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Performance of a plastic-wrapped composting system for biosecure emergency disposal of disease-related swine mortalities

Abstract

A passively-ventilated plastic-wrapped composting system initially developed for biosecure disposal of poultry mortalities caused by avian influenza was adapted and tested to assess its potential as an emergency disposal option for disease-related swine mortalities. Fresh air was supplied through perforated plastic tubing routed through the base of the compost pile. The combined air inlet and top vent area is ⩽ ~1% of the gas exchange surface of a conventional uncovered windrow. Parameters evaluated included: (1) spatial and temporal variations in matrix moisture content (m.c.), leachate production, and matrix O2 concentrations; (2) extent of soft tissue decomposition; and (3) internal temperature and the success rate in achieving USEPA time/temperature (T) criteria for pathogen reduction. Six envelope materials (wood shavings, corn silage, ground cornstalks, ground oat straw, ground soybean straw, or ground alfalfa hay) and two initial m.c.'s (15–30% w.b. for materials stored indoors, and 45–65% w.b. to simulate materials exposed to precipitation) were tested to determine their effect on performance parameters (1–3). Results of triple-replicated field trials showed that the composting system did not accumulate moisture despite the 150 kg carcass water load (65% of 225 kg total carcass mass) released during decomposition. Mean compost m.c. in the carcass layer declined by ~7 percentage points during 8-week trials, and a leachate accumulation was rare. Matrix O2 concentrations for all materials other than silage were ⩾ 10% using the equivalent of 2 m inlet/vent spacing. In silage O2 dropped below 5% in some cases even when 0.5 m inlet/vent spacing was used. Eight week soft tissue decomposition ranged from 87% in cornstalks to 72% in silage. Success rates for achievement of USEPA Class B time/temperature criteria ranged from 91% for silage to 33–57% for other materials. Companion laboratory biodegradation studies suggest that Class B success rates can be improved by slightly increasing envelope material m.c. Moistening initially dry (15% m.c.) envelope materials to 35% m.c. nearly doubled their heat production potential, boosting it to levels ⩾ silage. The 'contradictory' silage test results showing high temperatures paired with slow soft tissue degradation are likely due to this material's high density, low gas permeability and low water vapor loss. While slow decomposition typically suggests low microbial activity and heat production, it does not rule out high internal temperatures if the heat produced is conserved. Occasional short-term odor releases during the first 2 weeks of composting were associated with top-to-bottom gas flow which is contrary to the typical bottom-to-top flow typically observed in conventional compost piles. In cases where biosecurity concerns are paramount, results of this study show the plastic-wrapped passively-ventilated composting method to have good potential for above-ground swine mortality disposal.

Keywords

Livestock, Mortality, Disposal, Composting, Emergency, Biosecurity

Disciplines

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Performance of a Plastic-Wrapped Composting System for Biosecure Emergency Disposal of Disease-Related Swine Mortalities

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Abstract. A passively-ventilated plastic-wrapped composting method developed for biosecure emergency disposal of poultry mortalities caused by avian influenza was tested to assess its potential as an emergency disposal option for disease-related swine mortalities. Despite a 150 kg carcass water load, mean compost moisture content (m.c.) in the carcass layer declined by 7 percentage points. Leachate accumulation was rare, and O2 concentrations were ≥10% in all envelope materials except silage. Envelope material type and initial m.c. were significant performance factors. Success rates for USEPA Class B pathogen suppression criteria in the carcass layer ranged from 91% for silage to 33-57% for other envelope materials. Laboratory 10-d total oxygen uptake data showed, however, that moistening dry envelope materials to 35% m.c. doubles their heat production potential resulting in significantly higher heat production potential than that of silage.

Keywords livestock, mortality, disposal, composting, emergency, biosecurity

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1. Introduction

In 2004 the Canadian Food Inspection Agency (CFIA) used a novel composting procedure to biologically decompose and heat treat poultry mortalities (Spencer et al., 2004) following an outbreak of highly pathogenic (H7N3) avian influenza (AI) in poultry flocks in British Columbia. In a significant departure from composting practices typically used for on-farm disposal of routine (non-disease-related) poultry mortalities, the CFIA wrapped the emergency composting piles in plastic sheeting to reduce the risk of AI virus being carried into the surrounding environment by bird and insect activity, wind, and precipitation. The plastic-wrapped composting matrix was passively aerated through 10-cm diameter slotted plastic drainage tubing passing through the base of the pile (perpendicular to the long axis) at 1.2-m spacing intervals, and penetrating the plastic biosecurity barrier on each side. Water vapor and gases produced by the composting process were vented through perforations in the plastic located along the ridge of the piles at 1.2-m spacing intervals. The CFIA plastic-wrapped emergency composting design has a total inlet/vent area for gas exchange that is about 0.25% of that provided by the surface area of with a similarly sized conventional (unwrapped) composting windrow.

Successful implementation of the plastic-wrapped composting system for emergency disposal of chicken mortalities led CFIA to sponsor research to evaluate its feasibility as a biosecure emergency disposal option for swine or cattle. Because of its very limited ventilation area, the primary focus of the research was evaluation of the system’s ability to sustain an adequate oxygen supply and remove large quantities of water and decomposition gases throughout long decomposition periods associated with large animal species. Chicken mortalities weighing 3-4 kg can be composted in 2 to 4 weeks, but market weight (110 kg) swine can take as long as 6 months (Alberta Agriculture and Rural Development, 2011), and decomposition of mature (450 kg) cattle carcasses in unturned piles can take 4 to 6 months during warm weather and 8 to 10 months during cold weather (Glanville et al., 2013).

The duration of the mortality composting process is of concern due to associated changes in physical characteristics of the organic envelope material that provides the environment for microbial activity and animal tissue decay. Loss of mechanical strength is of particular concern and excess moisture caused by inadequate venting of carcass water is a primary cause. Weakened envelope material surrounding the carcasses causes compaction, reduced matrix porosity and gas permeability, and inadequate transport of O_2 throughout the compost pile. This fosters development of anaerobic zones, slow animal tissue decomposition, and increased production of odorous volatile organic compounds. Reduced matrix permeability also hinders water vapor transport, an important function because animal tissue - which is approximately 65% water by weight - releases considerable water during decomposition. Failure to vent excess water vapor from the pile can cause saturation and further weakening of the matrix. Ahn et al. (2008a, 2008b) reported that at 80% of their water-holding capacity, the mechanical strength and gas permeability of ground cornstalks were only 22% and 46%, respectively, of the strength and permeability of cornstalks at 20% of their water-holding capacity.

