Effects of Room Ozonation on Air Quality and Pig Performance


Abstract: Reducing odor emissions from swine farms to avoid complaints about odor nuisance is a major issue. Ozonation has been used to reduce odor in swine buildings, but little research exists on its benefits. A swine-finishing building was divided into two identical rooms and two treatments, ozonation and the control, were applied in a cross-over design. The treatments were switched between rooms every three weeks. The overall experimental period was 12 weeks, during which there were four trials. Pig growth performance, dust mass and size concentration, odor intensity, total sulfur compounds, hydrogen sulfide concentration, ammonia concentration, and total heterotrophic bacterial counts were measured and analyzed during the test period. Sulfur-containing compounds detected included dimethyldisulfide, dimethylsulfide (methanethiol), and dimethyltrisulfide. Ozone application to a swine building at the maximum safe concentration of 0.1 ppm did not have any statistically significant effects on dust mass concentration, odor concentration and emission rate, sulfur compound concentrations, and bacteria counts. However, it did increase ammonia concentration and decrease pig average daily gain. The ozonation effects on hydrogen sulfide concentration could not be evaluated by the gas tube method used during this study.

Keywords: Bacteria, Dust emission, Gas emission, Odor concentration, Particulate matter, Pig growth.

Over the past decade, the livestock industry has developed toward large and intensive production facilities. Air pollutants such as ammonia (NH₃), hydrogen sulfide (H₂S), particulate matter (PM₁₀, PM₂.₅), odor, and pathogens emitted by animal production units represent risks to the health and well-being of animals, workers, and neighboring inhabitants, and to the global environment (NRC, 2003). The reduction of air emissions from swine farms to improve working conditions inside the barn, and the minimization of nuisance complaints about odor are currently priority needs of the industry.

Ozone is an unstable and strong oxidizing gas, which can oxidize aldehyde, ethers, alcohols, and hydrocarbons (Reynolds et al., 1989). In addition to the oxidation capability of ozone, high levels of ozone can lyse bacteria (Block, 1982), thus reducing the number of pathogenic and odor-producing microorganisms. Because of its high oxidation potential, ozone has been successfully used to disinfect and deodorize air and water. A number of commercially available ozone generators are currently being used to clean air in residential and office buildings. Recently, this technology has been applied to reduce odor from swine manure slurry (Watkins et al., 1997; Wu et al., 1999). Priem (1977) studied ozonation effects on ammonia (NH₃) removal in a swine building and found that ozone reduced ammonia levels by about 50% under winter ventilation conditions. However, the ozone concentration occasionally reached 0.2 ppm during Priem’s study, exceeding the current U.S. Food and Drug Administration (FDA) and Occupational Safety and Health Administration (OSHA) limits for ozone exposure. Based on available research, the FDA has set 0.05 ppm as the safe level for continual human exposure (FDA, 1998), and OSHA has set 0.1 ppm as a safety threshold for a maximum 8 h exposure (OSHA, 1998). Limited studies have been conducted where ozone is used within permissible limits (<0.1 ppm) to clean air in animal facilities. Recent work has shown that ozone concentrations between 0 and 0.15 ppm concentration removed 58% of ammonia and 60% of dust mass in a swine building (Keener et al., 1999). A comprehensive evaluation of ozonation effects is needed before ozone can be effectively used for odor and dust control in livestock buildings.

The objective of this study was to determine the effectiveness of ozonation at a concentration of 0.1 ppm for reducing ammonia, hydrogen sulfide, sulfur compound, odor, dust, and bacterial concentrations in a swine finishing building and its impact on pig performance.
MATERIALS AND METHODS

EXPERIMENTAL PLAN
This study was carried out as a cross-over design with two treatments. A swine finishing building (Building 914, Moorman Research Farm, University of Illinois, Urbana-Champaign, Ill.) was divided into two identical rooms with solid partitions between the rooms and respective slurry pits. Each room had identical environmental control systems and floor layouts.

The experimental units were the rooms; during alternate periods one of the rooms received the experimental treatment (ozonation), and the other served as the control room. Treatments were designated as “ozonation” and “control.” The cross-over design ensured that the two treatments were carried out during the same time period, and thus period effects were eliminated from comparisons between treatments. Each of the experimental units eventually received both treatments.

