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Concentrations of Bioaerosols, Odors and Hydrogen Sulfide Inside and Downwind from Two Types of Swine Livestock Operations

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Abstract

Few data on in-barn and downwind concentrations of endotoxin, bioaerosols and odors from livestock facilities are available and no studies have compared conventional confinement operations to the more animal-friendly hoop operations. Hoops are open to the environment and use a composted bedding system rather than housing pigs on slatted floors over pits holding manure slurry as in conventional confinements. We assessed airborne toxicants upwind, in-barns and downwind and evaluated determinants of exposure. Inhalable particulate matter, endotoxin, odor threshold, hydrogen sulfide, culturable mesophilic bacteria, culturable fungi, and total airborne microbes along with wind speed, temperature, and humidity were measured at separate mid-sized livestock facilities (1 hoop, 1 confinement) in Central Iowa on ten occasions over two years. Significant differences in contaminants were observed between hoops and confinement buildings and across seasons for endotoxin, odors, airborne microorganisms, and hydrogen sulfide. For hoops and confinements, respectively, geometric mean in-barn concentrations were 3250 and 3100 EU/m³ for endotoxin; 1400 and 1910 µg/m³ for particulates; 19.6 and 146 ppb for hydrogen sulfide; 137 and 428 dilutions for odor threshold; and 3.0×10⁶ and 1.5×10⁶ organisms/m³ for total microbes. Endotoxin, odor, and culturable microorganisms exceeded recommended exposure limits. Reduced analysis of variance models for these contaminants demonstrated differences by barn type, season, number of pigs, and, in some cases, temperature and humidity. Both types of swine operations produced high airborne concentrations of endotoxin, odor, hydrogen sulfide, bacteria and fungi. Endotoxin and odors were found downwind at concentrations previously associated with adverse health effects.

Keywords

Endotoxin; Bioaerosols; Hydrogen Sulfide; Odors; Concentrated Animal Feeding Operations; Livestock Confinements

INTRODUCTION

The industrialization of agriculture has led to a growing recognition of environmental hazards and exposures for livestock confinement workers and the surrounding

environment.⁽¹⁾ Research studies have shown the potential for adverse health effects due to those exposures.⁽²⁻⁴⁾ Traditional methods of hog production did not require extensive time periods inside hog barns, but nevertheless were associated with respiratory diseases. With the increased size and capacity of hog buildings and greater specialization of operations towards a single facet of swine production, workers are exposed in confinement buildings for longer periods increasing the potential for adverse health effects. For instance, one livestock producer schedules employees to work for 10 days in a row, 10 hr/day and then off work for 4 days.

Confinement buildings are often stocked with very high animal densities and operated with more limited air exchange than traditional hog barns. Reduced air exchange in confinement buildings increases the concentration of effluents which include organic dust, endotoxin, and toxic gases and vapors such as hydrogen sulfide, ammonia and odoriferous compounds. Workers in confinement buildings experience a variety of symptoms including chronic cough, production of excess phlegm, rhinitis, scratchy throat, eye and mucous membrane irritation, shortness of breath, and wheezing.⁽⁴⁻⁸⁾ The duration of exposure to contaminants inside confinement buildings has been shown to be associated with increased respiratory symptoms.⁽⁴⁾ The appearance of these symptoms among swine confinement workers is associated with greater risk for the development of chronic respiratory symptoms, such as bronchitis, occupational asthma, respiratory tract infections or disease^(4, 9-11) and can also result in accelerated declines in lung function over time.⁽¹²⁾

Those residing or attending school in the vicinity of large-scale confinement facilities as compared to those who do not are at increased risk of respiratory symptoms, diminished quality of life and possibly depression and mood disorders.⁽¹³⁻¹⁷⁾ Workers represent a highly selected population and may be less susceptible to exposures in livestock feeding operations than the general public. The general population and certain susceptible subpopulations such as the elderly, children, or asthmatics, may respond to environmental contaminants at much lower levels.