While compaction and impeded gas/vapor transport occurs to some extent in all composting operations, the primary question driving the CFIA research was whether addition of the plastic biosecurity barrier would significantly exacerbate these problems during the lengthy composting periods associated with large animals. In addition to possible internal O_2 and moisture transport problems associated with envelope material compaction, there were questions regarding the long-term functionality of the passive aeration/ventilation system. The CFIA plastic-wrapped composting design provides a combined inlet/vent area available for gas exchange with the ambient environment that is only about 0.25% of that available with a similarly sized conventional (unwrapped) composting windrow. If long-term internal gas transport declines, it seemed likely that the number and/or size of aeration tubes and vents may need to be increased.

To answer the questions described above, the CFIA sponsored field and laboratory studies at Iowa State University to evaluate the performance of the CFIA emergency poultry mortality composting system when applied to swine and, if needed, to propose appropriate adaptations to the system design. Project objectives included documentation of:

1. Spatial and temporal variations in matrix moisture content (m.c.), leachate production, and matrix O_2 concentrations;
2. Time required for decomposition of swine carcasses;
3. Achievement of USEPA time/temperature (T) criteria for pathogen reduction; and
4. The effect of envelope material type and initial m.c. on items 1-3.

In addition to the above, the types and timing of volatile organic compounds (VOCs) produced during mortality composting were studied. The objective of this work was to determine if carcass decomposition can be reliably tracked by monitoring VOCs, thereby avoiding biosecurity risks associated with removing the plastic biosecurity wrap and excavating the mortality compost pile. Results of the VOC study are reported in papers by Akdeniz et al. (2010a, 2010b, 2011).

2. Materials & Methods

2.1 Treatment Variables

Since livestock disease emergencies can occur at any time of year, it is important to understand how the performance of an emergency mortality composting method is affected by seasonal T; wind, and precipitation. To investigate this, replicated (N=3) field trials were carried out during cool- and warm-season trials lasting 8 weeks. Warm-season trials (#2 and 3) were begun in June and August; cool-season trials (#1 and 4) in November and April. Average daily T during the first 30 d of warm season trails were 22.4 °C and 20.5 °C; and 4.4 °C and 13.7 °C during cool seasons.

Results of previous research (Glanville et al., 2013) indicated that the envelope material surrounding the animal carcasses significantly affected the performance of conventional (unwrapped) composting windrows. To test the effects of envelope material type on the performance of plastic-wrapped composting systems, 6 materials (wood shavings; corn silage; ground cornstalks; ground oat straw; ground soybean straw; and ground alfalfa hay) were included in the study. These were selected in consultation with the project sponsor and chosen because they are commonly used in poultry and livestock operations and are generally available in large quantities in the event of a disease emergency. Three materials were tested during each warm and cold season trial, and each was triple-replicated (9 test units per seasonal trial).

Initial m.c. of envelope materials varies depending on whether they are exposed to precipitation or stored in protected piles. To evaluate performance impacts associated with differing initial m.c., trial #1 and #3 were conducted with envelope materials that had been stored indoors (initial m.c. 15 to 30% w.b.). Prior to trial #'s 2 and 4, the envelope materials were moistened (45 to 65% w.b.) to simulate materials that have been exposed to seasonal precipitation. The exception was corn silage which is an inherently moist material and was tested only in its as-received (moist) condition.

Testing all combinations of envelope material type and initial m.c. during single warm and cold seasons would have been preferable as this would have exposed all experimental treatments to identical ambient T conditions. This was impractical, however, due to the large quantities of swine carcasses, envelope material, experimental space, instrumentation, and personnel necessary for simultaneous replicated testing of all treatments.

2.2 Test Bins

Field composting trials were conducted in 2 m × 2 m × 1.2 m (high) wooden test bins (Fig. 1A & B). Floors and sidewalls were insulated with 5 cm thick Styrofoam insulation to aid heat retention and simulate operating T likely to occur in larger piles. Bins were lined with rubber membrane to facilitate capture and quantification of leachate, and the tops and sidewalls were wrapped in sheet plastic to simulate the CFIA biosecure emergency composting procedure. Three lengths of 10 cm diameter plastic drainage tubing were embedded in envelope material placed in the bottom of each bin. These were extended vertically, through the sheet plastic and over the sidewalls, to carry ambient air to the base of the compost matrix (Fig. 1B & C). A 2 m length of tubing also was laid on top of the matrix. This passed through the plastic biosecurity barrier at two locations to provide a vent for warm gases and water vapor released by the composting process. A similar but larger plastic-wrapped composting system designed for emergency disposal of cattle mortalities was tested by Xu et al. (2010, 2011).

A total of approximately 225 kg of swine carcasses – individually weighing 45 to 65 kg - were placed in each test bin. As is typical for on-farm composting of routine (non-emergency) swine mortalities, the compost matrix consisted of three layers (Fig. 1B). The “base” layer consisted of a 30 cm thick layer of envelope material in the bottom of the bin to absorb excess moisture and prevent release of leachate. Swine carcasses were positioned on the base layer at least 30 cm from the bin walls and with at least 30 cm of separation distance between them. Space surrounding the carcasses was filled with envelope material creating a “carcass” layer approximately 30 cm thick. An additional 60 cm of envelope material was placed on top of the carcass layer to retain heat and moisture thereby creating a “bio-filter” layer that absorbs and decomposes odorous VOCs. Each carcass was loosely wrapped in plastic netting to facilitate post-trial recovery and weighing of remains (Fig. 1D).

