



Pile mixing increases greenhouse gas emissions during composting of dairy manure

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ABSTRACT

The effect of pile mixing on greenhouse gas (GHG) emissions during dairy manure composting was determined using large flux chambers designed to completely cover replicate pilot-scale compost piles. GHG emissions from compost piles that were mixed four times during the 80 day trial were approximately 20% higher than emissions from unmixed (static) piles. For both treatments, carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) accounted for 75–80%, 18–21%, and 2–4% of GHG emissions, respectively. Seventy percent of CO₂ emissions and 95% of CH₄ emissions from all piles occurred within first 23 days. By contrast, 80–95% of N₂O emissions occurred after this period. Mixed and static piles released 2 and 1.6 kg GHG (CO₂-Eq.) for each kg of degraded volatile solids (VS), respectively. Our results suggest that to minimize GHG emissions, farmers should store manure in undisturbed piles or delay the first mixing of compost piles for approximately 4 weeks.

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1. Introduction

Animal manure management activities in the US emitted an estimated 62 Tg (million metric tons) of CO₂ equivalents (Tg CO₂-Eq.) in the form of methane (CH₄) and nitrous oxide (N₂O) in 2008, accounting for about 1% of US greenhouse gas (GHG) emissions. Emissions of CH₄ (45 Tg CO₂-Eq.) and N₂O (17 Tg CO₂-Eq.) from animal manure management practices have increased approximately 55% and 20%, respectively, since 1990 (US EPA, 2010). Concerns about climate change have increased the demand for regulations to minimize GHG emissions and for implementation of carbon trading markets. Regulations coupled with a carbon trading market would create economic incentives to stimulate reductions in GHG emissions. Therefore, research in the area of characterizing existing emissions and strategies to minimize emissions has become increasingly important.

Composting is an environment friendly technology for treating and recycling a variety of organic wastes. It is both a simple and economical process that converts manure to a stabilized fertilizer and also reduces GHG emissions (USCC, 2008). The US Environmental Protection Agency (US EPA) and the US Composting Council (USCC) have concluded that composting does not contribute to GHG emissions. Well-managed composting operations produce biogenic CO₂, which is not considered an additional source of GHG emissions, and the amounts of CH₄ and N₂O gases produced

are considered to be negligible (USCC, 2008). However, CH₄ and N₂O emissions could potentially increase if proper composting conditions are not maintained. Studies of different composting operations have found a wide range of CH₄ and N₂O emissions, accounting for 0.01–8% of the total carbon loss and 0.1–5% of the total nitrogen loss, respectively (Hellebrand, 1998; Sommer, 2001; Sommer et al., 2004; Brown et al., 2008; Hellebrand and Kalk, 2000; Tamura and Osada, 2006; Wolter et al., 2004).

Aeration, in addition to the moisture content and the carbon/nitrogen ratio of the feedstocks, is an important factor influencing GHG emissions from the composting process. Aeration is usually accomplished by pile mixing, forced aeration, or reduced pile size. Most previous studies have reported that aeration reduced CH₄ emissions from composting systems (Szanto et al., 2007; He et al., 2001; Hellebrand, 1998; Fukumoto et al., 2003), while one found the opposite result (Paul et al., 2001). The effect of aeration on N₂O emission is more complicated. Hellebrand (1998), Fukumoto et al. (2003), and Szanto et al. (2007) observed that larger static piles and less ventilated composting systems increased N₂O emissions. However, Hao et al. (2001), He et al. (2001), and Czepiel et al. (1996) found the opposite; aeration elevated N₂O emissions a maximum of 2.8 times. Due to the disparity among the previous studies, further investigation into the influence of aeration on GHG emissions from composting systems is necessary to develop proper GHG management strategies.

The purpose of this study was to evaluate the effect of pile turning on GHG emissions during dairy manure composting and suggest suitable turning strategies for reducing GHG emissions during the composting process. Recently, large-scale flux chambers have been used to entirely cover compost piles improving accuracy

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of GHG emission measurements (Wolter et al., 2004; Andersen et al., 2010; Tamura and Osada, 2006). Andersen et al. (2010) proved the dynamic plume method using large flux chambers was more effective than small scale flux chamber and funnel methods. Therefore, large flux chambers designed to cover a whole pile were used in this study. Greenhouse gas production is dependent on changes in pile composition over time during the composting process. However, previous studies have considered GHG production only in terms of initial composition of feedstocks and final compost. To account for changes in pile composition during composting and its effect on GHG emissions we measured changes in pile composition for each GHG sampling period.