In conventional confinement barns, pigs are confined on slatted floors over manure pits and often exhibit aggressive behavior that can increase airborne PM. In these buildings, animals are housed in close quarters without bedding and they eat, rest and defecate in the same area. An alternative is the deep-bedded hoop barn in which pigs are housed in an arched, fabricroofed structure (resembling a half cylinder) open on one or both ends. Hoops typically have a concrete floor at the front end. The remaining area is unpaved and is covered with straw or corn stover bedding. In hoops, the pigs exhibit more natural behaviors eating at the front end, rooting and resting in the middle and usually defecating in a far corner.

The overall goal of this study was to quantify and compare concentrations of airborne contaminants inside, upwind and downwind (30 m and 160 m downwind) from two types of animal feeding operations. The study was designed to test: 1) if toxicant concentrations inside hoop barns are significantly different from concentrations inside conventional confinement buildings; 2) if there are significant differences in toxicant concentrations upwind and downwind of these swine facilities; and 3) if there are identifiable determinants

of toxicant concentrations in hoop barns and conventional confinement buildings, such as number of pigs, pig housing density, temperature wind speed, season, and humidity.

MATERIALS AND METHODS

Air samples were collected on 10 occasions over 15 months in Central Iowa at 2 sites. Selection criteria were, 1) sites had to be typical of hoops and conventional confinement buildings in the Midwest region; 2) sites had to be close enough to have similar meteorological conditions; 3) sites could not have any livestock facilities, manure lagoons, or municipal waste treatment plants within 2 km; and 4) the producers and the contracting company that owned the pigs and to agree to the study. One site held 3 hoop barns and the other site 24 km away held one, 4 room, deep-pitted conventional confinement building. Neither site had a manure lagoon nor other animals. Samples were taken at thirteen locations: locations 1–3: inside of three adjacent hoop barns; locations 4–6: outside of the hoop barns (30 m (100 ft) upwind, 30 m downwind, 160 m (500 ft) downwind); locations 7–10: inside four conventional confinement rooms; and locations 11–13: outside the conventional confinement building (30 m upwind, 30 m downwind, 160 m downwind). Upwind sampling was performed to ensure that there were no significant sources contributing to measured toxicants other than the swine facilities under study. Samples were collected in the center of each barn or room at a height of 2 m and included inhalable particulate matter (PM), inhalable endotoxin, culturable bacteria on two different media (TSA and R2A), culturable fungi, total microorganisms (viable + nonviable), hydrogen sulfide (H₂S) and odoriferous gases and vapors.

Seasons were distinguished as follows: spring: March, April, May; summer: June, July, August; autumn: September, October, November; and winter: December, January, and February. There were five sampling events in each of 2 years with 1 spring, 2 summer and 2 autumn events in the first year and 2 spring and 3 summer events in the second year. Sampling days were selected randomly with respect to the swine operations to avoid introduction of an operator bias (Hawthorne effect). Winter sampling was not performed because there were no pigs housed in the hoop structures during the winter months due to lower feed conversion in cold weather (i.e. more feed is needed to fatten pigs in winter)

Inhalable Particulate Matter and Endotoxin Sampling

Inhalable dust and endotoxin samples were collected using IOM samplers equipped with Whatman glass fiber filters (SKC, Inc., Eighty Four, PA) and GilAir-5 sampling pumps (Sensidyne, Clearwater, FL) operating at a flow rate of 2.0 L/min, for 4h at a height of 2m. Total inhalable dust was determined by comparing blank-adjusted, pre- and post-sampling filter weights using a MT5 calibrated microbalance (Mettler Instrument Corp., Hightstown, NJ) in a controlled-environment Gravimetrics Laboratory. Sampled filters were eluted with 60 min shaking (at 22°C) in pyrogen-free water with 0.05% Tween20 and analyzed for endotoxin concentration using the kinetic chromogenic *Limulus* Amebocyte Lysate (LAL) Assay (Lonza, Inc., Walkersville, MD) as previously described.⁽¹⁸⁾ Twelve of 13 endotoxin sampling blanks were below detection (<0.05 EU/ml) while the remaining blank returned a value of 0.208 EU/ml. These values were well below endotoxin loading on sampling filters

so samples were not corrected for EU loading of the blanks. Sample values that were below the limit of detection (LOD) were assigned the value $10 \mu\text{g}/\text{m}^3$ for inhalable particulate and $0.22 \text{ EU}/\text{m}^3$ for endotoxin which was the $\text{LOD}/\sqrt{2}$.⁽¹⁹⁾