2.3 Data Collection & Analysis

2.3.1 Temperature

To characterize temporal and spatial T variability within the layered composting matrix, nine thermocouples (Omega Engineering, Stamford, CT) were installed in each if the three layers and their output was logged at 2 min intervals. To insure consistent positioning the thermocouples were mounted inside vertical T and O_2 sampling probes constructed from 3.8 cm diameter PVC (polyvinyl chloride) pipe (Fig. 1B). Each probe was fitted with three 7.6 cm lengths of 3.8 cm diameter slotted PVC well screen positioned to expose the thermocouples (and O_2 sampling tubes) to environments in the base, carcass, and bio-filter layers. Foam insulation was injected between the screened sections to prevent heat and gas transfer. A diagram of the probes is shown in Akdeniz et al. (2011). A CR10X logger (Campbell Scientific, Logan, UT) was used to record the T data, and these were aggregated to obtain daily averages for each location and layer.

Temperature during the initial phase of composting was characterized by computing mean T_{30} values within the carcass layers of the 6 tested envelope materials, where T_{30} is defined as the mean daily temperature of a layer during the first 30 d of composting. Temperature early in the composting process is relevant to process biosecurity for two reasons: during previous mortality composting research the highest T typically occurred during the first month (Glanville et al., 2013). Furthermore, work by Schumann (2000) suggests that low T early in the treatment process allow microbes to acclimate to higher T thereby reducing subsequent pathogen suppression potential.

Envelope materials also were ranked based on their success rate in achieving U.S. Environmental Protection Agency (USEPA) Class A and Class B time/T criteria for pathogen reduction in composted biosolids at least once during the 8 week field trials. Class A criteria require sustained composting T of 55 °C or greater for at least 3 consecutive days. Class B criteria call for sustained T of at least 40 °C for 5 or more consecutive days, and T must exceed 55 °C for at least 4 h during this period (USEPA, 2003).

2.3.2 Oxygen

Matrix O_2 concentrations were measured at the beginning of each seasonal trial, and at the end of each of the 8 weeks during the trial. Nine locations in each layer (base, carcass, bio-filter) were sampled using the previously-described multilevel T/gas sampling probes. An air pump and system of 27 logger-controlled solenoids sequentially pulled gas samples through tubing connected to each sampling location, and passed them through an O_2 sensor (Apogee, Logan, UT). Each sample line was purged for 2 min prior to taking an O_2 reading. The 9 weekly data points for each layer were averaged to obtain mean weekly O_2 concentrations by layer for each type of material. Mean concentrations were compared with recommended O_2 benchmarks published in composting references indicating that 5% (by volume) is considered to be the minimum O_2 concentration necessary to support aerobic composting, and that 10% or greater is considered optimal (Rynk, 1992; Chiumenti et al., 2005). The percentage of the 27 weekly mean values (9 weekly O_2 measurements x 3 replicated bins for material) for each combination of layer and material that failed to meet the minimum and optimal O_2 benchmarks was used as a quantitative indicator of an envelope material's ability to sustain target O_2 concentrations.

2.3.3 Moisture Content

Swine tissue in each test bin contained an estimated 150 kg of water (225 kg body weight x 65% H_2O content, w.b.) that was released during decomposition. The impacts of this water load on matrix m.c. were determined by collecting envelope material samples through ports installed in the sidewalls of the test bins. Three samples were collected from each layer at the start, mid-point, and end of each 8-week trial. Sample moisture content was determined by drying at 105 °C for 24 h, and the mean starting and ending m.c. for each combination of layer and material were compared to evaluate moisture build-up in the plastic-wrapped composting system and the impact of material type on moisture retention. The volume of leachate present in each bin at the end of a trial also was measured and recorded to determine if leachate accumulation is associated with a particular type of envelope material.

2.3.4 Animal Tissue Decomposition

Soft-tissue decomposition was quantified by weighing carcass remains (bone and undecomposed soft tissue) recovered at the end of the 8-week trials and calculating the soft tissue portion as a percentage of initial soft tissue weight. Research by Kuhn et al. (1997) concluded that skeletal weight in pigs is typically about 12% of total body weight. This amount was calculated for the initial carcass weight and subtracted from the initial weight and the weight of the remains to estimate soft-tissue weights. Supplemental 10 d animal tissue decomposition studies also were conducted in the laboratory so that process T and initial envelope material m.c. could be controlled more precisely.

2.3.5 Envelope Material Biodegradability (Laboratory Study)

Since the performance of the 6 envelope materials could not be field tested under identical ambient T and initial moisture conditions, supplemental lab-scale studies were conducted to further evaluate and rank their biodegradability and heat production potential under controlled conditions. Ten-day total oxygen uptake (TOU) was used as a measure of envelope material biodegradability. To simulate matrix conditions at the interface between animal tissue and envelope material, test surrogates were prepared by enveloping a sample of swine muscle, adipose tissue, and hide (10 cm diameter × 1 cm thick, weighing approximately 56 g) - in approximately 0.7 L of envelope material. These were incubated for 10 d at 45 °C in OxiTop®

(Global Water, Sacramento, CA) respiration bottles. A detailed explanation of the procedure for determining microbial oxygen uptake using OxiTop bottles can be found in Wageningen University and Nutrient Management Institute (2003). Moisture content was adjusted to 15, 25, 35, and 60% w.b. to observe the effect of a wide range of envelope material m.c.. Oxygen uptake rates were evaluated at 2-d intervals and TOU was calculated for the 10-d test period.

3. Results and Discussion

3.1 Moisture Content

Condensation observed on the inner surface of the plastic wrap indicated that evaporation from the compost matrix was being impeded, and dripping condensate caused the surface of the piles to look wet. Despite reduction in evaporation from the pile, however, mean (N=3) m.c. of compost samples collected from the carcass layer at termination of the 8-week field trials was seven percentage points ($p < 0.01$) below initial levels.

In the base layer – which is typically wettest since it receives excess liquid draining from the carcass layer – sample compost m.c. at termination of trials # 1-3 averaged about five percentage points less that at the beginning (Fig. 2). This decline was not statistically significant ($p < 0.09$), and mean m.c. in the base layer of envelope materials tested during trial #4 (cold season, pre-moistened) exceeded initial levels by five to 15 percentage points. Terminal m.c. during trial #4 did not, however, exceed 65% - the upper limit for moisture typically recommended in composting literature (Rynk, 1992; Chiumenti et al., 2005).

Animal tissue remains retrieved and weighed at the conclusion of each seasonal trial often included dried hair and skin suggesting that tissue decomposition had been terminated by desiccation. A very small (< 1L) volume of leachate was observed in two of the 36 test bins.

