Air Emissions from In-Vessel Rotating Drum and Open Static Pile Composting of Swine Carcasses, Whole and Ground

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Abstract. *Swine carcasses (292 ± 7.3 kg per batch), whole or ground, were composted using rotating drum in-vessel (IV) or open static pile (OSP) composting systems, in the 2 × 2 factorial designed experiment. Dairy manure compost, horse stall bedding, and dry wood shavings were mixed together (analyzed % H_2O, % N, and C:N of 48.7 ± 0.32%, 0.76 ± 0.075%, and 31.8 ± 2.51, respectively) and added amendment to each batch of mortality compost. Total mass per batch was 812 ± 7.3 kg. The 8 batches were placed in eight individual rooms (2 reps/trt), and air emissions including NH_3, H_2S, CH_4, N_2O, and CO_2 were measured continuously for 20 d during the primary phase (d 1 to 20), and a 15 d period 1.5 months later (secondary phase), where all batches were further composted as open static piles (identity preserved). Oxygen consumption did not differ among treatments, being unaffected by compost system, carcass form and phase of composting. Carbon dioxide emission was greater ($P < 0.05$) in the primary phase than in the secondary phase. Mass of CO_2 per day tended to be greater with use of the IV system of composting ($P = 0.07$). The IV system emitted more ($P < 0.05$) NMTHC, NH_3, and SO_2, and less ($P < 0.05$) CH_4, NO, N_2O than the OSP system. Composting system did not affect the daily mass of NO_2 and H_2S emitted. In the*

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primary phase, the IV system generated about 95% less ($P < 0.05$) CH_4 than did the OSP system (0.31 vs. 6.7 g/d, respectively). Other environmentally-interesting differences ($P < 0.05$) between the IV and OSP systems in the primary phase were NMTHC (4.13 vs. 0.19 g/d), NH_3 (86.96 vs. 5.04 g/d), and N_2O (-1.00 vs. 1.94 g/d) emissions for IV and OSP systems, respectively. The amount of CH_4, NMTHC, NO, and SO_2 gases emitted in the second phase did not differ among treatments. Nitrous oxide emissions were greater ($P < 0.05$) with the use of the OSP system than with the IV composting system in the secondary phase. Emissions were greater ($P < 0.05$) for CH_4, NMTHC, NH_3, NO, and SO_2 gases in the primary phase as compared to the secondary phase, but not for N_2O, which was greater ($P < 0.05$) in the secondary phase than it was in the primary phase. Carcass form did not affect amounts of emissions. For a 2000 head finishing swine farm with a 2% mortality rate, we estimate that CO2e emitted annually from the composting of mortality for 6 months, 1908 and 1596 kg depending on which method of composting was used (IV or OSP, respectively). In conclusion, whether carcasses were ground or left whole changed did not result in differences in gas emissions. In-vessel and OSP composting systems emitted different amounts of gases in the early, active phases of composting; including those gases considered greenhouse gases.

Keywords. Mortality, composting, in-vessel, open static pile, air quality, emissions.

Introduction

Very little is known about the emissions coming from the composting of on-farm mortality. Traditionally, the most popular method of composting has been the open static pile (OSP) either uncontained or contained in a bin, with management of primary, secondary and curing stages. In recent years, other systems of composting have been introduced to farmers, including the use of in-vessel (IV) systems; of which the most popular are rotating drums.

Emissions from OSP with bovine mortalities have been reported by Xu and coworkers (2007 a and b) and Thomson and Van Heyst, (2008). Emission samples were collected using flux rooms. Carbon dioxide, CH_4, and N_2O emissions were greater in mortality OSP's than in those containing only manure (Xu et al., 2007a & b). Collection was for 310 days and GHG surface fluxes during composting were measured weekly during the first 4 weeks and every 2–4 weeks for the remainder of the experimental period. Gas concentration profiles were described using a vented room technique. Cumulative emissions were approximated by assuming that daily fluxes represent the average for the whole week. Turning of piles caused greater CH_4, and N_2O emissions, with them being even greater if a shredder bucket was used instead of a front-end loader (Xu et al., 2007a). Currently, no published data exist for emissions from IV systems or from the composting of poultry or swine mortalities.

The objectives of this study was to compare the quantity of emissions from IV and OSP mortality composting systems, and to measure the impact of grinding carcasses on emissions when composted in the same two composting systems.

Materials and Methods

Experimental Design. Swine mortalities were composted in sealed rooms at the Michigan State University Animal Air Quality Research Facility (AAQRF) to measure gas emissions during active decomposition. Four treatments were employed which were combinations of IV or OSP compost system and whole (W) or ground (G) carcass form. Treatment designations were IVG, IVW, OSPG, and OSPW. The experiment was planned to use two observations per treatment, which were randomly assigned to eight rooms in the AAQRF.