Bioaerosol Sampling Methods

Culturable bacteria were collected using AGI-30 liquid impingers (ACE Glassworks, Vineland, NJ) and Gilian AirCon II pumps (Sensidyne, Clearwater, FL) at a flow rate of 12.5 L/min for 15 min at a height of 2m as previously described.⁽²⁰⁾ Samples were kept on wet ice until plated onto three types of media: tryptic soy agar (TSA) and R2A for growth of mesophilic bacteria and malt extract agar (MEA) for fungi. Samples were plated the same day they were collected in a series of 10-fold dilutions: full strength, 1:10 dilution, 1:100 dilution, and 1:1000 dilution. TSA, R2A and MEA plates were incubated at 25°C. Emerging colonies were enumerated over a period of 24–72 h (TSA and R2A) and 48–120 h (MEA).

Before plating, an aliquot of the impinger fluid sample was preserved with 2% formaldehyde and treated with acridine orange to obtain a total count of viable and nonviable organisms in the sample. Samples were stained with 1 mg/ml acridine orange, filtered onto black polycarbonate filters (SKC, Inc., Eighty Four, PA), and counted under epifluorescence microscopy as previously described.^(20–21)

Meteorological Conditions

Relative humidity was measured using manual sling psychrometers (Bacharach, Inc., Pittsburgh, PA) and digital hygrometers (Fisher Scientific, Hanover Park, IL). In-barn, upwind and downwind temperatures and wind speeds were measured with digital anemometers with thermistors (Extech Instruments, Waltham, MA). Wind speeds were reported as midpoint values, obtained from wind speed ranges measured during sampling. All readings were taken at the same location as the bioaerosol sampling. Hourly wind speed and direction for each sampling period were obtained from the Iowa Department of Transportation's closest monitoring site (Webster City, IA) using the Iowa Automated Weather Observation System.

Hydrogen Sulfide and Odor

Hydrogen sulfide was measured using calibrated Jerome 631-X Hydrogen Sulfide Analyzers in sample mode (Arizona Instruments, Tempe, AZ) with a lower LOD of 5 ppb. These devices were calibrated annually by the manufacturer and checked daily using zero air and 250 ppb H_2S calibration gas. Samples for odor quantitation were collected in 10L Tedlar bags using a Universal pump (SKC Inc., Eighty Four, PA). The bag was placed inside a VacU Chamber (SKC, Inc, Eighty Four, PA) and air from the environment was drawn into the bag. Odor samples were evaluated within 24–48 hours of collection at the Iowa State University Olfactometry Laboratory following American Standards of Testing and Measurement Methods E1432-91⁽²²⁾ and E679-91⁽²³⁾ using triangular forced-choice olfactometry with the AS'SCENT International Olfactometer (St. Croix Sensory, Stillwater, MN). Olfactometry uses a trained panel of odor evaluators to sniff increasing dilutions of the sampled air randomly delivered to one or another port of the olfactometer with pure air delivered to the other port until the odorous air cannot be reliably detected. The detection

threshold for each panelist is given by the GM of the concentration of the last incorrect guess and the next higher concentration at which the odor port was correctly detected. The odor threshold is the GM of the individual panelist detection thresholds.

Statistical Analysis

Statistical analyses were performed using SPSS (Ver. 16, SPSS Inc., Chicago, IL). The Kolomogorov-Smirnov statistic was used to test normality of data and demonstrated the need for logarithmic transformation for normalization. Geometric means (GM) and geometric standard deviations (GSD) were determined as measures of central tendency and variation. Variables available for analysis of variance (ANOVA) models included the following: barn type (hoop, conventional confinement); season (spring, summer, autumn); wind speed; temperature; relative humidity; number of pigs; pig density; and total pig mass. Pearson correlation coefficients were computed to test for association of pig mass, pig density, and number of pigs in barns and also to test season, temperature and relative humidity. Spearman correlation coefficients were determined to test for association of wind speed (not normally distributed) with season, temperature and relative humidity. After preliminary ANOVA model evaluation, reduced models were utilized to address *a priori* hypotheses. Variables other than barn type with a p value less than 0.15 were included as candidates in the reduced model. If model reduction resulted in a p value over 0.15 the model was further simplified. P values less than 0.05 in reduced models were deemed significant.