Although evaporation was impeded, the plastic-wrapped duct-ventilated composting system – which had a total ventilation duct end area < 1% of the free surface of a conventional compost pile - successfully evaporated a carcass water load of roughly 150 L and simultaneously reduced the initial m.c. of the envelope material without producing significant amounts of leachate. These results contrast with early field studies by Xu et al. (2009) in which cattle carcasses composted in plastic-wrapped piles using feedlot manure as the envelope material exhibited highly variable m.c. with some pooling of leachate. In a subsequent study (Xu, 2010), leachate was eliminated by placing an additional 60 cm of absorptive material beneath the cattle carcasses, and by using feedlot manure with lower initial m.c.

3.2 Oxygen Concentrations

During cold-season field trial #1, mean O_2 concentrations in both the base and carcass layers of bins using silage as the envelope material failed to meet the minimum (5%) and optimal (10%) O_2 concentration benchmarks during 27% and 67%, respectively, of the 27 O_2 monitoring events. During the same trial, O_2 concentrations in bins using ground cornstalks and oat straw consistently exceeded the 10% benchmark.

The large differences during trial #1 between O_2 concentrations in silage and those in drier and less dense envelope materials suggested that the cornstalk and oat straw test bins were over-aerated, and that initially dry materials did not require three aeration ducts to achieve desired O_2 concentrations. Further, since over-aeration can cause excessive heat and moisture loss, it was concluded that continued use of three ducts in field tests of cornstalks, oat straw, (and the three initially dry materials tested during trials #3 and 4) could result in inaccurate assessment of their performance with respect to biosecurity and tissue degradation. This is supported by the work of Ahn et al. (2008b) characterizing physical characteristics affecting airflow through envelope materials. Results of this study showed that ground cornstalks, oat straw, alfalfa hay, soybean straw, and wood shavings all had significantly lower bulk density and higher air-filled porosity than silage. Thus, it was decided that subsequent field trials using initially-dry low-density envelope materials would be conducted using a single aeration duct. To maintain a consistent physical setup – three aeration ducts were installed in test bins using non-silage envelope materials, but two of the ducts were capped and air was delivered only through the center duct.

During seasonal trials #2, #3, and #4, 100% of the 27 weekly mean O_2 concentrations computed for each layer and material type of non-silage envelope materials exceeded 10% (using a single functional air duct). During warm season trial #2 (ambient air T_{30} = 22.4 °C) mean O_2 in both the base and carcass layers of silage test bins always exceeded the 5% target O_2 concentration, but O_2 in the base layer fell below the 10% in about 4% of the sampling events. It is believed that the much higher O_2 failure rates in silage during trial #1 were due in part to very cold ambient T (ambient air T_{30} = 4.4 °C). Visual observation and probing of silage test bins during trial #1 revealed frost accumulation in the bio-filter layer and this is believed to have impeded airflow through the matrix thereby causing low O_2 concentrations.

Results for the non-silage materials using a single duct indicate that O_2 concentrations exceeding 10% can be reliably achieved with 2 m duct spacing. For very moist and dense envelope materials like corn silage, duct spacing of 0.5 m or less is likely to be needed to insure achievement of the recommended minimum matrix O_2 concentration of 5%. Relatively low O_2

concentrations observed in silage test units during trials #1 and 2 also are consistent with earlier work by Ahn et al., (2008a, 2008b) showing the gas permeability of silage to be <40% of that for moist ground cornstalks (<19% if dry), and < 35% of that for moist oat straw (<26% if dry).

3.3 Temperature, Heat Production, Pathogen Inactivation Potential

3.3.1 Internal Temperature (Field Trials)

Mean (N=3) T_{30} within the carcass layer ranged from 11 °C in very dry oat straw at ambient air T_{30} of less than 5 °C, to 65 °C in moist silage at ambient air T_{30} of 22 °C (Fig. 3). Linear regression analysis indicated that carcass layer T_{30} had a moderately weak but consistent relationship ($R^2 = 0.37$; $p < 0.001$) to ambient air T_{30} and to initial envelope material m.c. ($R^2 = 0.25$; $p < 0.0012$). The relatively low R^2 values for these factors are due, in part, to uncontrolled and unquantified factors such as wind exposure, solar heat gain, and pile ventilation rates which also affect T_{30}. The relationship between initial envelope material m.c. and T_{30} is consistent with work by Ahn et al. (2008a) that documented increased rates of envelope material biodegradation and heat production as m.c. increased.

Single factor ANOVA of mean T_{30} data for the different envelope materials indicated significant differences denoted by the letter designations in Fig. 3. The inherently moist nature of silage is believed to have stimulated early development of aerobic microbial activity leading to rapid heat production and much higher T than observed in dry cornstalks and oat straw during trial #1. During trial #2 when all materials were initially moist, mean T_{30} values for silage remained significantly ($p < 0.05$) greater than in the other two materials suggesting that additional characteristics, such as the presence of readily degradable organic acids produced during ensiling, also contribute to rapid heat production.

In some instances, chemicals present in envelope materials may have a deleterious impact on decomposition and heat production. Contrasting T_{30} trends observed during trials #3 and 4 are believed to be an example of this. T_{30} for moistened alfalfa and soybean straw are higher during the relatively cool trial #4 than during the warmer unmoistened trial #3 (Fig. 3). T_{30} for moistened wood shavings, however, are noticeably lower during trial #4. The chemical composition of the pine shavings used in this study suggests a possible explanation. Work by Akdeniz et al. (2010a) on VOCs released during composting reported that several terpenes (e.g., camphene, limonene, β -pinene, β -phellandrene) were detected in mortality compost that employed pine shavings. These compounds, which have antimicrobial properties (Dermirci et al., 2007, Imelouane et al., 2009; Leite et al., 2007), may have been made more available by wetting the shavings, thereby suppressing microbial activity and heat production.