2. Methods

2.1. Compost pile construction and mixing frequency

Ten replicate pilot-scale compost piles were constructed for this study using a mixture of dairy manure solids and bedding from the USDA's Dairy Research Unit in Beltsville, MD. Uniform cylindrical piles (1200 kg mass, 1.9 m³ volume, 1.2 m height, 1.4 m diameter) were constructed using galvanized steel fencing panels (10 cm mesh size) and were placed on individual platforms to enable determination of pile mass values. Three piles were randomly chosen for the mixed pile treatment and were taken apart for sampling, mixed, and reconstructed four times (days 10, 23, 36, and 52) during the 80 day study. Following sampling on the four dates, the collective contents of all three mixed piles were mixed together using a front end loader prior to reconstruction into three separate piles of the same pile dimensions as prior to mixing. Seven remaining piles were selected for the static pile treatment to allow for destructive sampling of two piles at each of three time points (days 23, 52, and 80).

2.2. Gas sampling system

Three 8.6 m³ volume flux chambers (1.9 m height and 2.1 m square) were fabricated from sheet metal for this study. Each chamber was equipped with an internal fan (0.5 m³/min) to mix the inside air and an external fan (2.0 m³/min) to draw air through the chamber. The flow rate was set to exchange the chamber air every 4.3 min. Chambers were placed on three replicate piles for each treatment for 2 h to allow the chambers to reach equilibrium conditions prior to measurements. Flux chamber measurements were conducted twice a week for the first 50 days and once a week thereafter. When mixing was scheduled, flux measurements were made immediately prior to and following mixing. Gas samples were taken from flux chamber outlet and analyzed for CO₂, CH₄, and N₂O using a photoacoustic field gas monitor (INNOVA 1412; Lumasense Technologies, Ballerup, Denmark). In order to test the accuracy of the gas sampling system, recovery tests were conducted. Pure CO₂ gas was released into each chamber at a known flow rate while monitoring gas concentration at the outlet. Comparison of the measured gas concentrations with calculated values revealed very high accuracy (recovery rate above 98%; data not shown).

Prior to flux chamber measurements, GHG and oxygen concentrations as well as temperature values were determined at nine different locations within each pile. Aluminum probes of three different lengths (15, 45, and 75 cm) with perforated tips were inserted into each pile and gases were withdrawn using an external pump for analysis with the INNOVA and an oxygen sensor (SO-220; Apogee Instruments, Inc. Logan, UT, USA). Temperatures were measured at the same locations using type-T thermocouples.

Temperature and oxygen data were collected using a data acquisition system (CR23X, Campbell Scientific, Logan, UT, USA).

2.3. Compost sample analysis

To account for potential pile heterogeneity, triplicate samples were collected from nine locations within duplicate treatment piles and analyzed for moisture content, VS, total carbon (TC), and total nitrogen (TN). Moisture and VS content of samples were analyzed according to Standard Methods (APHA, 1998). Total carbon and TN were analyzed using an elemental analyzer (Elementar Vario Max CNS, Elementar Analysensysteme GmbH, Hanau, Germany).

2.4. Statistical analysis

The results of mixed and static compost piles were analyzed using PROC T test (SAS/STAT[®]9.2, SAS Institute, Inc. Cary, NC) to determine the differences between the means.

3. Results and discussion

3.1. Temperature of compost piles

Fig. 1 shows temperature values in the center of the mixed and static piles. The temperature of all compost piles increased rapidly to above 65 °C in a few days followed by a gradual decrease to 60 °C by day 10. Temperatures of static piles slowly declined but values remained over 50 °C by day 60 despite low ambient temperatures. Static pile temperatures decreased significantly after day 60 to a low of 15 °C by the end of the 80 day study period. The temperature of the mixed piles dropped immediately following each mixing event (days 10, 23, 36, 52), subsequently returning to a slightly lower level than the pre-mixing temperature Andersen et al. (2010) and Fukumoto et al. (2003) reported similar trends. However, an abnormal pattern was observed after the third mixing. Following this event pile temperature dropped to ambient temperature (<10 °C) after mixing and did not increase until the fourth mixing (day 52). Due to diminished microbial activity, microbes exposed to cold temperature (3 °C) during mixing failed to produce enough heat to increase pile temperature. However, the pile temperature increased again to above 60 °C about 2 weeks after the fourth mixing when the microbes recovered from cold temperature exposure and ambient temperatures became relatively warmer. It took almost 1 month for the pile temperature to rise to the previous level following the cold temperature shock. Therefore, a compost pile turning plan in winter season needs to be carefully considered to maintain composting performance.

