Effects of Manure Removal Strategies on Odor and Gas Emission from Swine Finishing


ABSTRACT. Odor, ammonia (NH₃) and hydrogen sulfide (H₂S) concentrations, and emission rates were measured in two small rooms of finishing pigs with various manure removal strategies. The strategies included daily flush and static pits with 7, 14, and 42 d manure accumulation cycles, with and without pit recharge with some secondary lagoon effluent after emptying. In each room, tests were conducted with three successive groups of 25 pigs, which were fed standard corn-soybean diets. Ammonia and H₂S concentrations were measured automatically 15 to 24 times daily at various locations with chemiluminescence and pulsed fluorescence analyzers, respectively. Odor concentration, intensity, and hedonic tone of air samples were evaluated by a panel of eight trained subjects. Flushing and static pit recharge with lagoon effluent resulted in significantly less NH₃, H₂S, and odor emissions (P < 0.05). Draining static pits more frequently also significantly reduced H₂S and odor emissions. Geometric mean odor emission rates were 19, 33, and 29 OUₑ s⁻¹ AU⁻¹ (OUₑ = European odor unit equivalent to 123 μg n-butanol, AU = 500 kg live mass) for the 1 d (daily flush), 7 d, and 14 d cycles without pit recharge, respectively, and 2.6 and 25 OUₑ s⁻¹ AU⁻¹ for the 7 d and 42 d cycles with pit recharge, respectively. Mean NH₃ emission rates were 15, 27, and 25 g d⁻¹ AU⁻¹ for the 1, 7, and 14 d cycles without pit recharge, and 10, 12 and 11 g d⁻¹ AU⁻¹ for the 7, 14, and 42 d cycles with pit recharge, respectively. Mean H₂S emission rates were 0.11, 0.27, and 0.41 g d⁻¹ AU⁻¹ for the 1, 7, and 14 d cycles without pit recharge, and 0.16, 0.34, and 1.42 g d⁻¹ AU⁻¹ for the 7, 14, and 42 d cycles with pit recharge, respectively. The mean H₂S emission rate during daily flushing was 0.40 g d⁻¹ AU⁻¹ when flushing—induced burst emissions were included in the means, as compared with 0.11 g d⁻¹ AU⁻¹ when flushing times were excluded. Sudden emissions during the flushing event had a significant influence on the mean emissions from these relatively small rooms; however, without valid data from week 1, the mean H₂S emission rate of 0.40 g d⁻¹ AU⁻¹ was probably an overestimate. Daily flushing reduced odor emissions by 41% and 34% (P < 0.05) as compared with the 7 d and 14 d cycles, respectively. The 7 d cycle resulted in 35% and 53% lower H₂S emissions as compared with the 14 d cycle with and without pit recharge, respectively. The 14 d cycle had 76% less (P < 0.05) H₂S emission than the 42 d cycle, both cycles with pit recharge. Mean daily NH₃ emissions from the rooms with static pits were 51% to 62% lower (P < 0.05) with recharge than without recharge. Similarly, mean daily H₂S emissions were 18% to 40% lower with pit recharge. In summary, lower NH₃ and H₂S emissions occurred when pits were recharged after emptying, and when pits were emptied more frequently.

Keywords. Flushing, Manure dilution, Manure removal strategy, Odor and gas concentrations.

Ammonia (NH₃), hydrogen sulfide (H₂S), and odoriferous gas compounds are produced by animals and decomposing manure. These gases affect the health of both pigs and workers, deteriorate equipment and buildings, cause potential damage to the ecosystem, are associated with odor complaints, represent a significant loss of nitrogen fertilizer value, and cause loss of pig performance (Arogo et al., 2003; Donham et al., 1986; Ni et al., 2000a; Ni et al., 2002). Abatement methods and strategies to alleviate these problems involve building hygiene, waste management, ventilation, and manure and feed additives (Strobel and Heber, 1998). Measurements of odor and gases at finishing buildings with different manure management systems will facilitate the validation and use of setback guidelines and atmospheric dispersion models (Jacobson et al., 2001; Lim et al., 2000).

Therefore, the objectives of this study were to:

- Evaluate odor, NH₃, and H₂S emissions from finishing pigs.
- Determine effects of manure removal strategies on odor, NH₃, and H₂S emission rates.

Previous Measurements of Odor and Gas Emissions

Different odor concentration (OC) and emission values result from the use of various olfactometry standards, most likely because of differences in flow rate, face velocity, panel...
selection, and olfactometer calibration (Watts, 1999). The 1995 version of the Dutch NVN 2820 olfactometry standard (NNI, 1995) results in odor concentrations (OC) that are two to five times higher than with the EN13725 standard (CEN, 2002) currently being followed by many laboratories in Europe, Australia, and Canada (Watts, 1999). Likewise, measurements with the EN13725 standard result in higher OC values than those measured with the U.S. standard (ASTM Standards, 1992). Olfactometry standards used for evaluating air samples should therefore be reported along with the data.

Heber et al. (1998) measured odor emission rates from four mechanically ventilated swine finishing houses between April and August. The buildings had long-term manure storage beneath fully slatted floors. Grab samples of air were evaluated (ASTM olfactometry), and gross odor emission rates were calculated assuming zero inlet concentrations. The mean OC of 109 measurements was 142 OU m$^{-3}$, and the mean odor emission rate was 36 OU s$^{-1}$ AU$^{-1}$. The geometric mean building odor emission rate was 3990 OU s$^{-1}$, or 5.0 OU s$^{-1}$ per m$^2$ of floor area.

Zhu et al. (2000) measured odor emissions (ASTM olfactometry) from a 475-head mechanically ventilated nursery with a deep pit. Seven measurements were made 2 h apart during one sampling visit to the nursery. The mean ventilation rate and inside temperature were 31 m$^3$ h$^{-1}$ pig$^{-1}$ and 27°C, respectively, and the average pig mass was 20.5 kg. The means of ventilation exhaust OC and building odor emission rate were 765 OU m$^{-3}$ and 149 OU s$^{-1}$ AU$^{-1}$, respectively.