RESULTS

Toxicant Concentrations Inside and Outside Animal Feeding Operations

Air sampling was performed simultaneously at swine animal feeding operations in Central Iowa including a 4-room, deep pitted, conventional confinement building without a manure lagoon and a three building hoop barn site employing a corn stover bedding and compost system. These operations were separated by 24 km and had no other animal feeding operations within 2 km.

For inhalable PM, 9 of 120 samples (7.5%) were below the limit of detection, and for endotoxin only 1 of 121 (0.8%) were below detection. Concentrations of inhalable endotoxin were comparable in hoop barns (hoops) and conventional confinement buildings (confinements) with GM levels for all buildings across all seasons of 3250 and 3100 EU/m³, respectively (Table I). Concentrations ranged as high as 37,700 EU/m³ for hoops and 57,800 EU/m³ for the confinement buildings. Only one sample measured less than 50 EU/m³. Assessment of inhalable PM yielded a GM of 1910 µg/m³ in confinements and 1400 µg/m³ in hoops (Table I). In contrast to endotoxin and PM, the GM for H₂S and odors were significantly higher in confinements than hoops (p=0.004 and 0.014, respectively). Confinements had 7-fold higher H₂S and 3-fold higher odor thresholds. Airborne culturable bacteria were more than an order of magnitude higher in hoops while total microbes were 2-fold higher in hoops (Table I, p=0.030 and 0.012, respectively). Maximum airborne microorganisms exceeded 10 million org/m³ in both hoops and confinements. As indicted in Table I, culturable mesophilic fungi were comparable in hoops and confinements with GM

of 2.83×10^4 and 2.05×10^4 cfu/m³. Generally, a higher proportion of airborne bacteria in hoops were culturable than in confinements.

The season in which the sampling was performed was an important determinant of in-barn toxicant levels and the effect of season differed between the two barn types (Table II). Whereas hoop barns had highest concentrations of endotoxin and odor in the autumn, confinements saw their highest levels in the spring. Total microbes and culturable bacteria were highest in autumn and summer, respectively, for hoops but were highest in summer and spring for confinements. Since the autumn was not sampled in year 2, caution is advised in interpreting these findings.

Wind speeds measured in barns and downwind during sampling are shown in a box plot (Figure 1). Outdoor wind speeds ranged from 0 to 6.3 m/s while in-barn wind speeds ranged from 0 to 4 m/s and averaged less than 1 m/s. Wind direction data from the Iowa Automated Weather Observation System indicated predominantly west, southwest and south winds were experienced. Over the sampling days the average wind direction was 220° (southwesterly) and the average standard deviation over a sampling day was 19°. In no cases did the wind direction change substantially during sampling.

Upwind, in-barn and downwind GM concentrations (and geometric standard errors) of the measured toxicants are shown in Figures 2a, 2b and 2c with data for hoops shown on the left half of the graphs and confinement data on the right. Endotoxin concentrations (filled circles, left Y-axis) and inhalable PM (open triangles, right Y-axis) were lowest 30 m upwind of both types of swine operations (Figure 2a). Endotoxin was less than 10 EU/m³ 30 m upwind of both barn types. At 30 m downwind, endotoxin averaged 194 EU/m³ at hoops and 59.5 EU/m³ at confinements, both significantly higher than upwind ($p < 0.01$ hoops; $p < 0.05$ confinements). At 160 m downwind, average endotoxin was approximately 30 EU/m³ at both hoops and confinements and hoops were significantly higher than upwind levels ($p < 0.01$). Inhalable PM was significantly higher inside the swine buildings than outside upwind ($p < 0.01$). The concentration of PM 30 m downwind was also significantly higher than upwind for hoops ($p < 0.01$). The PM concentration at 160 m downwind did not differ from upwind for either barn type.