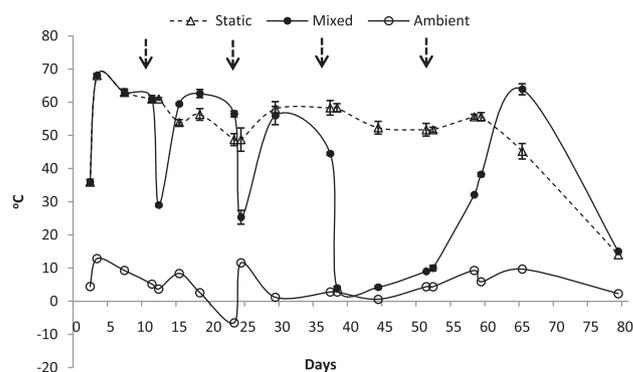


Fig. 1. Temperature in the center of the static and mixed compost piles. The arrows indicate mixing dates. Values are means \pm SE of 3 piles.

Table 1
Moisture, volatile solids, nitrogen, and carbon content of compost materials in mixed and static piles^a.

	Moisture (% w.b. ^b)		VS (% d.b. ^c)		TN (% d.b. ^c)		TC (% d.b. ^c)	
	Mixed ^d	Static ^d	Mixed	Static	Mixed	Static	Mixed	Static
Initial (Day 0)	76 ± 0.1		93 ± 0.3		1.8 ± 0.04		48 ± 1.3	
Day 10	76 ± 0.2		91 ± 0.2		1.9 ± 0.03		47 ± 0.5	
Day 23	76 ± 0.1	76 ± 0.3	89 ± 0.3	90 ± 0.5	2.3 ± 0.04	2.1 ± 0.03	46 ± 0.4	45 ± 0.6
Day 36	76 ± 0.2	–	87 ± 0.2	–	2.5 ± 0.03	–	45 ± 0.4	–
Day 52	74 ± 0.4	77 ± 0.5	86 ± 0.3	88 ± 0.4	2.4 ± 0.03	2.5 ± 0.03	44 ± 0.3	45 ± 0.1
Day 80	71 ± 0.4	76 ± 0.7	84 ± 0.7	88 ± 0.5	2.6 ± 0.03	2.8 ± 0.01	43 ± 0.4	44 ± 0.5

^a Values are means ± SE from 54 samples (27 samples from duplicate piles).

^b w.b., Wet basis.

^c d.b., Dry basis.

^d Three mixed piles were mixed and reconstructed on days 10, 23, 36, and 52. Two static piles were destructively sampled on days 23, 52, and 80.

Table 2
Loss of water, volatile solids (VS), carbon, and nitrogen from static and mixed compost piles^a.

		Water		VS		TN		TC	
		Mixed ^b	Static ^b	Mixed	Static	Mixed	Static	Mixed	Static
Initial mass (kg)			875 ± 4		259 ± 1		5.0 ± 0.1		133 ± 1
Final mass (kg)		476 ± 7	524 ± 1	154 ± 2	147 ± 0.3	4.5 ± 0.1	4.7 ± 0.1	80 ± 1.3	75 ± 0.1
Cumulative mass loss	Days (0–10)		8 ± 0.5		11 ± 0.5		2 ± 0.5		10 ± 0.5
(% of initial mass)	Days (11–23)	20 ± 0.6	19 ± 0.3	25 ± 0.6	22 ± 0.3	2 ± 0.5	3 ± 0.4	24 ± 0.6	23 ± 0.3
	Days (24–36)	29 ± 0.3	–	34 ± 0.3	–	7 ± 0.4	–	33 ± 0.3	–
	Days (37–52)	35 ± 0.4	32 ± 0.5	34 ± 0.2	39 ± 0.4	8 ± 0.9	9 ± 0.6	33 ± 0.3	39 ± 0.4
	Days (53–80)	46 ± 0.8a ^c	41 ± 0.3b	41 ± 0.7a	44 ± 0.3b	10 ± 1.0a	8 ± 0.5a	40 ± 0.8a	45 ± 0.3b

^a Values are means ± SE of 3 replicate piles.