Compost Amendment and Carcasses. Dairy manure compost, horse stall bedding, finished swine mortality compost, and dry wood shavings were blended at the Michigan State University

Composting Facility to achieve a desired initial moisture content of 40 to 60%, and a carbon-to-nitrogen ratio of 25:1 to 30:1. A chemical analysis of the final amendment for composting is shown in Table 1. Three batches of amendment were made by loading specific proportions of each feedstock into a rear-delivery manure spreader and then discharging the mixture into a pile. That pile was then loaded and run through the manure spreader a second time, and then loaded a third time for transport in same manure spreader to the AAQRF.

Table 1. Amendment composition on as-is basis[a].

Item	Measure
Moisture, %	48.3
Mineral matter, %	5.91
N, %	0.761
P, %	0.176
P_2O_5, %	0.402
K, %	0.512
K_2O, %	0.617
Ca, %	0.864
Mg, %	0.190
Na, %	0.129
S, %	0.146
C, %	24.113
B, ppm	7.4
Fe, ppm	1308.6
Mn, ppm	86.8
Cu, ppm	16.5
Zn, ppm	46.7
C:N	31.8
pH	8.72

[a] The analysis was completed at Brookside Laboratories, Inc., New Knoxville, OH 45871, except for bulk density, which was completed at the AAQRF.

Either whole or ground carcasses were mixed with the amendment. The carcasses were the remains of 24 hogs, which were approximately 4.5 months of age and ranging in weight from 70 to 100 kg from the MSU Swine Farm. Animals for whole carcasses (n = 12) were euthanized with an injection of 86.24 mg/kg Na-pentobarbital IV. Animals for ground carcasses (n = 12) were transported to a local butcher plant where they were electrically-stunned and euthanized by exsanguination. The blood was not collected and retained for composting. Viscera were removed, sealed in black plastic 3 mm bags (55.9 ×50.8 ×121.9 cm) for transport back to the AAQRF; they were not ground. Carcasses were sawn into 4 portions (quartered) and then were ground using a 20 hp Rietz Prebreaker/Grinder (Model No. PB-10-H3228 and Serial No. P-740353; Rietz Manufacturing, Santa Rosa, CA 95402). It was operated without a die or plate. Large bones were reduced to “sheared fragments or slivers” of approximately 10 cm in maximum length. Ground carcasses were then placed into 208 L barrels and sealed appropriately for transporting to the AAQRF.

Based on known weights of the whole carcasses and the measured weights of ground carcass and viscera, similar amounts of animal tissue (292 ± 7.3 kg per batch) were added to IVG, IVW, OSPG, and OSPW compost batches. When initiating batch formation, all animal tissues were placed on a layer of amendment approximately 30 cm thick to absorb any effluent leaving the carcasses. A total of 520 kg amendment was included in each batch of mortality compost so that a “mortality-to-amendment ratio (volume coefficient) of 160 kg/m^3 was achieved. Total mass per batch was 812 ± 7.3 kg. The mass of carcasses and compost amendment were predetermined so that IV’s and OPS’s initially contained approximately 2.2 and 3.8 m^3 total compost (amendment and mortality combined), respectively. The resulting bulk density estimates were 424 kg/m^3 and 256 kg/m^3 for IV and OSP, respectively. The difference in BD is believed to be a result of significant packing of amendment and tissue into the IV units but no packing of the same into OSP batches. The OSP batches settled noticeably, from about 90 cm in height to about 75 cm by the end of one week of composting. In addition to bulk density, the desired conditions for initial moisture content and carbon-to-nitrogen ratio (On-Farm Composting Handbook, 1992).

Compost Systems. Four IV rotating drum composters (Model 408; BW Organics, Inc., Sulphur Springs, Texas), one per room, were used. Each IV unit consisted of an insulated steel (0.635 mm thick) drum (2.44 m long, 1.22 m in diameter, 2.29 m^3 capacity), a #100 chain power drive unit with duel sprockets, two steel channel frames plus one power driven channel frame, three slide gate unloading doors, mounted on four steel rotor casters or plastic glides. Materials were loaded through the 45.7 cm circular-shaped opening on one end of the drum and removed through 3 rectangular doors, cut into the curvature of the opposite end of the drum.

Open static piles were formed as parabolic windrows 1.524 × 3.048 m, which sat in plastic coated pans of the same dimensions. Pans had 20 cm sides and were sealed so that no effluent would be lost. They sat on steel casters for portability and had four hooks on the sides for weighing of the pan with/without material.

Compost Phases. Emissions were measured continuously during two phases of active composting: a 20-d primary phase (d 1 to 20) and a 15-d secondary phase (d 65 to 80 d after initial formations of batches). In the secondary phase the OSP system was used for all batches. The IV composters were used in the primary phase only as is commonly done on-farm or in commercial composting. The primary phase was October 28, 2009 through November 16, 2009. Compost was then removed from the AAQRF rooms and randomly allotted to and placed in open-fronted, concrete-sided bins at another location for 44 days. After composting at that location, the compost was brought back into the AAQRF rooms (randomly allotted to room) and emissions were measured for another 15 days. This, the second or secondary phase was from December 31, 2009 through January 14, 2010. The emissions-measuring portion of the experiment was concluded after the secondary phase.

