$$

where: Y_1 is the NH_3 emission in mg m^{-3}; X_1 is the NH_3 concentration in ppm; X_2 is the NH_4^+-N concentration in % DM; Y_2 is the N_2O emission in mg m^{-3}; and X_3 is the N_2O concentration in ppm.

The correlation coefficient between theoretical results and experimental values for each equation was I) 0.928, II) 0.909 and III) 0.756, respectively.

In equations (2) and (3), good correlations were observed, suggesting that NH_3 or NH_4^+-N concentration in the surface layer could be a good indicator of NH_3 emission. There is also a possibility that N_2O concentration in the surface layer could be an indicator of N_2O emission.

In this study, the composting was conducted under controlled conditions. Any pile turning or forced aeration was not conducted. In normal composting, numerous environmental factors would affect gas emission and generation during the process, and differences in handling manure would impact them. Therefore, the equations above should include more factors to improve their accuracy, using data from composting experiments in various situations.

CONCLUSIONS

Comparison between gas emission and gas concentration inside the heap showed that a high concentration of gaseous components at the surface layer of the heap would lead to intensive gas emission, while gaseous components in the middle and in the bottom of the heap would not contribute much to gas emission. There was also a good correlation between the NH_4^+-N concentration in the surface layer and NH_3 emission. NH_3, NH_4^+-N and N_2O concentrations at the surface layer could be a good indicator for predicting NH_3 and N_2O emissions, respectively.

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