^b Three mixed piles were mixed and reconstructed on days 10, 23, 36, and 52. Two static piles were destructively sampled on days 23, 52, and 80.

^c Means with different letters are significantly different ($p < 0.05$).

3.2. Composition and mass balance of compost materials

Tables 1 and 2 show the composition, average initial mass and cumulative loss of water, VS, TN, and TC of the mixed and static piles. The removal rate of each component for both mixed and static piles during first 10 days was assumed to be the same because uniform results were obtained from three randomly selected piles. Therefore, a single value is reported for each parameter during this period. After 80 days of composting, greater water (46 ± 0.8%) and TN (10 ± 1.0%) reductions were observed in the mixed piles than in static piles (water: 41 ± 0.3%, TN: 8 ± 0.5%). Relatively more aerobic conditions caused by mixing induced more water evaporation and N loss in the mixed piles compared to the static piles. This result coincides with results from many previous studies illustrating the positive influence of pile mixing on water evaporation, organic material degradation, and nutrient reduction (Szanto et al., 2007; Haug, 1993). However, mixed piles degraded about 10% less VS (41 ± 0.7%) and TC (40 ± 0.8%) than static piles (VS: 44 ± 0.3%, TC: 45 ± 0.3%) over the entire composting period. This atypical result is likely caused by the temperature stress following the third mixing. Organic material degradation by microbes within mixed piles after the third mixing essentially ceased for the two weeks that the mixed pile temperature remained similar to ambient temperature (below 10 °C). Conversely, the static piles remained above 50 °C, a temperature which is suitable for microbial activity (Fig. 1). Differences in the trend for VS reduction between the mixed and static piles during the time the mixed piles were cold proved this point. Fig. 2 illustrates the daily VS reduction of the mixed and static piles. The mixed piles degraded more VS than static piles throughout the composting period, except during the interval between days 24 and 52 when mixed pile temperatures were low. In contrast to the remainder of the study, the daily VS reduction rate of the static piles was almost twofold greater than the mixed piles during this period.

3.3. GHG emission patterns

Emission of CO₂ and CH₄ from static piles peaked within a few days after construction and gradually decreased to ambient levels over time (Fig. 3). About 70% of total CO₂ emissions and 95% of total CH₄ emissions occurred within first 23 days in both treatments (Table 3). This trend is consistent with the observations of previous researchers (Hellmann et al., 1997; Sommer and Møller, 2000; Hao et al., 2001; Hao et al., 2004; Hellebrand and Kalk, 2000). However, N₂O emissions exhibited a different pattern from emissions of CO₂ and CH₄. More than 60% of total N₂O emissions from the static piles occurred during the middle of the composting period (days 24–52) and 75% of N₂O emissions from the mixed piles occurred during last 20 days of the composting experiment. These results are in agreement with those from previous studies that have reported that most of the N₂O emission occurred during the late composting

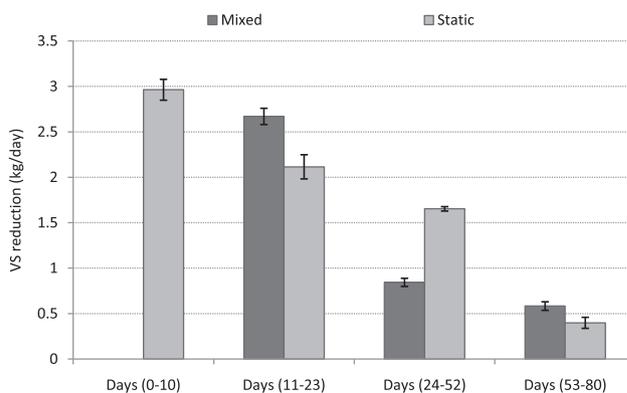


Fig. 2. Volatile solids (VS) reduction in mixed and static piles. Values are means ± SE of 3 piles.