Measurements. Composting was conducted in individual, sealed rooms designed to continuously monitor incoming and exhaust concentrations of gases. Measurements of gaseous concentrations in air were made following procedures described previously by Powers et al. (2007) and more recently by Li et al. (2011).

The 24-hr maximum temperature was measured in both the IV and OSP compost systems using a Fisher Scientific minimum/maximum digital thermometer. A single compost temperature probe was placed in the OSP piles at a location approximately two-thirds of the height of the compost pile. A single temperature compost probe was mounted to the outer wall at mid-length of the IV. Moisture content and pH were measured weekly in samples collected from the IV systems, and then in both IV and OSP compost when removed from the AAQRF rooms (AOAC, 2000). Moisture content, pH and electrical conductivity were measured in all composts at the beginning and end of the secondary phase. Compost stability or maturity was assessed using CO_2 and O_2 measures. The mass of each compost treatment was measured at the end of the primary phase, and then again at the beginning and end of the secondary phase.

Compost Management. Moisture content was increased by water addition to maintain a concentration of 40 to 60% H_2O. Open static piles were left undisturbed for the entire phase. In-vessel drums rotated continuously for the first 3 days, but when temperatures failed to increase a decision was made to turn off the IV motors for 8 hr each day. The 8-off/16-on regimen was followed for d 3-13 of the primary phase. Generally, rotating drum IV systems are operated intermittently based on the achievement of desired temperatures of 54 to 65ºC.

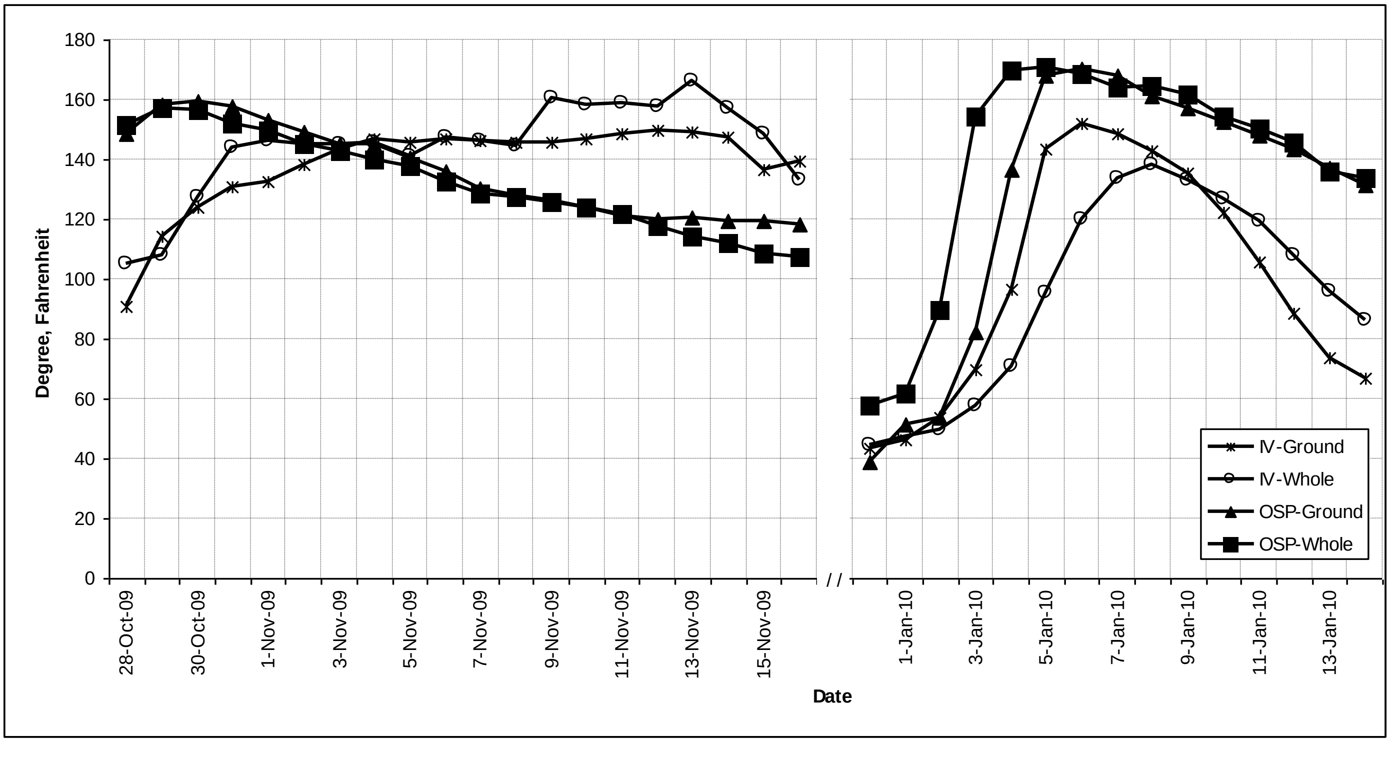
Global Warming Potential (GWP) Calculation. Carbon dioxide equivalents (CO_2e) were estimated as the sum of the 100-yr GWP for CO_2, CH_4, and N_2O. The CO_2e's from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Forster et al., 2007) were used and are 1, 25, and 310, times the potential of CO_2e for CO_2, CH_4, and N_2O, respectively;.