Jacobson et al. (1998) measured odor and gas concentrations in a pig nursery. The geometric mean OC (ASTM olfactometry) of ventilation exhaust air samples was 461 OU m$^{-3}$ (arithmetic mean = 529 OU m$^{-3}$). No emission data were reported.

Odor emission rates (ASTM olfactometry) were evaluated at two commercial swine nurseries in Indiana from March to May with five sampling visits per room (Lim et al., 2001). The nurseries, housing 94 to 250 pigs each, were mechanically ventilated with long-term manure storage under wire floors. The geometric mean OC in the ventilation exhaust air was 199 OU m$^{-3}$. The overall mean odor emission rate was 34 OU s$^{-1}$ AU$^{-1}$ (1.8 OU s$^{-1}$ m$^{-2}$).

Amon et al. (1995), using NVN9820 olfactometry (NNI, 1995), reported a mean exhaust OC of 2800 OU m$^{-3}$ in buildings with 600 pigs weighing 8 to 27 kg. Measurements were conducted in the autumn with mean inside temperatures of 25°C. The buildings, located in Slovenia, were mechanically ventilated and equipped with manure pits beneath fully slatted concrete floors. Mean emission rates were 9400 and 8620 OU s$^{-1}$ for the control and treated (De-Odorase manure additive) rooms, respectively. The overall mean odor emission rate was 488 OU s$^{-1}$ AU$^{-1}$.

Verdoes and Ogink (1997) measured odor emission rates from a partially slatted pig nursery that was designed for low NH$_3$ emission. The mean ventilation rate and inside temperature were 9.2 m$^3$ h$^{-1}$ pig$^{-1}$ and 27°C, respectively. The means for exhaust fan OC and odor emission rate were 2109 OU m$^{-3}$ and 272 OU s$^{-1}$ AU$^{-1}$, respectively (NVN9820 olfactometry).

Odor emission rates measured at swine buildings in Australia were two to four times greater in summer than in winter (Watts, 1999). The greatest increase occurred when inside temperatures exceeded 25°C. The data also showed that higher humidity increased odor emission rate. It was concluded that regular flushing of manure reduces odor emission rates compared with deep-pit systems. The odor emission factor for new Australian swine houses (pig type not specified) with daily flush systems was estimated to be 150 OU s$^{-1}$ AU$^{-1}$ (NVN9820 olfactometry) by Watts (1999). The winter and summer odor emission factors were estimated to be 100 and 200 OU s$^{-1}$ AU$^{-1}$, respectively.

Ni et al. (2000b) measured NH$_3$ emission rates from one of the swine finishing buildings studied by Heber et al. (1998). A total of 88 d of data were obtained during warm weather from June 26 with 887, 19-kg pigs to September 25 with 874, 83-kg pigs. The mean inside NH$_3$ concentration (of all sampling locations in the buildings) was 3.9 ± 0.3 mg m$^{-3}$ and ranged from 1.9 to 7.4 mg m$^{-3}$. The average daily mean building NH$_3$ emission rate was 11.2 ± 1 kg d$^{-1}$, equivalent to 145 ± 10 g d$^{-1}$ AU$^{-1}$. The emission rate per AU was higher than values reported by other studies, probably because of warmer temperatures and higher ventilation rates, and was correlated to total pig mass (r = 0.49). The building NH$_3$ emission rate was somewhat correlated to total pig mass (r = 0.52) and ventilation rate (r = 0.41).

Ni et al. (2002) measured H$_2$S emission rates between March and September from two of the buildings studied by Heber et al. (1998). Air from pit fans, wall fans, and pit headspaces was continuously sampled. Average building H$_2$S emission rate was 591 g d$^{-1}$ or 740 mg d$^{-1}$ per m$^2$ of floor area or 6.3 g d$^{-1}$ AU$^{-1}$. Hydrogen sulfide emission rate increased with temperature and building ventilation rate.

**Materials and Methods**

**Description of Environmental Rooms and Growth Cycles**

Odor and gas concentrations and emission rates were measured in two identical mechanically ventilated finishing rooms that were located in a building at the Purdue University Swine Research Center. The dimensions of the rooms were 7.32 × 4.88 m with floor and pit surface areas of 35.7 m$^2$ (fig. 1). Rooms A and B were located on opposite sides of a 1.83 m wide hallway. The rooms had identical ventilation and manure management systems.

The underfloor manure pit was 1.1 m deep with a pull-plug drain located at the north end of the pit (fig. 1). The pits either accumulated manure over a period of 7 to 42 d or were flushed clean with recycled secondary lagoon effluent that was conveyed under pressure through 15 cm diameter PVC pipes underneath the slatted floor (fig. 1). The effluent entered the pit through four, 15 cm, 90° tees or elbows (at the end) positioned at the quarter points along the south wall, at a height of about 0.87 m above the pit floor. Flushing volume was 1.42 m$^3$ d$^{-1}$ based on recommendations of 56.7 L d$^{-1}$ pig$^{-1}$ by MWPS (1985).

A constant ventilation rate in each room was provided by an independent environmental control system with centrifugal blowers, located in a small annex at the north end of each room. Ventilation inlet air consisted of a constant blend of about 16% outdoor air and 84% recycled, filtered room air that exhausted under the floor in the pit (fig. 2). It was conditioned to a constant temperature of 20°C to 25°C by a water chiller and heating coils in the air handler. While
mechanical air conditioning was utilized, it is not practiced in commercial swine production.