Two-way ANOVA modeling using envelope material type, ambient air T_{30}, initial m.c., and material type x m.c. as predictor variables (adjusted $R^2 = 0.92$) indicate that material type has a significant ($p < 0.0001$) effect on carcass layer T_{30}. Model predictions for each envelope material (Table 1) fall into three performance ranges: > 50 °C (silage); ~ 40 °C (alfalfa hay, soybean straw, and cornstalks); and ~30 °C (oat straw, wood shavings). The predicted T_{30} for silage and ground cornstalks were similar to those reported in the carcass surface zone of conventional (non-wrapped, no ducts) cattle mortality composting windrows (silage, 54 °C; ground cornstalks, 34 °C) documented during multi-season emergency mortality composting field studies by Glanville et al. (2013).

3.3.2 Envelope Material Biodegradability (Laboratory Study)

Under controlled ambient T and initial moisture conditions in the lab, initial m.c. had significant ($p < 0.0001$) effect on TOU. Mean TOU values predicted by two-way ANOVA modeling (Table 2) indicate that raising the m.c. of dry (15% w.b.) materials to 35% nearly doubled O_2 uptake of all envelope materials. Furthermore, TOU at 35% is predicted to be statistically ($p < 0.05$) equivalent to that at 60%. These results have useful implications for emergency mortality composting practices since the m.c. of envelope materials is typically < 20%. Composting references typically recommend 50-75% as the optimal moisture range for composting (Rynk, 1992; Chiumenti et al., 2005; Haug, 1993). Under emergency conditions, however, there may be insufficient time to raise the m.c. to recommended levels since moistening dry material must be done slowly. Rushing the process can waste water and cause uneven moistening and release of leachate. Moderate moistening to only 35%, as suggested by the laboratory TOU results would: (a) take less time and water than moistening to 60%; (b) reduce the risks of over moistening and leachate release, and (c) produce equivalent microbial activity.

ANOVA modeling also showed that envelope material type had significant ($p < 0.0001$) impact on 10-d TOU. Model predictions (Table 3) indicate that animal tissue enveloped in oat straw, cornstalks, soybean straw, or wood shavings exhibited significantly ($p <0.05$) greater 10-d average TOU values than animal tissue enveloped in silage. Since heat production is proportional to TOU - averaging approximately 14.4 J of biological heat energy released for each mg of O_2 consumed during volatile solids degradation (Cooney et al., 1968; Finstein et al., 1986) - these TOU data also indicate that, when sufficiently moistened, envelope materials that exhibited low T_{30} during field trials have potential to produce more heat than silage. The predicted low biodegradability for silage also suggests that the high T observed in silage test bins in the field were probably the result of low heat loss rather than high heat production. The primary causes of heat loss in compost are convection and evaporation resulting from air movement through the matrix. The relatively low O_2 concentrations in silage suggest that airflow through the silage was lower than in other materials, and this also is consistent with the research cited earlier indicating that the gas permeability of moist silage is 25% or less of that for dry cornstalks or oat straw.

3.3.3 USEPA Class A/B Success Rate

During field trials, silage was the only envelope material that exhibited a high success rate in achieving USEPA Class A/B time/T criteria for pathogen suppression. Silage test bins achieved Class B criteria at 91% of monitored locations in the carcass layer. Class B success rates for the other envelope materials ranged from 33 to 57 % (Table 4). Class A criteria were more difficult to achieve, and success rates were 5 to 30% lower than for Class B.

Although USEPA Class A and B criteria were originally developed as guidelines for reducing bacterial pathogens in composted sewage bio-solids, recent studies indicate that Class A/B temperature criteria are relevant for several common viral pathogens as well. Work by Guan et al. (2009) showed that avian influenza and Newcastle disease viruses (NDV) in chicken carcasses were rapidly inactivated when compost T were between 40 and 50 °C. In later work, this group reported that compost T of 35 °C for a day killed bovine viral diarrhea virus (BVDV), and that similar conditions were expected to be sufficient to destroy closely related classical swine fewer virus (CSFV) (Guan et al., 2012).

3.4 Animal Tissue Decomposition

3.4.1 Decomposition in Field Test Units

One-way ANOVA modeling of the 8-week field soft tissue decomposition indicated that material type had a significant ($p < 0.0095$) effect. The greatest decomposition (>85%) occurred in cornstalks and soybean straw and was significantly ($p<0.05$) greater than in silage (72%), the material with the lowest decomposition (Table 5). Performance ranking based on carcass decomposition in the field, and on TOU in the lab, are nearly identical with cornstalks, oat straw, and soybean straw grouped at the top, and wood shavings, alfalfa, and silage at the bottom.

The field decomposition results also demonstrate that envelope materials with the highest internal T do not necessarily produce the most rapid soft tissue decomposition.

Significant loss of moisture and observation of desiccated remains in the carcass layer led to speculation that initial m.c. of the envelope material could be a significant causative factor, but ANOVA modeling of decomposition data did not confirm this.

3.4.2 Decomposition in Laboratory Tests

ANOVA modeling of 10-d animal tissue sample weight loss observed in the lab indicated that envelope material type had a significant effect ($p < 0.0001$) on tissue decomposition. Similar to the field decomposition and laboratory TOU results, cornstalks, oat straw, and soybean straw exhibited the greatest decomposition, and alfalfa and silage the least. Unlike the other results, wood shavings - which had moderate to low TOU and field decomposition – had the highest laboratory tissue decomposition (Table 6).

Initial envelope material m.c. had a significant effect ($p < 0.0009$) on animal soft tissue decomposition in the lab. Tissue decomposition at 15% was significantly ($p < 0.05$) less than at 25%, but increasing initial m.c. above 25% did not significantly improve tissue decomposition (Table 6).