Statistical Analyses. Average daily mass of gas emission and oxygen consumption of treatments were determined and compared using analysis of variance (MIXED) procedures of SAS (SAS Inst., Inc., Cary, NC).

Results and Discussion

Compost Temperatures. The temperatures achieved in both phases are indicative of microbial activity. Figure 1 shows the temperatures in the primary phase. Open static pile temperature rose more quickly as did those with whole carcasses. In the first days of the primary phase, IV systems were releasing heat faster than they could accumulate heat because of the rotation. On October 30, an '8-hr off/16-hr on' regimen was followed for the IV units. Temperatures increased within 24 hr. This continued until November 10. We met the safety criteria of the Canadian Council of Ministers of the Environment (CCME, 2005) in observing temperatures of 54ºC or greater for at least 15 d during OSP composting and at least 3 d for IV composting.

Figure 1. Daily maximum temperature during the primary and secondary phases of composting.



In the secondary phase, a slow increase in temperatures was observed (Figure 1). The IVW batches attained a temperature of greater than 54ºC on only 3 d. An average temperature of OSP material was greater than IV compost material. Material had been brought into heated rooms from outside bins at the Boar Test Station. Between the primary phase and the secondary phase compost was placed in individual bins in a covered, open fronted building. Bins were exposed to outdoor ambient temperatures in Michigan in December, which ranged from -13 to 13°C from November 17 to December 30 (mean daily average temperature was 0°C). During this time compost temperatures ranged from 6.4 to 80°C.

Consumption of O_2 and Evolution of CO_2. Oxygen consumption did not differ among treatments, however CO_2 emissions differed ($P < 0.05$) among treatments (Table 2). Carbon dioxide emission was greater ($P < 0.05$) in the primary phase than in the secondary phase. Mass of CO_2 per day tended to be greater with use of the IV system of composting ($P = 0.07$), providing the strongest indication that the tenet is true, that the IV system, with its mixing and aeration, does result in greater microbial activity. Mass of CO_2 emitted daily did not differ because of carcass form.

Compost Maturity. In this study we used respiration in the last week of the secondary phase and the change in compost temperature after the secondary phase to describe compost maturity (a.k.a. stability, completeness, doneness, finishing). Respiration is O_2 consumption (a.k.a. intake, demand) and CO_2 evolution (a.k.a. emission, production). An increase in temperature in recently aerated and moistened compost reflects microbial activity and nutrient availability in, and maturity of, that compost.

The standards for compost maturity most often referred to are those of the California Compost Quality Council (CCQC, 2001) and those of the CCME (2005). In order to be considered mature or stable, compost material must meet one or more requirements of ≤ 12 or 9.6 mg O_2 per g of organic matter per day, ≤ 2 or 4 mg C (as CO_2) per g of organic matter per day, and a temperature rise of the compost above ambient temperature of ≤ 46 or 50 ºF, for CCQC (2001) and CCME (2005), respectively. When ‘active’ composting ends and ‘curing’ starts is not an exact science, and in the present study we planned to monitor two phases of what we believed would be ‘active composting’, not knowing when the compost would or could have been characterized as in the ‘curing’ phase.