There were four trials in this study, and each trial included one week for acclimatization and two weeks for ozonation and sample collection. The ozonation treatment was alternated between the rooms between successive trials so that each room was ozonated twice during the 12-week study. Pigs remained in their assigned rooms throughout the experiment.

A total of 160 pigs of 50.5 ± 4.41 kg live weight were randomly allocated to the two rooms (80 pigs randomly allocated across pens in each room on the basis of weight, gender, and genotype). Each room had 10 experimental pens, each pen accommodating 8 pigs for a space allowance of 1.2 m² per pig for the duration of the study.

Each pen was equipped with one 2-hole feeder and a nipple drinker. Pigs were offered standard diets that met or exceeded recommended nutrient requirements of swine (NRC, 1998). The diets contained 14.16% crude protein for 50 to 80 kg pigs and 13.45% crude protein for 80 to 120 kg pigs. The open-top feeders were filled by an automated feeding system. Feeders were checked and adjusted to maintain a constant feed flow, and feed was added only three times per week to minimize the frequency of worker entries. The concrete floors were fully slatted. The rooms had solid partitions between the rooms and respective slurry pits.

Champaign, Ill.) was divided into two identical rooms with treatments. A swine finishing building (Building 914, Farmington Hills, Mich.) located just outside the building (fig. 1). Ozone was distributed through a 10 cm aluminum tube connecting the ozone generator output to two duct fans and plastic inflatable ducts inside the building. Fresh air was supplied to the control room through an identical 10 cm tube. Both rooms had identical ducts and fans, which continuously operated to provide similar air distribution patterns. The two distribution ducts and fans were suspended in parallel from the ceiling of each room. The ductwork was approximately 2.3 m above the floor.

The distribution equipment consisted of a pair of 25.4 cm diameter duct fans attached to a pair of 25.4 cm inflatable poly ducts with 2.54 cm diameter holes spaced 30 cm apart along the length of the ducts. The holes were placed at the 3 and 9 o’clock positions around the duct. The duct fans drew in ozonated or fresh air from the 10 cm supply ducts and mixed it with room air, then distributed the mixture along the length of the room through the ducts. Each duct fan operated at full power continuously with an airflow capacity of 1530 m³ h⁻¹ at 5 to 13 Pa static pressure.

The ozone sensor supplied with the generator was used to monitor the operation of the ozone generator. The ozone sensor had green, orange, and red LEDs signifying that the ozone concentration of the indoor air was below, slightly above, and beyond the 0.1 ppm OSHA safe limit, respectively. When the red LED was on, the ozone generator would be shut off. The sensor was suspended in the center of the ozone treatment room approximately 1.5 m above the floor. The ozone generator had 12 ultraviolet bulbs that were each controlled by manual switches. The level of ozone supply was adjusted manually according to the ozone sensor lights by turning bulbs on and off. The ozone generator was adjusted to maintain ozone levels that were close to but not exceeding 0.1 ppm. In case power to the ventilation fans and sensor failed, the ozone generator would also be turned off because the generator was wired in series with the continuous 25.4 cm ventilation fan.

Ozone concentrations in the test room were also verified for several consecutive days at the beginning of the test with an EPA-approved Dasibi (model 1003) ozone analyzer to verify the performance of the ozone distribution system. The Dasibi analyzer had a specified accuracy of 1 ppb. Ozone concentrations within the room were monitored during the first day of trial 1 at points A, B, and C, as shown in figure 1. A total of 20 readings were taken throughout the day at a height of 1.5 m, which represents human breathing level. The readings were taken every 20 min between 9:00 a.m. to 4:00 p.m. The average ozone concentrations and standard deviations were 0.114 ± 0.006, 0.093 ± 0.007, and 0.064 ± 0.005 ppm at points A, B, and C, respectively. Ozone concentrations were also measured for the first 7 days of trial 2 in the center of the room at a height of 1.5 m. Ten readings were taken over each of the days. The average ozone concentration for that period was 0.098 ± 0.021 ppm.
Power consumption of the ozonation system is also important and was monitored over the entire study period. Energy consumption of the ozone generator was about 2.8 kWh per day, and the cost was about $0.26 per day based on a cost of $0.09 per kWh. Energy consumption of the duct fans was about 8 kWh per day, and the cost was about $0.72 per day. Therefore, the energy consumption of the ozonation system for one room was about 10.8 kWh per day, and the cost was about $0.98 per day.