Airflow rates of blended air and outdoor air (fig. 2) were measured in both rooms. Ventilation rates were 0.86 and 0.87 m³ s⁻¹ for rooms A and B, respectively, based on air velocity traverses (Henderson and Perry, 1976) in the 0.165 m² air ducts with a hot-wire anemometer (model 444, Kurz, Inc., Monterey, Cal.). The rates of system exhaust airflow and outdoor make-up airflow were 0.14 m³ s⁻¹ in Kurz, Inc., Monterey, Cal.). The rates of system exhaust airflow and outdoor make-up airflow were 0.14 m³ s⁻¹ in each room.

This study involved three groups or growth cycles of finishing pigs from March to July 2000 (fig. 3). Testing began in room B during the last week of a 6-week growth cycle, which ended on March 13. The experiment continued with a similar 6-week cycle from March 23 to May 2, and ended with a 9-week cycle in both rooms from May 13 to July 14. For the first and second cycles, the manure storage pit was initially recharged with about 5 cm of secondary lagoon effluent, and manure was drained after 42 d of accumulation. The third growth cycle consisted of three, 3-week sequences in manure exhaustion and outdoor make-up airflow were 0.14 m³ s⁻¹ in each room.

Between growth cycles, the pits were emptied into the primary cell of a 3-stage anaerobic treatment lagoon system, flushed with secondary lagoon effluent, and washed with fresh water. Also, the rooms were power-washed and disinfected. Initial and final mean pig masses were 81 and 114 kg for GC 1 and 2, respectively. The mean pig mass ranged from 61 to 120 kg during GC 3 based on biweekly measurements.

**ODOR SAMPLING AND EVALUATION**

Odor sampling was conducted twice at the end of GC 1 and six times during GC 2 (fig. 3). Sampling was conducted twice weekly during GC 3. Air samples were collected outdoors (n = 1), at the room air inlet (n = 2), and at the room exhaust (n = 2) for a total of 10 samples (fig. 2). For the room inlet sample, one end of a Teflon tube was secured at the center ceiling inlet, and air was withdrawn from the other end of the tube in the hallway without disturbing the pigs. The tubes were flushed with compressed air prior to each sampling event, at which time the pit was drained. Pits were not recharged during the third growth cycle. In the third cycle, odor measurements were completed on July 14 and gas measurements were completed on July 24.

The manure removal strategies were characterized by manure accumulation cycles in the pit and whether pits were initially recharged with lagoon effluent. The accumulation cycles were 1, 7, 14, or 42 d (S1, S7, S14, and S42) for daily flush, and weekly, biweekly, and 6-week removals by pulling a drain plug (pull-plug method), respectively. The pits were initially charged with lagoon effluent for the first two growth cycles; thus, the treatments were indicated with an R, e.g., S7R, S14R, and S42R. Emission rates for each strategy (S1, S7, etc.) were reported as the mean over the entire manure accumulation period rather than the emission rate at the end of the period.

All diets met the National Research Council (NRC, 1998) requirements for finishing pigs. In a companion study of diet modification (Kendall et al., 2000) during GC 1 and GC 2, a standard diet in one room was compared with a reduced-CP diet in the other room, which is not included in this article. The standard diets consisted of corn-soybean meal with CP of 11.5% and 12.6% for GC 1 and GC 2, respectively. The CP levels in the third growth cycle were 15.1%, 13.1%, and 11.7% for pigs weighing 45 to 68 kg, 68 to 91 kg, and >91 kg, respectively.

Between growth cycles, the pits were emptied into the primary cell of a 3-stage anaerobic treatment lagoon system, flushed with secondary lagoon effluent, and washed with fresh water. Also, the rooms were power-washed and disinfected. Initial and final mean pig masses were 81 and 114 kg for GC 1 and 2, respectively. The mean pig mass ranged from 61 to 120 kg during GC 3 based on biweekly measurements.
event. Room exhaust and outdoor air samples were taken directly from ventilation air ducts.

Air samples were collected in the morning and analyzed in the Purdue University Agricultural Air Quality Laboratory within 30 h to minimize bag losses. Samples were collected using new, 0.05 mm thick, 10 L Tedlar bags. The bags were flushed with either compressed air or nitrogen prior to sampling. Each bag was filled with 2 to 3 L of sample air and emptied manually before collecting a 6 L or larger sample. Air pumps (model 224–PCXR8, SKC, Inc., Eighty-Four, Pa.) were used to create negative pressure in air sample collection chambers (Vac–U–Chamber, SKC, Inc.), causing air to enter directly into the bags.

A total of 243 air samples were evaluated for OC, odor intensity, and hedonic tone (HT) according to methods described by Lim et al. (2001). Odor concentrations were assessed by dynamic dilution, forced-choice olfactometry (ACSCENT International Olfactometer, St. Croix Sensory, Stillwater, Minn.) with eight human subjects as panelists. Airflow rates of the olfactometer were calibrated prior to and after each evaluation session using a precision calibration device (Gilibrator–2, Sensidyne, Inc., Clearwater, Fla.).

The odor dilutions to threshold (DT) of an air sample is the dilution factor required to reduce its concentration to that which cannot be distinguished from odorless air by 50% of an odor panel (Heber et al., 2002). The panel DT was calculated as the geometric mean of individual DTs. Odor concentration (OU m⁻³) was numerically equivalent to the panel DT. Thus, the gross odor emission rate (OU s⁻¹) from a livestock building is the product of ventilation airflow rate (m³ s⁻¹) and OC (OU m⁻³) of exhaust air. All averages of odor concentrations and emission rates were reported as geometric means (CEN, 2002).

A reference odorant (40 or 58 ppm n–butanol in nitrogen) was evaluated identically to the other samples during each odor session. In accordance with the EN13725 standard (CEN, 2002), the evaluations were used to assess panelist performance by calculating odor detection concentration (ODC) of the n–butanol, which is the concentration at the detection threshold. The ODC of n–butanol for each panel was calculated with equation 1:

\[
\text{ODC}_b = \frac{1000 C_b}{\text{DT}_b} \quad (1)
\]

where

- ODCₕ = odor detection concentration of n–butanol (ppb)
- Cₕ = concentration of n–butanol gas (ppb)
- DTₕ = DT of the n–butanol sample.