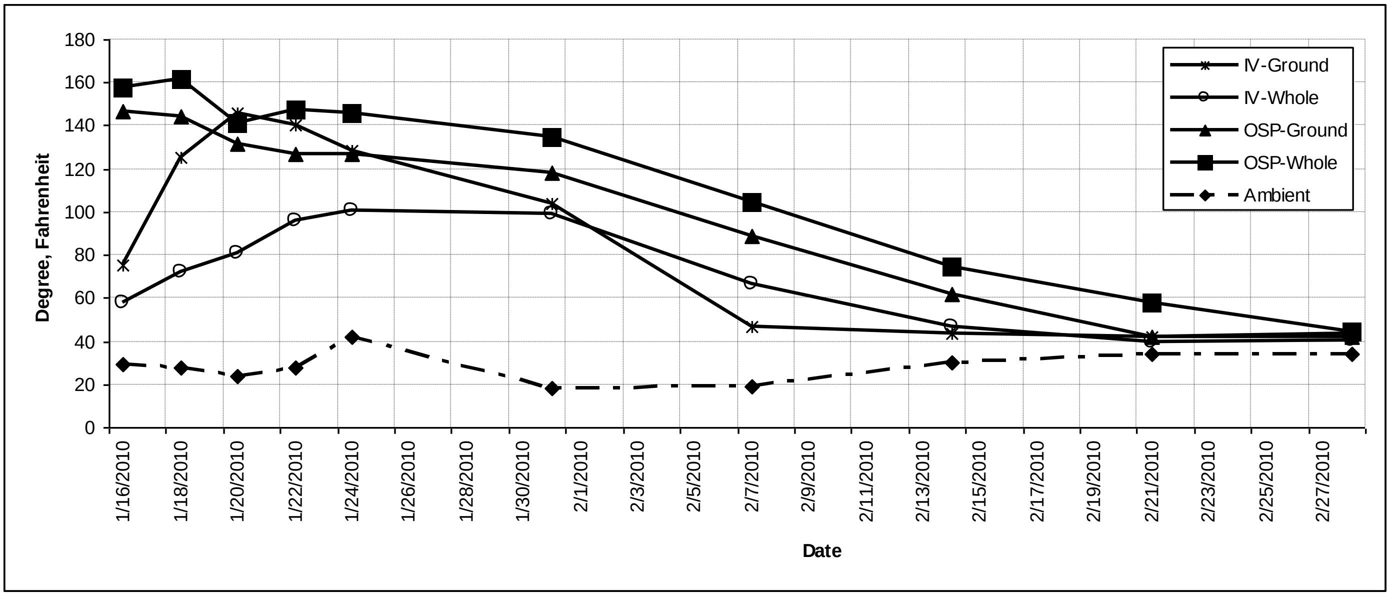
We chose to use the O_2 consumption and CO_2 evolution measures taken in the last week of the secondary phase to assess if active composting had ended and curing had started. Oxygen consumption was 3.47, 2.51, 9.25, and 5.95 mg O_2 per g of organic matter per day and carbon dioxide evolution was 1.49, 1.90, 2.52, and 1.95 mg CO_2 per g of organic matter per day for IVG, IVW, OSPG, and OSPW, respectively. Oxygen consumption of the two IV treatments was less ($P < 0.001$) than OSP treatments. Oxygen consumption in the last 7 d of the secondary phase was less ($P = 0.05$) when carcasses were left whole as compared to when ground prior to composting. Carbon dioxide evolution in the last week of the secondary phase did not vary by treatment, composting system, or carcass form.

Consumption of O_2 and evolution of CO_2 at the end of the secondary phase, of all treatments, indicates that the compost was very mature by both CCQC (2005) and CCME (2005) suggested standards. It is noteworthy to recognize that the O_2 uptake limit of the CCME in 1996 (previous version of guidelines for compost quality), was ≤ 3.6 mg O_2 per g of organic matter per day. If the earlier standard was considered in assessing the maturity of the compost in the present study, then the IVG and two OSP treatments would be considered moderately mature. The reason for the increase in O_2 per g of organic matter per day is not stated in the 2005 CCME document.

Using these methods and the current guidelines of California and Canada, a conclusion about the maturity of the compost could not be made. There are numerous methods to estimate compost maturity and whether those we employed, or others, are most accurate is debatable (Briton, 2010). We chose to measure respiration after our planned secondary phase, but conspicuously our compost in both the primary and secondary phases would have been considered very mature by O_2 consumption standards. It leads us to question the legitimacy of our respiration methodology as compared to the bench-top lab methodology followed by both CCQC (2001) and CCME (2005). We may have observed too much variation in our O_2 consumption measures to draw conclusions about the biology of composting. Two replications per treatment may not have been statistically powerful enough to get full agreement among CO_2 evolution, O_2 consumption, and temperature rise. Furthermore, the CCQC (2001) and CCME (2005) respirometry tests are typically conducted with a subsample, in a laboratory, at a constant moisture and temperature, immediately following mixing or aeration. The respiration assessment we completed was at the end of a 15-day period in which the material was left undisturbed. We measured O_2 consumption and CO_2 evolution on entire open static piles and this test technique has not been validated and reported previously. Comparisons of our approach to the same tests done in a laboratory setting were not made.

Temperature of compost indicated typical compost activity in the primary and secondary phases (Figure 1). As noted above, average temperatures of OSP material was greater than IV compost material, possibly indicating that the material was less mature going into the secondary phase. Again, we chose to assess maturity at the end of the secondary phase. Temperature change may be used as an indicator of maturity (CCME, 2005). A temperature increase of the compost above ambient temperature of 46 degree units (Fahrenheit) suggests that the compost is not mature. After the secondary phase was concluded and the batches were moved from the AAQRF to bins, the increase in temperature of all batches was greater than 46 Fahrenheit degree units above ambient temperatures, suggesting that all compost material was not mature or stable (Figure 2). The temperature techniques followed in the present study have not been validated previously, and the "rise tests" of CCME (2005) are typically conducted in a more controlled or standardized laboratory setting than the procedure employed in the present study.

Figure 2. Temperature of compost in relation to ambient temperature after the movement of compost batches from AAQRF to Boar Test Station bins, after the secondary phase.



Although the respiratory O_2 and CO_2 measurements we recorded suggested that the compost was mature and ready for application to the fields as a nutrient source, we did not measure the phytotoxic potential of the compost after composting and this is the maturity indicator of significant interest to plant growers who include compost in container mixes. Further research is needed to assess whether this material if used as potting medium would hinder germination or plant growth. Although not researched, we think that the 80-d old compost would not be a detriment to field-crop growth if applied to cropland similar to agronomic application of raw manure. A major concern about 80-d old compost would be presence of intact bones. Bones take much longer to decompose and to be brittle enough to shatter when spread. We did not measure bone breaking strength in the present study, but we do not think that the bones of these 5-mo old hogs would be brittle enough to shatter into acceptably small pieces when encountering the beaters, chains, or paddles of a manure spreader.