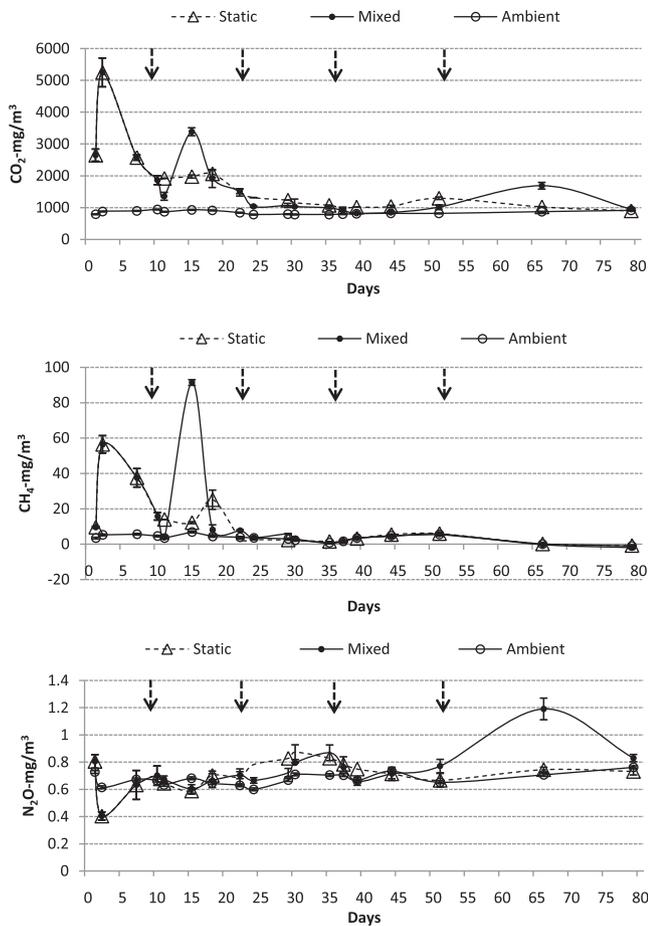


Fig. 3. Concentrations (mean \pm SE of 3 piles) of CO_2 , CH_4 , and N_2O in ambient air and in flux chamber emissions from static and mixed compost piles. The arrows indicate mixing dates.

period as available carbon is depleted and NO_3^- is denitrified under micro-aerobic conditions (Mahimairaja et al., 1995; He et al., 2001; Paul et al., 2001; Schenk et al., 1997; Fukumoto et al., 2003; Szanto et al., 2007; Maeda et al., 2010).

3.4. Effect of mixing on CO_2 and CH_4 production

The mixed piles produced approximately 16% greater GHG (as CO_2 -Eq.) in the form of CO_2 and CH_4 compared to the static piles (Table 3). The first mixing on day 10 produced a significant effect on concentrations of CO_2 and CH_4 in flux chamber emissions

(Fig. 3). The large peaks in the emission were due to greater pile porosity and improved diffusion rate following mixing. The same trend was observed by Fukumoto et al. (2003); CH_4 production increased in piles large enough to maintain anaerobic conditions and diffusion of the CH_4 actively occurred following the first turning. Oxygen concentrations within the static and mixed piles ranged below 5% during the first 23 days (Fig. 4). This was low enough to maintain anaerobic conditions during most of the first 23 days. Methane concentrations measured inside of both the static and mixed piles were high in this period coinciding with low O_2 concentrations within the piles and preceding the large emissions observed following mixing as shown in Figs. 3–5.

In order to properly control CH_4 emissions, pile turning during the first month should be avoided provided that the pile temperature and oxygen concentrations are in an appropriate range. In general, internal oxygen concentrations slowly increase as the composting progresses and this increased oxygen within the pile can be used to oxidize CH_4 produced during this early phase of composting (Paillat et al., 2005). Jäkel et al. (2005) observed that between 46% and 98% of CH_4 produced during composting was oxidized by methanotrophic bacteria. Therefore, a pile turning plan should be considered carefully to minimize CH_4 emissions and maximize CH_4 oxidation within the pile.