In-barn levels of H₂S were significantly higher ($p < 0.01$) than upwind levels (Figure 2b). Outside H₂S was higher at the nearer downwind sampling location than upwind while the far downwind site gave levels comparable to upwind. Odor thresholds inside both barn types were very high and significantly greater than upwind levels ($p < 0.01$). Odor levels upwind and downwind of hoops showed only modest differences while air samples 30 m downwind of confinements were substantially more odorous than upwind and exceeded recommended limits.⁽²⁴⁾ In-barn culturable bacteria were much higher in hoops than in confinements, but this was not the case for culturable fungi (Figure 2c). Culturable bacteria were higher downwind of the facilities than upwind for hoops but not for confinements. Culturable fungi were lower than bacteria and demonstrated smaller differences between indoor and outdoor levels.

Analysis of Determinants of Endotoxin and Odors

ANOVA was performed to characterize which assessed variables contributed to the concentrations of toxicants inside the swine buildings. Parameters with a P value ≥ 0.15 in the full model were retained in a reduced model. Comparison of number of pigs, cumulative weight of pigs, and pig density (mass of pigs per building floor area) indicated that these variables were significantly correlated (all $p < 0.01$) so only one could be included in the ANOVA. Since both barn types were finishing operations, pig weights did not differ substantially. Further, barn floor areas were comparable. Thus, number of pigs in the barn was selected for inclusion in the models. Season was not significantly correlated with wind speed, in-barn temperature, or with in-barn relative humidity.

Table III presents the reduced ANOVA models and illustrates that for endotoxin concentration (upper block) barn type (barn) and season sampled (season) and two-way interactions of barn type (hoop or confinement) with season, temperature, and number of pigs in the barn and two-way interactions of season with relative humidity and number of pigs were significant. This reduced model accounted for 72% of the observed variation in the endotoxin concentration.

The ANOVA model for inhalable PM showed that barn and wind speed and interactions of barn type with season, wind, temperature and number of pigs; season with wind, relative humidity and number of pigs; and temperature with wind were the major determinants. Analysis was similarly determined for odor threshold (Table III, third block). The reduced model included barn type, season, temperature, number of pigs and interaction terms. These factors accounted for 72% of the variance. Reduced models for TSA mesophilic bacteria and total microbes are also shown in Table III. As with endotoxin and odor, barn type, season and several interaction terms were important determinants of in-barn concentrations of mesophilic bacteria and total microbes. For hydrogen sulfide, the model was less robust and interactions of barn type and number of pigs as well as relative humidity and wind were most important.

DISCUSSION

Indoor contaminant concentrations for conventional confinement swine facilities have been previously characterized for airborne particulates and endotoxin.^(25–29) Few, if any, studies have quantified particulate matter, bioaerosols, odors and hydrogen sulfide and none have evaluated indoor, upwind and downwind contaminant concentrations in confinement facilities and hoop barns.

Hoop barns are attractive for swine production because they require relatively low capital expense and they are considered by some to be more humane. Since they are more open to the environment and do not use a manure slurry system, it has been suggested that they may produce lower levels of bioaerosols, hydrogen sulfide and odor than conventional confinement systems.⁽³⁰⁾ In deep pitted conventional confinement buildings urine and feces pass over a slatted floor without bedding into a pit below where it stands for up to a year. Here it undergoes anaerobic degradation leading to production of odoriferous fatty acids, hydrogen sulfide, ammonia, methane, carbon dioxide and bioaerosols.

This study is the first to quantify pollutant concentrations inside hoop barns and compare them to conventional confinement buildings nearby. Average in-barn concentrations were lower for hydrogen sulfide and odor in hoops than in confinements. However, concentrations of PM, endotoxin, and culturable fungi were similar and concentrations of cultural bacteria were higher in hoops.

In-barn geometric mean endotoxin concentrations measured in this study exceeded those reported by Clark et al., Attwood et al., Preller et al. and Vogelzang et al. (25,26,28,31) but were lower than those reported by Thorne et al. and Duchaine et al. (27,29) Endotoxin exposures can be considered above the no observed effect level (NOEL) when exposures exceed 50 EU/m³. (32) Yet the in-barn geometric mean endotoxin was 64-fold higher and the highest measured level was more than 1000-fold higher than this NOEL. Exposure at the maximum value of 57,800 EU/m³ while wearing a properly fitting N95 respirator would be expected to limit respiratory exposures to about 3000 EU/m³, still 60-fold higher than the NOEL. Thus, better management practices with more frequent cleaning and manure flushing plus better exhaust ventilation should be instituted to reduce bioaerosol concentrations. Further, workers should be provided with powered air purifying respirators when exposed to such high levels of endotoxin. Since hoops are passively ventilated, they may be less amenable to these exposure reduction approaches.