Total Gas Emission: CH_4, NMTHC, NH_3, NO, NO_2, N_2O, H_2S, and SO_2. The amount emitted daily for *CH_4, NMTHC, NH_3, NO, N_2O, and SO_2* differed ($P < 0.05$) among treatments (Table 2). The IV system emitted more ($P < 0.05$) NMTHC, NH_3, and SO_2, and less ($P < 0.05$) CH_4, NO, N_2O than the OSP system. When SO_2 is oxidized in the presence of a catalyst such as NO_2, H_2SO_4 is formed leading to acid rain. Composting system did not affect the daily mass of NO_2 and H_2S emitted.

Carcass form did not affect the emission of any gas. Based on the findings of this study, grinding of the carcasses does not appear to be necessary. Grinding is a challenge to manage, and one would consider the energy cost of grinding, handling large carcasses and the freezing of equipment in winter. We did not grind and mix carcasses with amendment simultaneously as is common when vertical grinder/mixers currently sold to composting firms, are used. A homogenous mixture of tissue and carbon source is achieved.

The primary and secondary phases of this study involved the same compost material, with different systems (IV and OSP) used in the first phase and the same OSP approach used in the second phase. Emissions were greater ($P < 0.05$) for CH_4, NMTHC, NH_3, NO, and SO_2 gases in the primary phase as compared to the secondary phase, but not for N_2O, which was greater ($P < 0.05$) in the secondary phase than it was in the primary phase.

In the primary phase, the IV system generated about 95% less ($P < 0.05$) CH_4 than did the OSP system (0.31 vs. 6.7 g/d, respectively). Other environmentally-interesting differences ($P < 0.05$) between the IV and OSP systems in the primary phase were NMTHC (4.13 vs. 0.19 g/d), NH_3 (86.96 vs. 5.04 g/d), and N_2O (-1.00 vs. 1.94 g/d) emissions for IV and OSP systems, respectively.

The amount of CH_4, NMTHC, NO, and SO_2 gases emitted in the second phase did not differ among treatments. Nitrous oxide emissions were greater ($P < 0.05$) with the use of the OSP system than with the IV composting system in the secondary phase. Why is not known for sure, but possibly related to differences in compost maturity noted above; with IV compost being more mature in the second phase.

The treatment × phase interaction was significant for CH_4, NMTHC, NH_3, NO, and N_2O, but not for SO_2. For NMTHC and NO the interaction reflected that there were treatment differences in the primary phase, but none in secondary phase. Methane emission of IVW, OPSG, and OSPW treatments decreased from the primary to secondary phase, but a similar decrease was not observed with the IVG treatment. Very little methane was emitted by IVG in both phases. The amount of NH_3 emitted was greater for IV treatments than OSP treatments in the primary phase, but in the secondary phase only IVW and OSPG treatments differed ($P < 0.05$) from one another. Nitrous oxide emissions decreased ($P < 0.05$) overtime (primary phase vs. secondary phase) for IV treatments, but not for OSP treatments.

Greenhouse Gas: For a modern swine farm with 2000 head finishing capacity and a 2% mortality rate, we estimate that mortality composting on the farm for a 20-d primary phase would emit 1273 and 850 kg (1.40 and 0.94 tons) of CO_2e annually depending on which method of composting was used (IV or OSP, respectively). Carbon dioxide emission accounted for 99.9 and 80.3% % of the CO_2e from IV and OSP systems in the 20-d primary phase.

In our study, the amount of CO_2e emitted was 10 to 20-fold less in the secondary phase as compared to primary phase of composting. Our measurements indicate that from days 65 to 80 of composting, only 0.07 and 0.08 tons of CO_2e would be emitted for IV and OSP, respectively. The dramatic decrease is believed to be a reflection of the greater anaerobic and aerobic microbial activity in the primary phase. Carbon dioxide emissions accounted for 99.8 and 35.9% of the CO_2e from IV and OSP systems in the 15-d secondary phase. Substantially more CO_2e was derived from N_2O emitted from OSP material in later composting.

Table 2. Oxygen consumption (g per d) and daily gas emissions (g per d) and of compost containing 5-month old dead swine in primary and secondary phases of composting.[a]