For each panelist, the CEN standard requires the mean ODCₕ of the previous 10 samples to lie between 20 and 80 ppb, and the log standard deviation to be less than 2.3. Most European olfactometry laboratories follow this n–butanol performance criterion to achieve more accurate and repeatable measurements (Sneath and Clarkson, 2000).

An n–butanol sample of known concentration was analyzed for each odor session in this study. Given that one European Odor Unit (OUₑ) = 123 µg n–butanol, and 1.0 OUₑ m⁻³ = 40 ppb (CEN, 2002), a normalized OC was calculated with equation 2:

\[
\text{OC}_E = \frac{\text{DT} \times \text{ODC}_b}{40} \quad (2)
\]

where DT is the dilutions to threshold.

The odor panel also evaluated intensity of sampled air at full strength (no dilution). Odor intensity is the relative perceived psychological strength of an odor that is above its detection threshold and is independent of the knowledge of the OC (McGinley and McGinley, 2000). Intensity can only be used to describe an odor at suprathreshold concentrations or concentrations above its ODC. Odor intensity was determined according to the ASTM standard (E544–79R8) using the static reference scale method (ASTM, 1992) consisting of five concentrations of n–butanol in water (BIW) to assure a geometric interval (3x progression) between each scale step.

Hedonic tone, the degree to which an odor is subjectively perceived as pleasant or unpleasant (McGinley et al., 2000), was subjectively rated from −10 (extremely offensive) to 0 (neither pleasant nor offensive) to +10 (extremely pleasant) (Lim et al., 2001). The reported value for a sample was the average of individual panelist’s HT.

**Gas Concentrations and Temperatures**

Air was continuously drawn from the following sampling locations in each room: (1) outdoor air, (2) room inlet, (3) room exhaust, and (4) system exhaust (fig. 2). Air at each location was sampled and measured continuously for either 7.5 min (March 10 to April 30) or 12 min (May 1 to July 24) before switching to another location group. The sampling period was lengthened to 12 min on May 1 to assure equilibrium before switching to the next sampling location. Data from the first 5.5 to 6.0 min (before May 1) and 11 min (after May 1) of the gas sampling periods were ignored to allow instrument equilibration. The mean gas concentration for a sampling period was the average of data recorded after reaching equilibrium.

Hydrogen sulfide concentrations were measured with a H₂S converter (model 340, Thermal Environmental Instruments (TEI), Mansfield, Mass.) and a 0 to 20 ppm, pulsed–fluorescence SO₂ analyzer (model 45, TEI) with a sampling flow rate of 1.0 L min⁻¹. Ammonia concentrations were measured with a 0 to 200 ppm (141 mg m⁻³) chemiluminescence NH₃ analyzer (model 17C, TEI) at a sample flow rate of 0.6 L min⁻¹. A vacuum pump (model PU426, KNF Neuberger, Trenton, N.J.) was used with the NH₃ analyzer. The NH₃ analyzer was calibrated with zero and 4,300 ppb (11,434 mg m⁻³) certified calibration gases (BOC Gases, Murray Hill, N.J.). The H₂S analyzer was calibrated with zero and 27.0 ppm (19 mg m⁻³) certified calibration gases (Matheson Gas Products, Joliet, Ill.). Both analyzers were calibrated once or twice per week for a total of 18 times.

Air temperatures were measured with semiconductor transducers with stainless steel probes (model SNSR–AD592–PRB6CN, Analog Devices, Norwood, Mass.). Indoor temperatures were measured about 15 cm below the ceiling at the center of each room. Room exhaust and outdoor air temperatures were measured in the ventilation air ducts located inside the utility annex. Blocks of data collected at 0.5 Hz were averaged and stored every 60 s. Thirty minutes during each 60 min cycle, or 48 min during each 96 min cycle, were required to measure gas concentrations in each room. Thus, there were 24 and 15 sampling cycles daily prior to and after May 1, respectively, at each location.

For analysis purposes, a day was divided into 15 equal sampling intervals. Each interval had at least one data subset...
that consisted of 60 or 96 min of continuous measurement of all variables except for gas concentrations, which were multiplexed to the next sampling location every 7.5 or 12 min. Calculations of daily mean gas emission rate required measurement of airflow rate (constant throughout experiment), daily mean gas concentration, and air temperature (for converting ppm to mg m\(^{-3}\)).

Several days were characterized by incomplete data because of problems with some software and hardware components, and lightning. Only days with complete sets of valid data were used to calculate daily means, and were referred to as “complete” days. Some complete days had 1 to 2 h of missing data because of analyzer calibrations.

**DETERMINATION OF ODOR AND GAS EMISSION RATES**

Room odor (\(E_{O,R}\), OU s\(^{-1}\)) or gas (\(E_{G}\), g s\(^{-1}\)) emission rates were determined by multiplying the make–up airflow (m\(^3\) s\(^{-1}\)) by the increase in concentrations (OU m\(^{-3}\) or g m\(^{-3}\)) between outdoor air (\(C_1\)) and room exhaust air (\(C_3\)) (Lim et al., 2001) (eq. 3 and fig. 2). The geometric mean \(C_1\) for the entire growth cycle was used when the outdoor air concentration was not available for a particular sampling event.

\[
E = Q_M(C_3 - C_1)
\]

where

- \(Q_M\) = volumetric rate of make–up airflow (m\(^3\) s\(^{-1}\))
- \(C_3\) = odor concentration (OU m\(^{-3}\)) of room exhaust air
- \(C_1\) = odor concentration of outdoor air.