Inhalable PM exhibited maximum values of 5470 and 7050 µg/m³ in hoops and confinements, respectively. Donham et al. recommended an exposure limit for agricultural dust of 2500 µg/m³ based on the closed-face cassette. (33,34) In a study comparing the IOM sampler to the closed-face cassette Reynolds et al. (35) reported the relationship in swine barns: PM_{CF} = 0.515 · PM_{IOM}. Applying this conversion yields an exposure limit of 4700 µg/m³ which was exceeded in this study. These would be considered high levels for general industry, but considering that much of the PM was composed of bioaerosols, especially endotoxin and bacteria, this exposure is of concern.

In-barn odor levels were extremely high, especially in confinements where the mean was 428 dilutions. This value means that one part of this gas/vapor mixture in 427 parts pure air is detectable as a malodor by a test panel of sniffers. The most significant components of swine facility odor are the organic acids including acetic acid, butyric acids, valeric acids, caproic acids, and propanoic acid; sulfur containing compounds such as hydrogen sulfide and dimethyl sulfide; and nitrogen-containing compounds including ammonia, methyl amines, methyl pyrazines, skatoles and indoles. (36) Thus, exposure to high odor levels represents exposure to this suite of toxicants. Exposure to odorous compounds from swine operations have been linked to chronic fatigue, neurological problems, breathing problems and mood disorders. (13,15,17,37,38)

Outdoor endotoxin measurements at the 30 m downwind location ranged as high as 3900 EU/m³. While the average values of endotoxin at the 160 m downwind location were 29.0 and 25.7 EU/m³ for hoops and confinements, respectively (see Figure 2a), some samples reached 140 EU/m³, which exceed the suggested NOEL of 50 EU/m³. (32) A study of ambient PM₁₀ endotoxin concentrations in 13 Southern California communities found airborne endotoxin levels ranged from 0.03 to 5.4 EU/m³. (39) The GM endotoxin

concentration for the Atascadero agricultural site in our Southern California study was 0.52 EU/m³ (range 0.19–2.63 EU/m³), far below the 160 m downwind values in this study (range 8.5 to 360 EU/m³).

There are a few states that require odor emissions be held below a threshold value. Colorado and Missouri have threshold limits based on scentometry measurements and dilution factors. Livestock facilities in Missouri must meet a 7:1 dilution limit at the property line. Similarly, Colorado facilities must meet a 7:1 dilution limit at the property boundary in addition to a 2:1 dilution standard at any receptor (i.e. school, city limits).⁽⁴⁰⁾ The University Air Quality Study recommended a threshold limit of 15:1 dilution at the property line and a 7:1 dilution at a residence. Facilities would be allowed to exceed these values 7 days out of the year with advance notice.⁽²⁴⁾ In this study, odor thresholds at all outdoor sampling locations exceeded a 7:1 dilution level. The 160 m downwind samples overall averaged 54 dilutions. If these facilities were located with sufficient setbacks (e.g. > 900 m), property line odor levels may not have exceeded these recommended limits or regulatory limits.

A growing number of U.S. states have established standards for hydrogen sulfide emissions from livestock facilities. These include Minnesota, Nebraska, Missouri, California, Iowa. Minnesota uses a level of 60 ppb as an acute health risk value and California uses 30 ppb as an acute reference exposure level.⁽⁴⁰⁾ These levels apply at the property line, so would be most comparable to 160 m downwind levels. The University Air Quality Study in Iowa recommended a 70 ppb one hour time-weighted average for property lines of confinement facilities, in addition to a level of 15 ppb at residences and public use areas, such as parks and schools. As with odors, operations would be allowed to exceed these levels up to seven times per year with advance notice.⁽²⁴⁾ In response to this recommendation the Iowa legislature established a regulatory level of 30 ppb for H₂S at the property line. The difference in average concentrations between barns is very striking, with levels inside hoop barns reaching over 180 ppb and over 900 ppb in the conventional confinement building. Hoop barn hydrogen sulfide exposures at 160 m downwind were lower than those downwind from conventional facilities. In comparison to the above guidelines, the downwind H₂S levels from this study appeared low, at levels of 2.4 ppb for the hoop barns and 3.2 ppb for the conventional confinement building. However, manure pumping and land application as well as meteorological conditions can have a great effect on the production and concentration of hydrogen sulfide, thereby causing great variability in measured levels. In addition, the facilities included in this study were relatively small in size, and without manure lagoons so one would expect lower emissions.