	Treatment[b]				P - value[c]			
Gas	IVG	IVW	OSPG	OSPW	Trt	Phase	Syst	Carc
O_2	-5595.195 [-9794.300, -2809.428] -1401.882 [-2513.071, -678.734]	-6496.181 [-8427.517, -4885.135] -1006.675 [-1667.927, -548.368]	-3688.455 [-5602.574, -2269.058] -2017.715 [-3089.808, -1227.655]	-2772.143 [-3782.561, -1959.883] -2214.181 [-3398.205, -1343.088]	0.56	< 0.001	0.38	0.65
CO_2	4760.963$^{d, x}$ [678.039, 15364.523] 330.197^{y} [41.544, 1111.999]	5595.857$^{e, x}$ [3509.660, 8378.291] 316.155^{y} [89.585, 766.111]	3376.755$^{f, x}$ [889.583, 8474.192] 174.893^{y} [33.940, 501.891]	2186.219$^{f, x}$ [1298.739, 3406.825] 98.164^{y} [8.751, 367.877]	0.01	< 0.001	0.07	0.70
CH_4	0.090^{d} [0.000, 0.574] 0.007 [-0.001, 0.100]	0.481$^{d, x}$ [0.160, 1.075] 2.989E-04^{y} [-0.009, 0.040]	6.924$^{e, x}$ [4.676, 9.798] -1.261E-04^{y} [-0.034, 0.011]	6.641$^{e, x}$ [4.410, 9.521] 0.010^{y} [-4.312E-04, 0.125]	< 0.001	< 0.001	< 0.001	0.16
NMTHC	4.183$^{d, x}$ [1.952, 7.676] -7.116E-05^{y} [-0.032, 0.013]	4.645$^{d, x}$ [2.943, 6.901] -3.434E-04^{y} [-0.035, 0.007]	0.194$^{e, x}$ [0.037, 0.562] 0.001^{y} [-0.005, 0.040]	0.218$^{e, x}$ [0.054, 0.565] -2.848E-05^{y} [-0.026, 0.013]	< 0.001	< 0.001	< 0.001	0.82
NH_3	73.397$^{d, x}$ [30.850, 143.664] 4.704$^{de, y}$ [1.312, 11.490]	78.326$^{d, x}$ [55.905, 106.059] 2.102$^{e, y}$ [0.574, 5.187]	6.951^{e} [1.769, 17.729] 7.742^{d} [3.554, 14.358]	5.582^{e} [2.620, 10.207] 3.931^{de} [1.334, 8.688]	< 0.001	< 0.001	< 0.001	0.28
NO	2.441E-02^{d} [-0.003, 0.382] 0.001 [-0.006, 0.053]	0.020^{d} [9.990E-05, 0.120] 0.049 [0.003, 0.210]	3.251$^{e, x}$ [1.706, 5.525] 0.014^{y} [1.829E-06, 0.105]	2.614$^{e, x}$ [1.632, 3.929] 0.020^{y} [2.851E-05, 0.134]	< 0.001	< 0.001	< 0.001	0.60
NO_2	0.236 [0.038, 0.728] 0.071 [0.007, 0.262]	0.665 [0.312, 1.218] 0.072 [0.008, 0.252]	0.976 [0.506, 1.672] 0.017 [7.671E-05, 0.108]	0.520 [0.233, 0.977] 0.011 [-7.301E-09, 0.088]	0.22	< 0.001	0.83	0.88
N_2O	-0.606$^{d, x}$ [-2.813, -0.022] -0.002$^{d, y}$ [-0.089, 0.009]	-1.166$^{d, x}$ [-2.250, -0.502] 0.004$^{d, y}$ [-0.001, 0.069]	1.649^{e} [0.555, 3.658] 0.533^{e} [0.174, 1.201]	1.799^{e} [0.986, 2.969] 1.099^{e} [0.443, 2.206]	< 0.001	0.01	< 0.001	0.45
H_2S	0.262 [0.039, 0.834] 8.108E-06 [-0.003, 0.006]	0.718 [0.452, 1.072] 1.654E-05 [-0.001, 0.003]	0.340 [0.133, 0.696] 0.001 [-7.223E-06, 0.011]	0.221 [0.124, 0.359] 1.042E-04 [-0.001, 0.006]	0.15	< 0.001	0.58	0.63
SO_2	0.189$^{de, x}$ [0.035, 0.549] -0.001^{y} [-0.011, 8.848E-05]	0.134^{d} [0.067, 0.235] -0.001 [-0.007, 8.024E-06]	0.144^{d} [0.046, 0.330] -0.003 [-0.017, -7.917E-05]	0.040$^{e, x}$ [0.016, 0.083] -0.006^{y} [-0.026, -3.681E-04]	< 0.001	< 0.001	0.03	0.12

[a] Least squares mean and [95% confidence interval] for the primary and secondary phases (described in footnote [c] below) are presented in each cell (lines 1 through 4, respectively). Emissions were measured continuously during two phases of composting: 1) a 20-d primary phase (d 1 to 20), and 2) a 15-d secondary phase (d 65 to 80 after initial formations of batches). Eight measurements were taken daily in each of room resulting in 16 observations recorded each day for each treatment, except for the IVG treatment in the primary phase, for which data from only one room was analyzed. In-vessel composting was conducted in the primary phase only, but compost identity was preserved and considered a treatment effect when compost was placed back into a room for measurements in the second phase.

[b] IVG = in-vessel system and ground carcasses, IVW = in-vessel system and whole carcasses, OSPG = open static pile and ground carcasses, and OSPW = open static pile and whole carcasses.