Weekly mean emission rates were the average of daily means, which were products of daily mean gas concentrations and constant airflow rate. Since airflow was kept constant throughout the experiment, air velocities in the exhaust duct were measured only once.

To allow comparison with other studies, odor and gas emission rates were specified to the total live mass of animals by dividing the total emission rate by the number of AU (animal unit = 500 kg of body mass). Area–specific emission rates were determined by dividing the total emission rate by the floor area (Groop Koerkamp et al., 1998; Lim et al., 2001). All mean values were calculated arithmetically, unless otherwise indicated.

**RESULTS AND DISCUSSION**

Complete and validated NH\(_3\) and H\(_2\)S concentration data were not available for empty rooms between groups of pigs. However, low concentrations observed at the beginning of growth cycles confirmed that the rooms had been thoroughly cleaned. The overall average room inventory was 25 pigs, with mean stocking density ranging from 46 to 68 kg m\(^{-2}\) (table 1). Room and exhaust air temperatures were relatively constant.

**ODOR CHARACTERISTICS AND EMISSIONS**

Data related to odor characteristics and emissions are summarized in tables 1 and 2. The \(\text{ODC}_b\) of the odor panels ranged from 44 to 250 ppb and averaged (geometric mean) 154, 60, and 83 during the first two, the third, and all three growth cycles, respectively. According to \(\text{ODC}_b\) data, the odor panels during the first two growth cycles were less sensitive than required by the EN13725 standard (CEN, 2002). All OC in this study were normalized using equation 2.

Mean OC of outdoor air samples ranged from 18 to 253 OU\(_E\) m\(^{-3}\) and averaged 58 OU\(_E\) m\(^{-3}\) during the study. Mean OC of room inlet air samples were 485, 746, 712, 82, and 530 OU\(_E\) m\(^{-3}\) for strategies S1, S7, S14, S7R, and S42R, respectively. Room inlet air contained more odor than outdoor air because it was blended with room exhaust. Mean OC of room exhaust air were 611, 1032, 956, 244, and 894 OU\(_E\) m\(^{-3}\) for S1, S7, S14, S7R, and S42R, respectively.

No air samples were collected during the second week of OC 2. The mean OC of the second week was therefore estimated by geometric interpolation between the first and third weeks. Daily mean OC\(_E\) of room exhaust air during the 6–week growth cycles (S42R) ranged from 136 to 2875 OU\(_E\) m\(^{-3}\), while daily mean OC increased from 26 to 1288 OU m\(^{-3}\). The OC\(_E\) generally increased with manure accumulation time and pig mass (fig. 4) with an apparent peak in odor release in the fourth week. However, OC generally increased until the end of the growth cycle, but only imperceptibly during the last two weeks.

Geometric mean odor intensities of room exhaust air were 2161, 2606, 2738, 2494, and 3776 ppb BIW for S1, S7, S14, S7R, and S42R, respectively (table 1). Odor intensity of S42R was significantly higher (\(P < 0.05\)) than the other growth cycles, and there were no significant differences between S1, S7, and S14. All room exhaust and blended room inlet samples were rated offensive (negative HT) by the odor panel. Mean HTs were −5.0, −5.1, −5.1, −5.9, and −6.2 for S1, S7, S14, S7R, and S42R, respectively. The HT of S42R was significantly more offensive (\(P < 0.05\)) than S1, S7, and S14, but similar to S7R. There were no significant differences between S1, S7, and S14.

Mean odor emission rates were 75, 137, 126, 11, and 111 OU\(_E\) s\(^{-1}\) (19, 33, 29, 2.6, and 25 OU\(_E\) s\(^{-1}\) AU\(^{-1}\)) for S1, S7, S14, S7R, and S42R, respectively (table 1). Odor emission rate of S1 was significantly lower (\(P < 0.05\)) than S7, S14, and S42R. There were no significant differences between S7, S14, and S42R, except between live mass specific odor emission rates for S42R and S7. Thus, it was concluded that daily flushing reduced odor emission rate by 41% and 34% (\(P < 0.05\)) as compared with the 7 d and 14 d pull–plug strategies, respectively.

While the manure accumulation time of S42R was much longer than S7 and S14, mean OC of room exhaust air and the odor emission rates were similar. The recharge in S42R apparently provided beneficial manure dilution, especially during the first 14 d.
The benefit of manure dilution was also observed by comparing S7 with S7R. The S7R strategy had the lowest pit OC and odor emission rate among all manure removal strategies (P < 0.05); however, the number of samples for S7R was low (n = 2).

Odor emission was relatively low at the beginning of the growth cycles, and was observed to increase with pig growth. A linear regression (P = 0.17) (eq. 4) of odor emission rate versus animal mass was similar to regressions reported by Amon et al. (1995) was probably due to a different olfactometry standard, the assumption of odor–free inlet air, and very poor hygiene of the building (Sneath, 2000).

\[
E_0 = 146W - 540 \quad (R^2 = 0.41)
\]  

where

\( E_0 \) = odor emission rate (OUE s⁻¹)

\( W \) = number of animal units (AU).

Higher odor emission rates toward the end of the cycle were probably due to increased manure production rate by the pigs, anaerobic activity in the pits, and manure accumulation on room surfaces.

Odor emission rates reported in the literature vary considerably (table 2). Many factors may contribute to the differences observed in previous studies, including building design, type of pigs, olfactometry standards followed, and manure strategy. Measured OC values in this study were comparable to 461 OU m⁻³ reported by Jacobson et al. (1998). However, they were much less than means reported by Amon et al. (1995), which was 2800 OU m⁻³ for a control building. The much higher OC reported by Amon et al. (1995) was probably due to a different olfactometry standard, the assumption of odor–free inlet air, and very poor hygiene of the building (Sneath, 2000).