3.5 Odor Emission

Offensive odors were emitted intermittently by 10 to 20% of the test bins during the field studies. This typically occurred during the first 2 weeks of the trials and odorous periods - lasting 1 to 2 d alternated with periods when no odor was detected. This was unexpected as odor releases were rare during earlier cattle mortality composting studies (Glanville et. al., 2013) conducted in unenclosed naturally aerated (no ventilation tubing) windrows. Smoke testing, combined with temperature monitoring in the top and base ducts, revealed that, when odors were emitted, air entered the test bin through the top vent and exited via the base ducts (Fig. 4). This top-to-bottom flow pattern is contrary to typical airflow through unenclosed passively-aerated windrows characterized by entry of ambient air near the base of the pile causing less dense warm/moist interior gases to be discharged at the top (Haug, 1993; Patni and Jui, 1994). Studies of airflow through enclosed passively-aerated composting reactors (Sylla et al., 2003; Barrington et al., 2003; Yu et al., 2008) also report bottom-to-top flow through the compost matrix. Insufficient time and resources were available to further study potential causes and solutions of the odorous reverse airflow. Review of composting literature, however, suggests that a likely cause is inadequate T differential between ambient air and gases within the compost pile. Haug (1993) suggested that a T differential of about 40 °C is associated with adequate natural-draft ventilation. This can be difficult to attain during the early stages of emergency mortality composting, however, if envelope materials have low m.c. which inhibits rapid microbial growth and heat production. It should be noted that the three enclosed reactor studies cited above were carried out in small scale reactors under conditions conducive to bottom-to-top airflow. All were conducted indoors, at initial compost m.c. of 60% or higher, and Sylla et al. (2003) used an electric heater to achieve desired initial internal T.

The correlation between airflow direction and odor emission is believed to be associated with the presence or absence of naturally-occurring odor bio-filtration occurring within the compost matrix. During periods of typical upward flow, odorous VOCs that are entrained in the matrix air stream as it passes through the carcass decomposition zone are subsequently exposed to biofilms on the surfaces of clean and moist envelope material overlying the carcass zone. Odorous VOCs are temporarily adsorbed and decomposed on the biofilms prior to being vented to the atmosphere in the same way that engineered biofilters remove odors from process gases produced by wastewater treatment plants and swine barns. During downward flow, however, odorous gas leaving the carcass decomposition zone passes through underlying materials that have been contaminated by liquid drainage from the carcass zone above. Biofilms on these materials are saturated with odorous gases leaving little, if any, capacity to remove odor. As a result, gas exits through the base aeration ducts and is vented to the atmosphere without benefit of bio-filtration.

4. Conclusions

Despite a 150 kg carcass water load, mean compost m.c. in the carcass layer declined by 7 percentage points. Leachate accumulation was rare, and O_2 concentrations were $\geq$10% in all envelope materials except silage. Envelope material type and initial m.c. were significant performance factors. Success rates for USEPA Class B pathogen suppression criteria in the carcass layer ranged from 91% for silage to 33-57% for other envelope materials. Laboratory 10-d TOU data showed, however, that moistening dry envelope materials to 35% m.c. doubles their heat production potential resulting in significantly higher heat production potential than that of silage.

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Figure Captions

Fig. 1. Replicated test units during a seasonal field trial (A), cross-section of loaded test unit & instrumentation (B), test unit being weighed to determine mass loss (C), swine carcasses (wrapped in plastic netting) in test unit among vertical thermocouple and O_2 sampling tubes (D).

Fig. 2. Individual and mean (line) moisture content in base layer (beneath carcasses) of test units (N=3), by trial number and envelope material, at the beginning, middle, and end (time = 0, 1, 2 months) of each trial. Moisture content of materials in trials 1 & 3 was “as received” from storage; materials in trials 2 & 4 (except silage) were moistened to 45-65% w.b.

Fig. 3. T_{30} in carcass layer of replicated (N=3) test bins during four seasonal field trials. Materials within the same trial that have different letter designations are significantly ($p < 0.05$) different.

Fig. 4. Daily mean temperature in ambient air (“air”), at the ends of the top vent (“VN”, “VS”) and in the base aeration (“AE”) ducts. Up-flow and down-flow arrows indicate periods when warm air was emitted through the top vent or base ducts.

Table 1. Predicted T_{30} in the carcass layer based on ANOVA modeling of field T_{30} data for six envelope materials during warm and cool seasons.

Material	Predicted mean T_{30} in carcass layer (°C)*
Silage	52.5^{a}
Alfalfa	41.4^{ab}
Soybean	41.4^{ab}
Cornstalks	37.9^{bc}
Wood shavings	29.7^{c}
Oat straw	30.1^{c}

* Values without a superscript letter in common are significantly different ($p < 0.05$).

Table 2. Predicted 10-d total oxygen uptake based on ANOVA modeling of lab-scale TOU data for envelope materials at four initial moisture levels.

Initial moisture content % (w.b.)	Total O_2 uptake (mg O_2)*
60%	37.8^{a}
35%	31.0^{a}
25%	23.4^{b}
15%	16.8^{c}

* Values without a superscript letter in common are significantly different ($p < 0.05$).

Table 3. Predicted 10-d mean O_2 uptake for six envelope materials based on lab-scale testing at 45 °C.

Material	Total O_2 uptake (mg O_2)*
Oat straw	51.4^{a}
Cornstalks	48.2^{ab}
Soybean	35.1^{b}
Wood shavings	21.5^{c}
Alfalfa	15.3^{cd}
Silage	10.9^{d}

* Values without a superscript letter in common are significantly different ($p < 0.05$).

Table 4. Success rate, by envelope material, for meeting USEPA Class A and B criteria for pathogen reduction in the carcass layer of all trials.

Material	Success rate (% of locations[*] monitored in carcass layer)[**]	
	Class A	Class B
Silage	85.2^{a}	90.7^{a}
Oat straw	24.1^{c}	35.2^{c}
Cornstalks	48.1^{b}	48.1^{bc}
Wood shavings	22.2^{c}	33.3^{c}
Soybean	27.8^{c}	57.4^{b}
Alfalfa	18.5^{c}	44.4^{bc}

[*] 54 total locations were monitored in the carcass layer of each envelope material (6 test bins per envelope material (3 warm season + 3 cool season) × 9 thermocouples in the layer)

[**] Within columns, values without a superscript letter in common are significantly different ($p < 0.05$).

Table 5. Mean 8-week carcass soft-tissue decomposition for all field trials, by envelope material.

Material	Mean soft tissue decomposition (%)[*]
Cornstalks	87.2^{a}
Soybean	85.4^{a}
Oat straw	82.3^{ab}
Wood shavings	81.2^{ab}
Alfalfa	81.1^{ab}
Silage	72.0^{b}

[*] Values without a superscript letter in common are significantly different ($p < 0.05$).

Table 6. Predicted mean **a**nimal tissue decomposition based on ANOVA modeling of 10-d laboratory data, as functions of envelope material and initial moisture content.