**SAMPLING METHODS AND STANDARD PROCEDURES**

**Dust Concentration**

Dust sampling was conducted on Mondays and Thursdays. A total suspended particulate (TSP) sampling apparatus was developed to measure the total particle mass concentration. This apparatus consisted of three samplers, with each sampler consisting of a 37 mm diameter glass-fiber filter (Millipore, 0.7 μm pore size), a 37 mm diameter filter holder (Millipore Aerosol Analysis Monitor), a critical venturi orifice, 1.25 cm I.D. plastic tubing, and a vacuum pump (Gast, model 1023-V131Q-G608X). The critical venturi orifice controlled the flow rate at 19.8 ± 0.2 L min⁻¹ for each filter. The critical venturi orifices were installed in the tube downstream of each sampler. Three samplers were installed in each room at locations that were spaced 0.13 m apart at a height 1.2 m above the floor and a distance of 1 m from the 25.4 cm fan (fig. 2). The samplers were facing upstream of the exhaust air.

The specific sampling locations were determined so that the room air velocity at the sampler inlets was equal to the sampler inlet air speed of 0.3 m s⁻¹ for isokineticity. According to air sampling criteria for negligible sampling error due to particle inertia (Hinds, 1999), the maximum air velocity is 0.3 m s⁻¹ for 30 μm. This means that the sampling errors caused by particle inertia are negligible if the air velocity is less than 0.3 m s⁻¹ for 30 μm particles. Since the air velocity at the sampling points in front of the fans was 0.3 m s⁻¹, the sampling efficiency was close to 100% for particle less than 30 μm. It was likely that the sampling efficiency was less than 100% for particles larger than 30 μm, but the sampling error was considered to be negligible because there were very few particles larger than 30 μm in the upper level of the swine building. This fan was the minimum ventilation fan and operated constantly. An hour meter was connected to each 61 cm temperature-controlled fan to calculate the total airflow during sampling. Each sample was collected for 24 h, to account for the changing dust levels over the course of a day, and a total of 28.8 m³ of air was sampled through each filter. The filters, both before and after sampling, were desiccated at 24°C for 24 h before weighing.

![Figure 1. Schematic of the two experimental rooms and the ozone distribution system.](image)

![Figure 2. Location of dust sampler.](image)
Ammonia and Hydrogen Sulfide Concentration

Ammonia and hydrogen sulfide concentrations were measured twice per week on Monday and Thursday of the test weeks. The gas concentrations were measured at the air inlet and exhaust areas of each room about 0.5 m above the floor with colorimetric sampling tubes (105SC, 120SD, and 182U, Matheson-Kitagawa, Montgomeryville, Pa.) using a handheld pump (model 8014-400A, Matheson-Kitagawa). At each sampling location, three colorimetric tubes were used for triplicate analysis of the gas sampling. According to the manufacturer’s specification, the accuracy of the colorimetric gas tubes is about 15% of the reading values, especially for low concentration values.

Sulfur Concentration

A gas chromatograph with a flame ionization detector as used to measure the concentration of sulfur compounds in the swine building air. Sulfur concentrations were sampled twice per week on each Monday and Thursday of the test weeks. The air was sampled using a volatile organic compounds trap (Style No. 6, Tekmar, Mason, Ohio), which consisted of a 0.3 cm diameter, 31 cm long stainless steel tube packed with adsorbent material (OV-1/Tenax/silica gel). During sampling, the trap was connected to a vacuum pump operated at a specified flow rate and approximately 0.25 L of air was sampled. The sampling locations inside the building were at the exhaust fan inlet and at the building air inlet.