3.5. Effect of mixing on N_2O production

Mixed piles released approximately 3.5 times more N_2O (as CO_2 -Eq.) than the static piles (Table 3). Similar elevated N_2O production from active aeration composting systems were reported by other researchers (Czepiel et al., 1996; Hao et al., 2001; He et al., 2001; Abd El Kader et al., 2007). However, other investigators have observed the opposite result, finding that aeration reduced N_2O emissions (Fukumoto et al., 2003; Szanto et al., 2007; Hellebrand, 1998). By increasing pile aeration, mixing should result in greater nitrification than in the static piles; in addition, mixing repositions NO_3^- produced near the pile surface to the central part or bottom of the pile where it could then be reduced to N_2O (Hao et al., 2001). Therefore, pile turning promoted N_2O production through nitrification near the surface and denitrification near the area under micro-aerobic conditions. Finally, similar to CO_2 and CH_4 , N_2O flux from the mixed compost piles increased due to greater porosity resulting in a greater gas diffusion rate relative to the static piles.

3.6. GHG emission rates based on degraded VS

Greenhouse gas emissions from the mixed piles were about 20% higher than the static piles during the 80 day composting period (Table 3). The amount of GHG produced is highly dependent on

Table 3
Greenhouse gas emissions from static and mixed compost piles^a.

		CO_2 -C (%)		CH_4 -C (%)		N_2O -N (%)	
		Mixed ^b	Static ^b	Mixed	Static	Mixed	Static
% of total emission	Days (0–10)	41 \pm 2.3 ^a	45 \pm 1.6	48 \pm 1.9	69 \pm 2.9	2 \pm 0.7	6 \pm 3.0
	Days (11–23)	28 \pm 0.6	26 \pm 1.9	48.9 \pm 1.9	28 \pm 2.5	4 \pm 0.5	13 \pm 1.7
	Days (24–52)	8 \pm 0.6	20 \pm 0.8	3 \pm 0.2	1 \pm 0.1	18 \pm 3.4	64 \pm 2.7
	Days (53–80)	23 \pm 2.9	9 \pm 2.9	0.1 \pm 0.1	2 \pm 0.6	76 \pm 3.3	17 \pm 0.5
Total emission (kg)		42.4 \pm 1.2a ^c	38.5 \pm 0.2a	1.3 \pm 0.03a	0.9 \pm 0.02b	0.0185 \pm 0.002a	0.0053 \pm 0.001b
CO_2 -Eq. (kg)		156 \pm 4a	141 \pm 1a	44 \pm 1a	31 \pm 0.8b	8.7 \pm 1a	2.5 \pm 0.2b

Total emissions from mixed piles: 208 \pm 4a
Total emissions from static piles: 174 \pm 1b

^a Values are means \pm SE of 3 replicate piles.

^b Three mixed piles were mixed and reconstructed on days 10, 23, 36, and 52. Two static piles were destructively sampled on days 23, 52, and 80.

^c Means with different letters are significantly different ($p < 0.05$).

Table 4
Greenhouse gas emission rates from static and mixed compost piles based on degraded volatile solids^a.

	CO ₂ -C (g/kg VS degraded)		CH ₄ -C (g/kg VS degraded)		N ₂ O-N (mg/kg VS degraded)	
	Mixed ^b	Static ^b	Mixed	Static	Mixed	Static
Days (0–10)	586 ± 24		21 ± 1.5		11 ± 5.2	
Days (11–23)	336 ± 4	331 ± 23	19 ± 0.2	8.5 ± 0.5	19 ± 1	23 ± 5
Days (24–52)	147 ± 14	199 ± 8	1.6 ± 0.1	0.3 ± 0.04	135 ± 19	89 ± 12
Days (53–80)	600 ± 88	245 ± 5	0.1 ± 0.1	0.9 ± 0.3	874 ± 151	60 ± 7
Overall (0–80 days)	404 ± 11a ^c	342 ± 2b	13 ± 0.3a	8.1 ± 0.2b	176 ± 5a	47 ± 5b
CO ₂ -Eq. (g/kg VS degraded)	1480 ± 41a	1255 ± 6b	418 ± 11a	271 ± 7b	83 ± 10a	22 ± 2b
Total emissions from mixed piles: 1980 ± 40a						
Total emissions from static piles: 1548 ± 9b						

^a Values are means ± SE of 3 replicate piles.

^b Three mixed piles were mixed and reconstructed on days 10, 23, 36, and 52. Two static piles were destructively sampled on days 23, 52, and 80.

^c Means with different letters are significantly different ($p < 0.05$).