	Compost envelope material[*]					
	Wood shavings	**Cornstalks**	**Oat straw**	**Soybean straw**	**Alfalfa hay**	**Silage**
Predicted mean % decomposition	69.7^{a}	69.3^{a}	65.8^{a}	64.9^{ab}	55.7^{bc}	54.3^{c}

	Initial moisture content (%)			
	35%	**25%**	**60%**	**15%**
Predicted mean % decomposition	66.5^{a}	66.3^{a}	63.8^{a}	56.5^{b}

[*] Within rows, means with differing superscript letters are significantly different ($p < 0.05$).

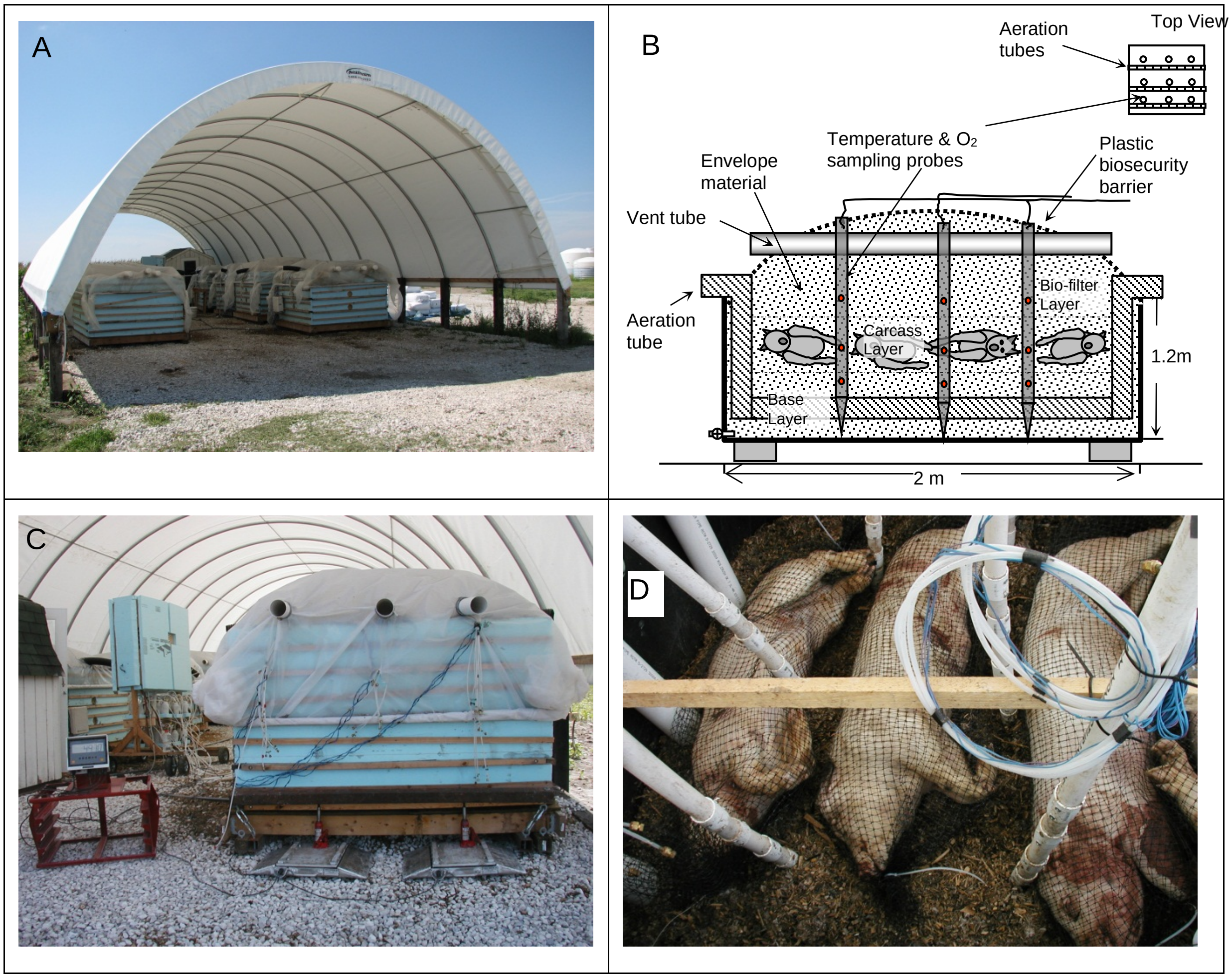

A
B
Aeration tubes
Top View
Temperature & O_2 sampling probes
Envelope material
Plastic biosecurity barrier
Vent tube
Bio-filter Layer
Aeration tube
Carcass Layer
1.2m
Base Layer
2 m
C
D

Fig. 1.