### GAS CONCENTRATIONS AND EMISSIONS

For determination of gas concentration and emission, the numbers of complete days were 42, 42, 82, 4, 11, and 36 for strategies S1, S7, S14, S7R, S14R, and S42R, respectively (table 3). As expected, outdoor air had the lowest NH₃ and H₂S concentrations. About 1.8% and 4.3% of the time, the daily mean NH₃ and H₂S concentrations of the blended room inlet air were slightly higher than room exhaust air, respectively, indicating measurement errors or contamination of the ventilation system.

Daily means of NH₃ concentration of room exhaust air were 7.9, 12.0, 12.0, 3.8, 4.5, and 5.5 mg m⁻³ for S1, S7, S14.
S7, S14R, and S42R, respectively (table 2). The average daily mean NH₃ concentration of room exhaust air during flushing (S1) was 36% and 31% lower (P < 0.05) than the 7 d and 14 d manure accumulation times (S7 and S14), respectively. There were no significant differences between S7 and S14, with or without recharge. This implies that ammonia emission is not affected by manure depth but is primarily a surface phenomenon. Mean NH₃ concentrations of strategies with recharge were significantly lower than those without recharge. Daily mean concentrations increased from 2.7 to 6.4 mg m⁻³ during the second cycle, but the variation of daily charge. Daily mean concentrations increased from 2.7 to 6.4 mg m⁻³ during the second cycle, but the variation of daily means was relatively low (st. dev. = 1.0 mg m⁻³). Manure accumulation time and pig mass had no statistically significant effects on NH₃ concentration.

The 14 d and 7 d pull–plug strategies had similar NH₃ concentrations, with and without recharge. The 14 d accumulation resulted in 7% lower and 28% higher NH₃ concentrations than the 7 d strategies. The average daily mean room exhaust H₂S concentration for the S42R strategy was 3 to 10 times higher (P < 0.05) than other strategies. Mean H₂S concentrations of S14 and S14R were 1.6 and 2.6 times higher than S7 and S7R, respectively.

Daily mean H₂S concentrations of room exhaust air were low at the beginning of each growth cycle, and increased steadily with time. Hydrogen sulfide concentrations increased with both time and pig mass until the fifth week of growth cycle 2 (fig. 5). This steady increase was probably due to increased manure volume and associated anaerobic manure decomposition in the pit. It is not known why H₂S concentrations decreased after the fifth week. This cannot be explained based on manure characteristics because manure samples were not included in the study.

Unusually high H₂S concentrations were observed during flushing in the first week of GC 3. Starting on June 5, automatic gas sampling was temporarily overridden to allow gas analyzers to capture the full rise and fall of room exhaust concentrations triggered by the flush. A sudden momentary increase in H₂S concentration by two orders of magnitude

### Table 2. Summary of odor concentration and emission rate data reported in the literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Building Type</th>
<th>Manure Management</th>
<th>Concentration (OU m⁻³)</th>
<th>Emission Rate (OU s⁻¹ AU⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amon et al. (1995)</td>
<td>Nursery</td>
<td>Deep pit</td>
<td>2800</td>
<td>488[^a]</td>
</tr>
<tr>
<td>Lim et al. (2001)</td>
<td>Nursery</td>
<td>Deep pit</td>
<td>199</td>
<td>34</td>
</tr>
<tr>
<td>Verdoes and Ogink (1997)</td>
<td>Nursery</td>
<td>Partly slatted</td>
<td>2109</td>
<td>272</td>
</tr>
<tr>
<td>Zhu et al. (2000)</td>
<td>Nursery</td>
<td>Deep pit</td>
<td>765</td>
<td>149</td>
</tr>
<tr>
<td>Heber et al. (1998)</td>
<td>Finishing</td>
<td>Deep pit</td>
<td>142</td>
<td>36</td>
</tr>
<tr>
<td>This research</td>
<td>Finishing</td>
<td>7 d storage[^b]</td>
<td>244[^c]</td>
<td>2.6[^c]</td>
</tr>
<tr>
<td>This research</td>
<td>Finishing</td>
<td>6 week storage[^b]</td>
<td>48[^c]</td>
<td>25[^c]</td>
</tr>
<tr>
<td>This research</td>
<td>Finishing</td>
<td>Daily flush</td>
<td>61[^c]</td>
<td>19[^e]</td>
</tr>
<tr>
<td>This research</td>
<td>Finishing</td>
<td>7 d storage</td>
<td>103[^c]</td>
<td>33[^c]</td>
</tr>
<tr>
<td>This research</td>
<td>Finishing</td>
<td>14 d storage</td>
<td>95[^c]</td>
<td>29[^c]</td>
</tr>
</tbody>
</table>

[^a]: Inlet concentration was unmeasured and assumed to be zero.
[^b]: With recharge.
[^c]: Normalized odor concentration (OU m⁻³).

### Table 3. Mean (±95% CI) NH₃ and H₂S concentrations and emission rates.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Manure Removal Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1[^a]</td>
</tr>
<tr>
<td>Duration (d)</td>
<td>42</td>
</tr>
<tr>
<td>Ammonia concentrations (mg m⁻³)</td>
<td></td>
</tr>
<tr>
<td>Outdoor air</td>
<td>0.6 ±0.04</td>
</tr>
<tr>
<td>Room inlet</td>
<td>5.8 ±0.5</td>
</tr>
<tr>
<td>System exhaust</td>
<td>5.6 ±1.0</td>
</tr>
<tr>
<td>Room exhaust</td>
<td>9.5 ±0.7</td>
</tr>
<tr>
<td>Hydrogen sulfide concentrations (µg m⁻³)</td>
<td></td>
</tr>
<tr>
<td>Outdoor air</td>
<td>2.4 ±1.8</td>
</tr>
<tr>
<td>Room inlet</td>
<td>45 ±15</td>
</tr>
<tr>
<td>System exhaust</td>
<td>42 ±15</td>
</tr>
<tr>
<td>Room exhaust</td>
<td>75 ±24</td>
</tr>
<tr>
<td>Emission rates (g d⁻¹)[^e]</td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>56 ±12 a</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.5 ±0.2 a</td>
</tr>
<tr>
<td>Emission rates (g d⁻¹ AU⁻¹)[^e]</td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>14 ±3 a</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.11 ±0.04 a</td>
</tr>
</tbody>
</table>