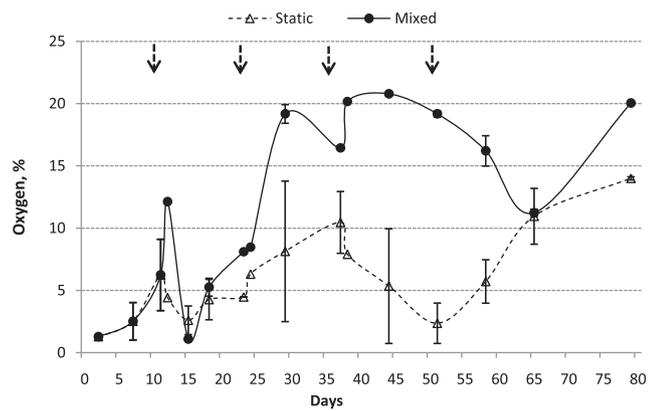


Fig. 4. Oxygen concentration (mean ± SE of measurements from six locations within duplicate piles) in center of static and mixed compost piles. The arrows indicate mixing dates.

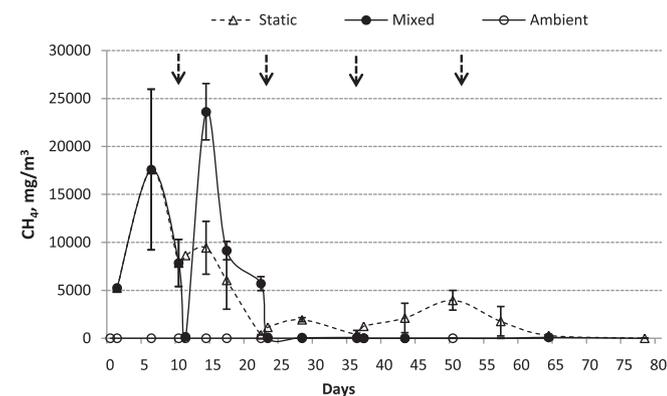


Fig. 5. Methane concentration (mean ± SE of measurements from six locations within duplicate piles) in center of static and mixed compost piles. The arrows indicate mixing dates.

the degree of organic material decomposition. Hence, released GHG should be considered on the basis of VS degraded to correctly compare GHG emissions from the static and mixed piles. Table 4 shows GHG emissions in terms of VS degraded for four different periods within the 80 day study period. Emission rates of CO₂-C per kg VS degraded were generally similar for both piles except during the last 20 days of composting. Carbon dioxide emission rates ranged from 150 to 600 g CO₂-C per kg VS degraded. Methane emissions from the mixed piles maintained a consistent rate (about 20 g CH₄-C per kg degraded VS) during the first 23 days,

whereas the static pile emission rates decreased by more than half in the period after 10 days of composting (8.5 g CH₄-C per kg degraded VS). Due to the increased gas diffusion rate after the first turning at day 10, the mixed piles exhibited an approximately 2.2 times greater CH₄ emission rate than the static piles. Both treatments had very low CH₄ emission rates (below 2 g CH₄-C per kg degraded VS) after 23 days. Nitrous oxide emission rate of the static piles ranged from 10 to 90 mg N₂O-N per kg VS degraded throughout the composting period. For the mixed piles, N₂O emission rates varied in a considerably wide range from 10 to 870 mg N₂O-N per kg degraded VS. Both static and mixed piles reached their maximum N₂O emission rates during the later part of the composting period.

During the 80 day study period, the mixed and static piles released about 2 and 1.6 kg GHG (CO₂-Eq.) for each kg of VS degraded, respectively (Table 4). Carbon dioxide, CH₄, and N₂O accounted for 75%, 21%, and 4% of GHG emissions from the mixed piles, respectively. For static piles, CO₂, CH₄, and N₂O accounted for 80%, 18%, and 2% of GHG emissions, respectively (Table 4).

4. Conclusions

Active aeration has been considered as a method to reduce GHG emissions during composting. However, our results showed turned piles emitted about 20% more GHG than static piles due to greater emission of CH₄ and N₂O. In turned piles, the relative contribution of each GHG changed over time with greater CH₄ emissions early in composting and increased N₂O emissions during a later stage. Turning strategies are more effective for CH₄ compared to N₂O management. If pile temperature and oxygen concentrations are appropriate, turning should be delayed until after the first month resulting in 6% lower GHG emissions in avoided CH₄ release.

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