Air was collected in the sulfur collection apparatus through a 0.3 cm Teflon tube into the volatile organic compounds trap. To avoid pulling dust into the trap, a 37 mm diameter filter holder (Aerosol Analysis Monitor, Millipore, Billerica, Mass.) with a 37 mm diameter glass fiber filter (Millipore, 0.3 μm pore size) was attached to the sampling end of the Teflon tube. The Teflon tube was connected to the trap and a vacuum pump. A vacuum pressure gauge and a flowmeter were used to determine the effect of ozonation on bacterial counts, rather than to quantify bacteria concentration, dust size, or dust mass concentration. Therefore, the air sampling method was modified, as the design flow rate of 28.3 L min⁻¹ was too high for bacteria counting due to the high dust and bacteria concentrations in the exhaust air, which would overload the Petri dishes of all stages of the sampler. A smaller pump was therefore used to sample air with a lower flow rate of 13.5 L min⁻¹ for collection of bacteria. The first and second stages were used to remove larger particles in the sampled air, and the Petri dish on the third stage was evaluated.

The sampler and Petri dishes were sterilized with 70% alcohol solution and dried before sampling. The sampling pump was operated for 2.0 min, and then the Petri dishes were removed from the air sampler and incubated for 24 h at 30°C (Buttner et al., 1997) in the UIUC Animal Sciences Microbiology Laboratory. Coliform counts were measured from colonies growing on the nutrient agar media (BACTO Microbiology Laboratory). Coliform counts were measured once per week using two Anderson Viable Samplers (1 ACFM Viable Particle Sampler, Andersen Instruments, Smyrna, Ga.). The air samplers were installed 1 m in front of the 25.4 cm minimum ventilation fans. The Andersen sampler consisted of a 28.3 L min⁻¹ air pump and six orifice stages along with specially designed Petri dishes at each stage level. The air samples were collected to determine the effect of ozonation on bacterial counts, rather than to quantify bacteria concentration, dust size, or dust mass concentration. Therefore, the air sampling method was modified, as the design flow rate of 28.3 L min⁻¹ was too high for bacteria counting due to the high dust and bacteria concentrations in the exhaust air, which would overload the Petri dishes of all stages of the sampler. A smaller pump was therefore used to sample air with a lower flow rate of 13.5 L min⁻¹ for collection of bacteria. The first and second stages were used to remove larger particles in the sampled air, and the Petri dish on the third stage was evaluated.

Animal Performance

Pigs in each room were weighed individually at the beginning and end of each 3-week treatment period. Average pig mass gain and average daily gain (ADG) of the pigs in each room as a group were calculated and recorded. Feed additions were recorded, and feeders were weighed at the same time as the pigs were weighed. Average daily feed intake (ADFI) was calculated from feed consumption of the pigs in each room during each trial without consideration of feed wastage. Feed efficiency was calculated as the ratio of the average weight gain and feed intake (G/F).
Ozone effects due to previous treatments were not significantly different among trials (P < 0.0001). The statistical analysis showed that ozonation treatment at 0.1 ppm mean concentration did not have a significant effect on dust mass concentration difference between the treatment and control rooms alternated with treatment sequence, trial, and the carryover effect of the previous treatment. Room nested within sequence was included as a random term. Analysis of variance (ANOVA) was selected as the main data analysis method. After four experimental trials, a total of 40 sets of air quality data and 8 sets of pig performance data were obtained. Table 1 shows sources of variation and degrees of freedom for the two-way ANOVA. The statistical significance level of 0.05 was used to judge whether the statistical hypothesis (no treatment effects) should be rejected.

**Statistical Data Analysis**

The purpose of the data analysis was to evaluate the effects of ozonation on air quality and pig performance by comparing an ozonated room with a non-ozonated room. General statistical data analysis was conducted initially to calculate means and standard deviations. Data were analyzed as a cross-over design using the PROC MIXED procedure of SAS, and the model included the effects of treatment, treatment sequence, trial, and the carryover effect of the previous treatment. Room nested within sequence was included as a random term. Analysis of variance (ANOVA) was selected as the main data analysis method. After four experimental trials, a total of 40 sets of air quality data and 8 sets of pig performance data were obtained. Table 1 shows sources of variation and degrees of freedom for the two-way ANOVA. The statistical significance level of 0.05 was used to judge whether the statistical hypothesis (no treatment effects) should be rejected.