[^a]: Does not include 3 h of data from start of flushing.
[^b]: Does not include data during dedicated monitoring of room exhaust air.
[^c]: Includes dedicated monitoring during flushing.
[^d]: Assumed equal to room exhaust, which contained dedicated monitoring and interpolated data.
[^e]: Within–row means followed by same letter are not significantly different at P < 0.05.
was observed, followed by a 60 to 90 min decay to preflushing concentrations of less than 100 ppb (fig. 6). During dedicated monitoring, the analyzer’s full scale of 20 ppm (28 mg m\(^{-3}\)) was exceeded once out of nine flushes in room A and three out of eleven flushes in room B. Excluding these data sets with unknown maximum values, the mean peak H\(_2\)S concentrations of room exhaust during flushing were 13,977 and 7238 μg m\(^{-3}\) in rooms A and B, respectively.

Only days with dedicated monitoring of room exhaust concentrations were used to calculate S1 daily means of H\(_2\)S concentrations. However, since a daily mean was the average of fifteen, 90 min means, the impact of the extra readings taken by this dedicated monitoring was inconsistent because of the emission burst and varying durations of dedicated monitoring periods. Therefore, a linear interpolation was performed to estimate values for each minute between valid measurements so that a weighted daily mean could be calculated to reduce bias caused by the extended monitoring during flushing. Since dedicated monitoring of system exhaust during flushing was not conducted, room exhaust concentrations were assumed equal to system exhaust concentrations for emission calculations. When flushing-induced emission bursts were included, mean H\(_2\)S concentrations of room exhaust air during S1 were 6% and 40% lower than S7 and S14, respectively. When the 3 h of data following flushing were excluded, the S1 mean H\(_2\)S concentration of room exhaust air was 49% and 67% lower (P < 0.05) than S7 and S14, respectively.

In this study, average daily mean NH\(_3\) emission rates were 15, 27, and 25 g d\(^{-1}\) AU\(^{-1}\) for 1, 7, and 14 d manure accumulation times (S1, S7, and S14) without pit recharge and 10, 12, and 11 g d\(^{-1}\) AU\(^{-1}\) for 7, 14, and 42 d manure accumulation times (S7R, S14R, and S42R) with pit recharge, respectively (table 2). The average daily mean NH\(_3\) emission rates of strategies with pit recharge were 51% and 62% lower (P < 0.05) than corresponding storage times without recharge. Ammonia emission rates did not significantly increase with storage times beyond 7 d. The average daily mean room NH\(_3\) emission rate of S1 was 45% and 42% lower (P < 0.05) than the static pit strategies S7 and S14, respectively. Recharge apparently provided a dilution effect that reduced NH\(_3\) emission since the mean emission rates of S7R, S14R, and even S42R were significantly lower (P < 0.05) than S7 and S14.

Average daily mean H\(_2\)S emission rates clearly increased with storage time. Average daily mean H\(_2\)S emission rates were 0.11, 0.27, and 0.41 g d\(^{-1}\) AU\(^{-1}\) for 1, 7, and 14 d manure storage times (S1, S7, and S14) without pit recharge, and 0.16, 0.34, and 1.42 g d\(^{-1}\) AU\(^{-1}\) for 7, 14, and 42 d manure storage times (S7R, S14R, and S42R) with pit recharge, respectively. The mean H\(_2\)S emission rate of daily flushing S1 was 58% and 73% lower (P < 0.05) than static pits S7 and S14, respectively. However, when flushing-induced emission bursts were included, the mean H\(_2\)S emission rate of S1 was 49% and 3% higher (P > 0.05) than S7 and S14, respectively.

The average daily mean building NH\(_3\) emission rate measured in finishing buildings by Ni et al. (2000b) was 13 times higher than the S42R strategy. In the same finishing buildings, Ni et al. (2002) reported a mean H\(_2\)S emission rate of 6.3 g d\(^{-1}\) AU\(^{-1}\), which was 4.4 times greater than the S42R strategy. The difference may be attributed to the higher temperatures and ventilation rates in the summertime tests of commercial swine buildings. The manure depths and storage times in these buildings were much greater, and the floors consisted of concrete slats instead of wire mesh.
DISCUSSION

The peak of $OC_E$ calculated in the fourth week of GC 2 may have been due to OC normalization based on $ODC_b$, which decreased significantly after week 4 (fig. 4) because the original OC values of weeks 5 and 6 were slightly larger than week 4. Research is needed to confirm the validity of normalization when $ODC_b$ values are up to five times greater than the target $ODC_b$ of 40 ppb.

However, $H_2S$ concentration exhibited a pattern similar to $OC_E$, as they both increased sharply during the first few weeks (figs. 4 and 5). The sharp increase of $H_2S$ from week 2 to weeks 4 or 5 followed by a gradual decrease until week 6 might be explained in terms of microbial kinetics. It appears that ample substrate was available to support maximum microbial growth until the fifth week, when substrate availability became a limiting factor. An increase in pH would also explain the decrease in $H_2S$ but, unfortunately, manure characteristics were not measured.