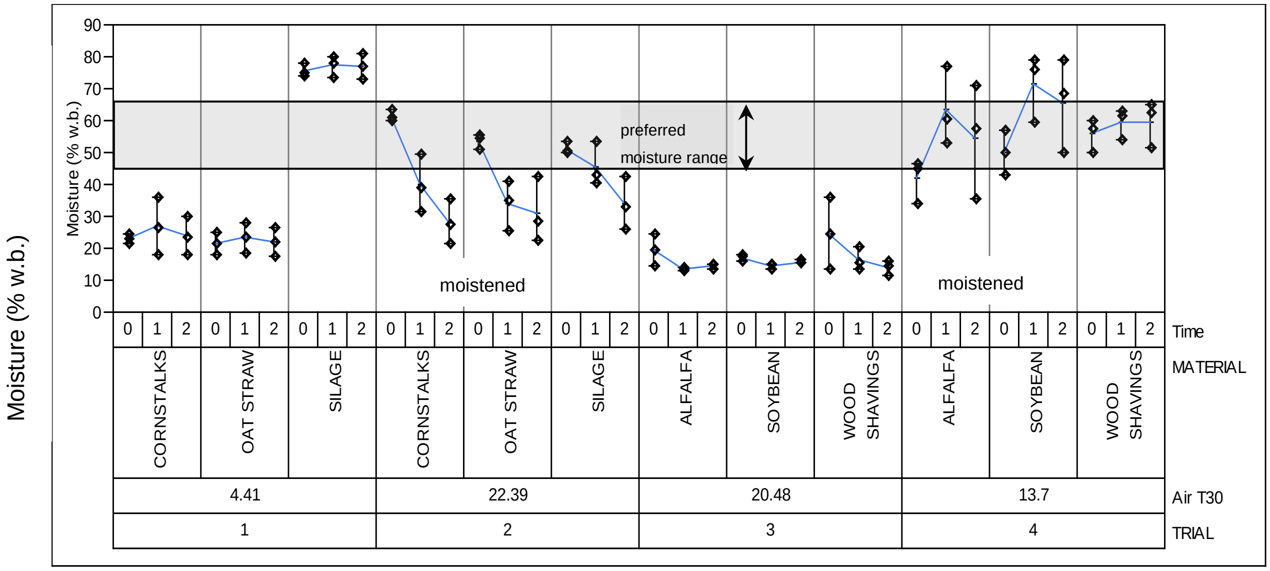
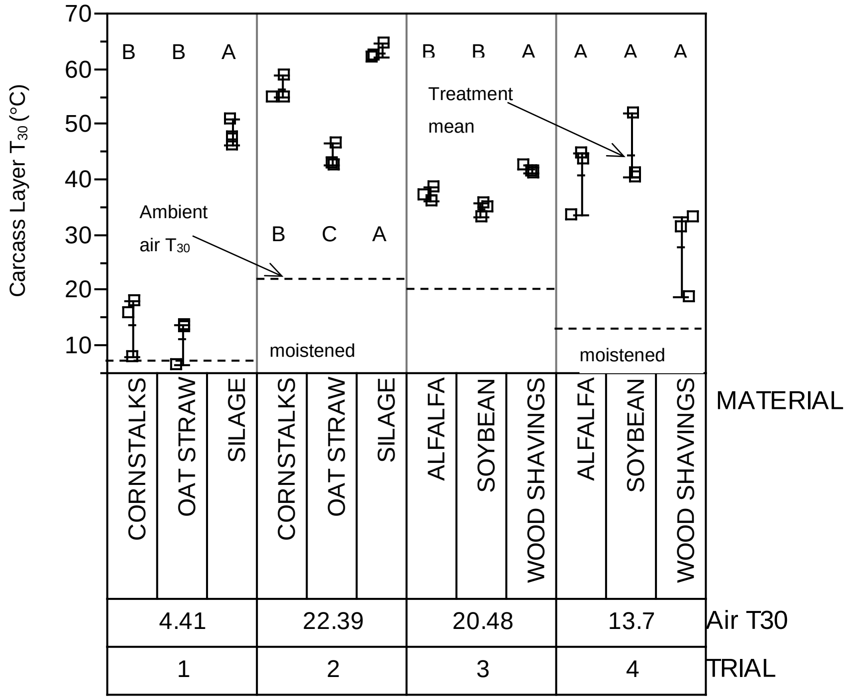

Moisture (% w.b.)
Moisture (% w.b.)
90
80
70
60
50
40
30
20
10
0
preferred
moisture range
moistened
moistened
0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2
Time
CORNSTALKS
OAT STRAW
SILAGE
CORNSTALKS
OAT STRAW
SILAGE
ALFALFA
SOYBEAN
WOOD SHAVINGS
ALFALFA
SOYBEAN
WOOD SHAVINGS
MATERIAL
4.41
22.39
20.48
13.7
Air T30
1
2
3
4
TRIAL

Fig. 2.


Carcass Layer T_{30} (°C)
70
60
50
40
30
20
10
B B A
B C A
B B A
A A A
Treatment mean
Ambient air T_{30}
moistened
moistened
CORNSTALKS
OAT STRAW
SILAGE
CORNSTALKS
OAT STRAW
SILAGE
ALFALFA
SOYBEAN
WOOD SHAVINGS
ALFALFA
SOYBEAN
WOOD SHAVINGS
MATERIAL
4.41
22.39
20.48
13.7
Air T30
1
2
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4
TRIAL

Fig. 3.

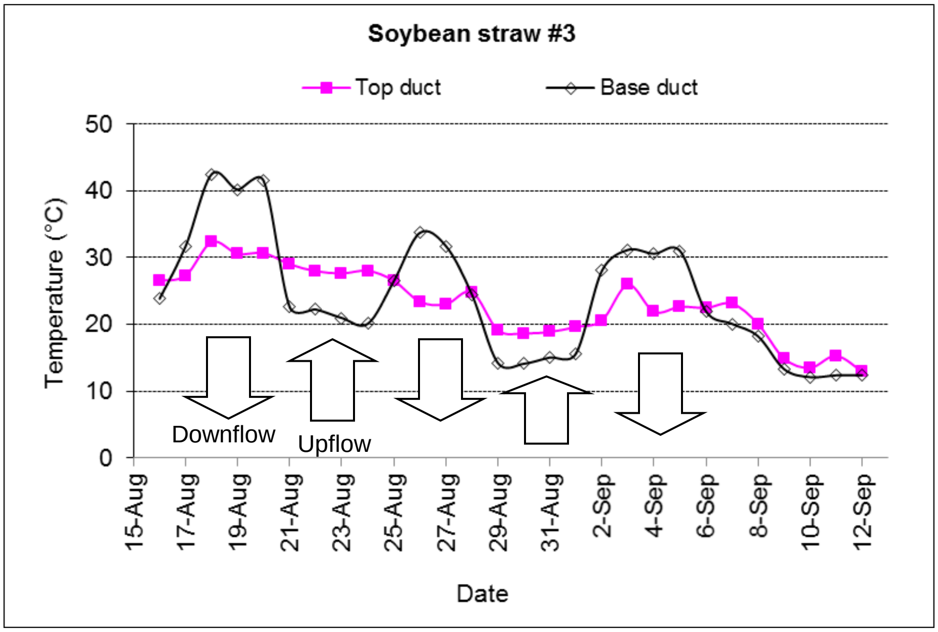
Soybean straw #3
Top duct
Base duct
Temperature (°C)
50
40
30
20
10
0
Downflow
Upflow
15-Aug
17-Aug
19-Aug
21-Aug
23-Aug
25-Aug
27-Aug
29-Aug
31-Aug
2-Sep
4-Sep
6-Sep
8-Sep
10-Sep
12-Sep
Date

Fig. 4.