**RESULTS AND DISCUSSION**

**Effect of Ozonation on Dust Concentration**

The raw dust concentrations in the treatment and control rooms for four consecutive trials are plotted in figure 3. The raw data showed that dust mass concentration difference between the treatment and control rooms alternated with trial. However, the statistical analysis showed that ozonation treatment at 0.1 ppm mean concentration did not have a statistically significant effect on dust mass concentration (P = 0.81). The analysis showed that the dust concentrations were significantly different among trials (P < 0.0001). The carryover effects due to previous treatments were not significant (P = 0.75). The estimated least squares means were 6.596 ±0.684 and 6.292 ±0.684 mg m⁻³ for the control room and ozone room, respectively. This finding agrees with a report of the U.S. EPA, which stated, “ozone does not remove particles (e.g., dust and pollen) from the air” (EPA, 1998).

During the first trial, the weather was cold and the rooms were under minimum ventilation conditions. Thus, the dust mass concentrations were higher during this first trial than the following trials. The floor was also drier in the first trial due to heating and low relative humidity compared with the other three trials. Dust concentrations in the test rooms were found to be higher than in typical commercial swine buildings. This may be due to differences in management practices and facility type.

**Effect of Ozonation on Ammonia and Hydrogen Sulfide Concentrations**

A plot of raw ammonia concentrations for trials 1 to 4 is shown in figure 4. The ammonia concentration varied between trials, and the ozonation room tended to alternate between higher and lower concentrations of ammonia as compared with the control room. The statistical analysis showed that the ozonation treatment had significantly higher ammonia concentration (P = 0.04). The least squares means were 4.7 ±1.6 and 10.8 ±1.6 ppm for the control room and ozonation room, respectively. In addition, the carryover effects on ammonia concentrations were significant (P = 0.02), and the ammonia concentrations were significant different among trials (P = 0.01).

Hydrogen sulfide remained mostly undetectable. On April 3 (trial 3), hydrogen sulfide was detected at 1 ppm in both rooms, and on April 4 (trial 4) it was detected in the ozonated room at about 0.5 ppm. Insufficient data could not lead to any conclusion on the ozonation effect on hydrogen sulfide concentration.

Other studies have shown that it is possible for ozone to oxidize ammonia and hydrogen sulfide in air, but in all circumstances the ozone was applied to an enclosed duct system or retention chamber at a concentration of at least an order of magnitude greater than the OSHA 8 h exposure limit of 0.1 ppm (Nebel et al., 1975; Gottschling and Nebel, 1975). Gottschling and Nebel (1975) indicated that ammonia in air from a compost processing plant can be deodorized with 5.5 ppm ozone, while Nebel and Forde (1976) stated that ozone is not effective in deodorizing ammonia. In water, ozone is able to oxidize ammonia in sewage but only at a pH greater than 9 and a gas stream of almost 6% ozone (Singer and Zilli, 1975).

**Table 1. Sources of variation and degrees of freedom of the ANOVA for the cross-over design.**

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**Figure 3. Effect of ozonation on dust mass concentration.**

**Figure 4. Effect of ozonation on ammonia concentration.**
**Effect of Ozonation on Sulfur Concentration**

Figure 5 shows sulfur concentration peak areas for trials 1 to 4. Trial 1 values may be biased because the samples were taken without first purging “old” air from the 15 m sampling tubes. The sampling protocol for trials 2 to 4 was modified to condition the tubes with the sample air through the tubes for a period of time before sampling with the traps. Trial 2 indicated higher sulfur emissions in the ozonation room, while trial 3 indicated lower emissions. Trial 4 appears to have no distinct trend. It is not clear why the sulfur increased in trials 2 and 3 before plummeting back down to near-zero concentrations. Airflow patterns do not explain this, nor do weather conditions. Trials 1 to 3 show an increasing trend in peak area per mL concentrations, and then the sulfur concentration decreased in the fourth trial. This drop could be caused by the building cleanliness before the start of each trial. The manure build up on the floors in trials 2 and 3 may have caused higher gaseous sulfur concentrations. The statistical analysis showed that ozonation treatment had no statistically significant effects (P = 0.25) on sulfur concentration. The least squares means of the sulfur concentration in the control and ozonation room were 16,549 ± 55,552 and 135,278 ± 55,552, respectively. The high standard errors may contribute to the non-significant treatment effects. The carryover effects were not significant (P = 0.11).