The $NH_3$ and $H_2S$ concentrations of room exhaust air appeared to be influenced by the type of manure removal strategy during the third growth cycle. Mean $NH_3$ and $H_2S$ concentrations seemed to increase with time (except for $NH_3$ during the second week of storage). During the 14 d static pit trials, ammonia concentrations peaked at 14 to 15 mg m$^{-3}$ on day 3 of manure accumulation during two trials and on day 8 during another trial. Following this peak, the concentration steadily decreased to a relatively constant level by day 14. The $NH_3$ peaks that occurred during growth cycle 3 without pit recharge did not occur during growth cycle 2 with pit recharge. Thus, it appears that the practice of recharging the pit following each pit draining removed the $NH_3$ peak.

Concentrations of $NH_3$ and $H_2S$ appeared to be inversely proportional to each other during GC 3. The peaks of $NH_3$ concentration measured during the first week ($S1$ and $S7$) were probably due to greater $NH_3$ emitted from fresh manure than aged manure. The reverse was true for $H_2S$, which increased continuously with time.

The longer manure accumulation time of 3.5 weeks at the end of GC 3 showed that both $NH_3$ and $H_2S$ stabilized and were comparable with the 6-week growth cycle (fig. 5). The data suggests that longer manure storage times (thus greater manure depth and older manure) promote $H_2S$ emission without affecting $NH_3$ emission.

The burst of $H_2S$ during flushing with lagoon effluent is newly discovered, since there appears to be no similar data reported in the literature. According to the Occupational Safety and Health Administration, the permissible exposure level (PEL) for general industries is 20 ppm (ceiling) with an allowable single 10−min exposure of 50 ppm (OSHA, 2001). Using fresh water for flushing the pits would eliminate the allowable single 10−min exposure of 50 ppm (OSHA, 2001). Using fresh water for flushing the pits would eliminate the permissible exposure level (PEL) for general industries is 20 ppm (ceiling) with an allowable single 10−min exposure of 50 ppm (OSHA, 2001). Using fresh water for flushing the pits would eliminate the

On the other hand, the turbulence of the effluent is greatest as it enters the pits and rapidly decreases as it flows through the gutter. Therefore, burst emissions created by flushing in a large 1000−pig building are not expected to influence the daily means as much as they did in these relatively small rooms. Ammonia concentration was unaffected by flushing activity, suggesting that recirculating lagoon effluent does not emit significant amounts of $NH_3$, which is emitted primarily by fresh manure.

The observed dynamic nature of $H_2S$ and $NH_3$ concentrations following flushing was most probably due to differences in chemical and biological processes in the generation and release of these manure gases. Emission rates of $NH_3$ and $H_2S$ from swine manure were measured from 140 L manure reactors (Ni et al., 2001). Release of $NH_3$ under steady−state conditions was quite consistent, even during manure disturbances. However, manure disturbances briefly increased $H_2S$ emissions by a factor of 40 or more. Ammonia release from manure occurs by mass transfer across the liquid−gas interface, which is influenced by concentration profiles, air velocity, and temperature, whereas $H_2S$ emission is dominated by gas bubble releases (Ni et al., 2001). Flushing the pits enhanced gas bubble release created by turbulent disturbance of lagoon effluent, resulting in the $H_2S$ concentration peaks observed in this study.

An increase in both daily means and flushing−induced peaks of $H_2S$ emission rates were observed with time. The mean $H_2S$ concentration during week 4 of GC 3 was 102 µg m$^{-3}$ (mean of last 5 d) and increased to 193 µg m$^{-3}$ (mean of last 6 d) during week 7. It is hypothesized that the mean concentration of week 1 was much lower than weeks 4 and 7 because of cleaner rooms and smaller pigs. Unfortunately, the mean $H_2S$ emission rate for week 1 was incalculable without dedicated monitoring. Therefore, the mean $H_2S$ emission rate of 0.40 g d$^{-1}$ AU$^{-1}$ for $S1$ (included flushing−induced emission bursts) was probably an overestimate without week 1 data. More research is needed to determine the effects of flushing on $H_2S$ emissions from full−size commercial buildings.

CONCLUSIONS

The following conclusions were drawn from this study:

- Odor concentration, normalized odor concentration, intensity, and hedonic tone of room exhaust air ranged from 47 to 1510 OU m$^{-3}$, 240 to 2875 OU$_E$ m$^{-3}$ (OU$_E$ = European odor unit equivalent to 123 µg m$^{-3}$ n−butanol), 369 to 7744 ppm BIW, and −7.9 to −2.7, and averaged 493, 879, 2732, and −5.3, respectively.
- Average daily mean $NH_3$ and $H_2S$ concentrations of room exhaust air ranged from 2.7 to 15.0 mg m$^{-3}$ and 9 to 1321 µg m$^{-3}$, and averaged 8.4 mg m$^{-3}$ and 439 µg m$^{-3}$, respectively.
- Pit recharge reduced $NH_3$ emission by 51% to 62% ($P < 0.05$). Daily flushing of pits with secondary lagoon effluent resulted in 45% and 42% ($P < 0.05$) lower $NH_3$ emission than the 7 d and 14 d manure accumulation cycles, respectively.
- Pit recharge reduced $H_2S$ emissions by 18% to 40% ($P < 0.05$), and daily flushing resulted in 58% and 73% less ($P < 0.05$) $H_2S$ emission than the 7 d and 14 d cycles. However, the advantage of more frequent manure removal was offset by burst emissions during flushing.
- Daily flushing of pits with secondary lagoon effluent created bursts of $H_2S$ with peak concentrations ranging from 7,171 µg m$^{-3}$ to the analyzer detection limit of 28,235 µg m$^{-3}$.
• Draining static pits more frequently significantly reduced H₂S emission rates. Daily flushing reduced odor emission rate by 41% and 34% (P < 0.05) as compared with the 7 d and 14 d storage times, respectively. Weekly pit draining had 35% and 53% less H₂S emission as compared with the 14 d pull–plug strategies with and without pit recharge, respectively. Biweekly pit draining had 81% less H₂S emission as compared with emptying the pits every six weeks.

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REFERENCES