[c] Trt = overall treatment *P* - value; Phase = *P* - value for comparison of primary and secondary phases of composting: 1) a 20-d primary phase (d 1 to 20), and 2) a 15-d secondary phase (d 65 to 80 after initial formations of batches); Syst = *P* - value for comparison of IV and OSP systems; Carc = *P* - value for comparison of form of carcass (ground and whole).

[d, e, f] Treatment means with different superscripts in the same row (within phase) differ $P < 0.05$.

[x, y] Means having different superscript letters within cell (within treatment and comparing phases) differ $P < 0.05$.

If we assumed that emissions we observed in the secondary phase of composting would be emitted for all the other days of a complete composting process that would last a total of 6 months (i.e. 20 d in primary emission amounts and 160 d of secondary emission amounts as measured in the present study) then the total CO_2e annually from mortality composting would be 1908 and 1596 kg (2.10 and 1.76 tons) for IV and OSP systems, respectively. As a portion of the total CO_2e emitted annually from such a farm, that from composting (either method) would be much less than the emissions from animal production, manure storage, and manure application to fields (29,836, 105,864, and 26,300 kg [32.9, 116.7, and 29 ton], respectively; Maycher, 2003).

This estimate may be inaccurate as the time between our primary phase and secondary phase, the time during turning of OSP compost material, and the time after our secondary phase were not measured. In our assessment of CO2e, we used an assumption that the emissions we measured during d 65 to 80 were the same as those which would be emitted from d 20 to 65 and from d 80 to 180 of a 6-mo complete composting process. It is possible that our assumption underestimates the emissions during d 20 to 45 and overestimates the emissions from d 80 to 180. Further research is needed to evaluate the emission patterns during these times in the complete composting process.

Implications

Total emissions of GHGs emitted during the first weeks of very active composting are greater with the IV composting system, than those emitted from an OSP system. Greenhouse gas emission and air quality improvement is not a justification for the added expense and energy used to grind carcasses pre-composting. We measured air emissions during two short periods, early in the composting process. We did not measure emission during the entire composting process or to a known point of maturity. What this point is and when it is reached with an IV or OSP system may differ. We do not know if the speed of the IV composting process in the primary phase results in less curing time and less total emissions if maturity of the compost is kept equal. If the OSP system takes longer to reach maturity, with rate of decomposition being slower because of less acceptable aerobic conditions, then if the total amount of emissions N_2O and CH_4 could be greater and then we may consider using an IV system. We did not measure emission during the turning (mixing, moving) of the OSP compost material. It is during this activity that the OSP is first disturbed and anecdotally, a great deal of NH3 is emitted. After conducting our study, we still do not know how much the mathematical modeling done here underestimates or overestimates the GHG emission from the entire composting process. Future research will is needed to compare total emission during the entire process from start to end (cured or mature), with the end being a point of stability as defined as little or no microbial respiration, and complete decomposition of phytotoxic substances. This process may take months for mature market hogs.

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References

Briton, W. 2010. Characterizing compost completeness. Biocycle 51:31-35.

California Compost Quality Council. 2001. Compost Maturity Index. Sited on August 31, 2010. www.ciwmb.ca.gov/Organics/Products/Quality/CompMaturity.pdf.

Canadian Council of Ministers of the Environment (CCME). 1996. Guidelines for compost quality, PN 1199. Sited on August 31, 2010. http://www.ccme.ca/assets/pdf/pn_1199_e.pdf

Canadian Council of Ministers of the Environment (CCME). 2005. Guidelines for compost quality, PN 1340. Sited on August 31, 2010. http://www.ccme.ca/assets/pdf/compostgdlns_1340_e.pdf

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf Accessed 6.6.11.

Li, W., W. Powers, and G. M. Hill. 2011. Feeding distillers dried grains with solubles and organic trace mineral sources to swine and the resulting effect on gaseous emissions. J. Anim. Sci. 89:3286-3299.

Maycher, N. 2003 Greenhouse Gas Emissions and Opportunities for Reduction from the Alberta Swine Industry. Climate Change Central. Discussion Paper C3-012.

On-Farm Composting Handbook. (NRAES-54). 1992. Robert Rynk, ed. Northeast Regional Agricultural Engineering Service, Ithaca, N.Y.

Powers, W.J., S. Zamzow, and B.J. Kerr. 2007. Reduced crude protein effects on aerial emissions from swine. Appl. Eng. Agric. 23:539–546.

Thomson, M.A. and B.J. Van Heyst. 2008. Ammonia emissions from the composting of on-farm mortalities as a function of pH. Paper No: 084244 presented at the 2008 ASABE Annual International Meeting. Rhode Island Convention Center, Providence, Rhode Island. June 29 – July 2, 2008

Xu, S., X. Hao, K. Stanford, T.A. McAllister, F.J. Larney, and J. Wang. 2007a. Greenhouse gas emissions during co-composting of cattle mortalities with manure. Nutr. Cycling Agroecosyst. 77:177–187.

Xu, S., X. Hao, K. Stanford, T.A. McAllister, F.J. Larney, and J. Wang. 2007b. Greenhouse gas emissions during co-composting of calf mortalities with manure. J. Environ. Qual. 36:1914-1919.