**Effect of Ozonation on Odor Concentration and Emission Rate**

The odor concentrations (OU m⁻³) and emission rates (OU s⁻¹) measurement during trials 3 and 4 are presented in Table 2. During trials 1 and 2, odor measurements were not conducted. Odor concentration is expressed as odor units per cubic meter of air and the odor emission rate is calculated by multiplying the odor concentration by the ventilation airflow rate in the room. P1 and P2 in Table 2 represent two sampling locations near the exhaust fans of the test rooms.

The statistical analysis of the trial 3 and 4 data showed that there were no significant ozonation effects (P = 0.25) on odor concentration. Odor concentrations were statistically different among trials (P = 0.01). Trial 4 had significantly lower odor concentrations compared to trial 3. This might be due to the increased ventilation rate. In addition, the statistical analysis showed that there was no significant ozonation effects on odor emission rates (P = 0.07). Odor emission rates were not statistically different in trials 3 and 4 (P = 0.2).

ASHRAE (1989) stated that while ozone can oxidize odorous compounds in water, the concentrations needed to do so in air would be well over the safety limit for occupants of the treated space.

**Effect of Ozonation on Total Coliform Bacterial Count**

From the raw data, no distinct trends in total coliform bacteria count were observed overall (fig. 6). Statistically, the ozonation treatment did not have any significant effects on bacteria counts (P = 0.74). The least squares means were 95 ± 35 and 74 ± 35 for the control room and ozonation room, respectively. The bacteria counts during the experimental trials were not statistically different from each other (P = 0.1). The carryover effects of previous treatments were not statistically significant either (P = 0.89).

An experiment conducted by Dyas et al. (1983) showed that in a small space, 0.3 to 0.9 ppm ozone over 4 h could effectively reduce bacteria counts. These concentrations, however, were above the OSHA 8 h exposure limit. Jordan and Carlson (1913) and Sawyer et al. (1913) stated that the use of ozone in breathable air for hygienic purposes should not even be considered because of the high concentrations necessary for bactericidal effects.

**Effect of Ozonation on Animal Growth Performance**

Table 3 shows the average daily gain, feed intake and feed efficiency in finishing pigs. From the raw data, no distinct trends in total coliform bacteria count were observed overall (fig. 6). Overall average daily gain of pigs in the control rooms was higher than that of the pigs in the ozonation rooms (P = 0.03). The least squares means of the average weight daily gain of pigs were 0.89 ± 0.003 and

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Table 3. Effects of ozonation on growth rate, feed intake, and feed efficiency in finishing pigs.

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Table 4. Effects of ozonation on growth rate, feed intake, and feed efficiency in finishing pigs.

- Average daily gain (kg)
- Average daily feed intake (kg)
- Gain/feed (kg kg⁻¹)

Table 5. Effects of ozonation on growth rate, feed intake, and feed efficiency in finishing pigs.

**Table 2. Odor concentration and emission rate data for trials 3 and 4.**

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Trial 4
0.76 ± 0.003 kg in the control room and ozonation room, respectively. This means that the ozonation treatment had negative effects on the weight gain of pigs. In addition, the daily feed intake (P = 0.9) and gain over feed ratio (P = 0.25) did not statistically differ between the two treatments. The carryover effects were not statistically significant either.

CONCLUSIONS
Ozone application to a swine building at the maximum OSHA safe concentration of 0.1 ppm did not have any statistically significant effects on dust mass concentrations, odor concentrations and emission rates, sulfur compound concentrations, and bacteria counts. However, it did result in higher ammonia concentrations and lesser pig average daily gain.

Hydrogen sulfide remained mostly undetectable with the Matheson-Kitagawa hydrogen sulfide detector tubes. Therefore, the ozonation effects on hydrogen sulfide release could not be evaluated by the gas tube method used during this study.

Sampling and measurement of volatile organic compound and sulfur compounds in swine buildings are still challenging. Further research on quantification of ozonation effects on these compounds, odor, and hydrogen sulfide are needed.

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