In-barn TSA culturable bacteria averaged 1.57×10^6 cfu/m³ and were as high as 18×10^6 cfu/m³. These levels exceed the health-based threshold recommended by Donham et al.⁽³⁴⁾ of 4.3×10^5 cfu/m³. Exposures among confinement workers above this threshold are predicted to produce pulmonary function declines in excess of 5% and be associated with symptoms. Total microbe concentrations also exceeded this threshold.

The ANOVA models demonstrated important differences between hoops and confinements and seasonal differences. The number of pigs was a weaker than expected independent determinant of the toxicants (endotoxin (p=0.124), inhalable PM (p=0.095), odor threshold

($p=0.014$)), and did not enter the reduced model for the other toxicants. We expected seasonal differences in concentrations of microbes and microbial agents. This was borne out in the ANOVA models where endotoxin, odor threshold, mesophilic bacteria and total microbes were significantly associated with season. However, most toxicants in hoops were highest in autumn while toxicants in confinements were highest in spring. The interaction plot for barn type and temperature showed that confinements had lower endotoxin at high temperatures, likely attributable to opening of the building curtain walls in very hot weather. Plots of barn type and number of pigs for TSA bacteria showed a sharp increase with increasing pig occupancy in hoops but not confinements. With greater occupancy, hoops likely have more bacteria growing in the composting bedding and a higher density of animals to make it airborne.

This study has several limitations. First, we studied relatively small animal feeding operations that are typical of swine operations but do not necessarily represent mega-swine facilities. In the U.S., the majority of swine operations have fewer than 5,000 hogs. There are currently 65,640 farm operations in the U.S. with hogs, 2538 with >5000 head and 57,868 with fewer than 2000 head.⁽⁴¹⁾ However, 54% of the pork comes from 110 facilities with over 50,000 hogs and 78.5% comes from operations with over 5,000 hogs. Thus, data from this study would be expected to underestimate exposures from the very large livestock confinement operations while providing reasonable estimates of the majority of swine operations. Second, the facilities studied, were not matched based upon the number of pigs. The conventional confinement site housed 300 pigs in each of 4 rooms and the hoop site had 200 pigs in each of 3 hoop barns. Ideally, the two sites would have housed approximately the same number of pigs. Third, contaminant concentrations, especially odors and vapors are dependent upon the time of day and are generally lowest in the middle of the day when radiative convection due to incoming solar radiation is highest. Thus, vapor and odor levels are highest during stagnant conditions that arise in the evening and early morning hours. In this study, since field staff had to travel 2.5 hours to reach the study sites, measurements of gases and odors were taken during midday hours and this would tend to underestimate exposures. A fourth weakness of the study is that corn growing around the facilities reached a height of over two meters for one of the sampling rounds placing the far downwind sampler below the tops of the corn stalks. This would also have the effect of underestimating exposure levels. Lastly, with this study design we cannot assess the representativeness of the study sites to the industry as a whole. Despite these limitations, we successfully amassed extensive exposure data simultaneously at two swine operations, in 7 barns, 30 m upwind, 30 m downwind and 160 m downwind on ten sampling days across two years.

CONCLUSIONS

Paired T-tests comparing contaminant levels between hoop barns and conventional confinement buildings demonstrated significantly higher levels of hydrogen sulfide and odor in confinements and significantly higher total microbes and mesophilic culturable bacteria in hoops. Hoops were found to produce substantial toxicant air emissions and cannot be considered less polluting than 1200 pig conventional confinement operations. This study also identified toxicant concentrations that exceed recommended exposure limits for human health including endotoxin, odor, and bioaerosols. ANOVA models for in-barn endotoxin,

inhalable dust, odors and total microbes demonstrated differences by barn type while season was an important predictor for endotoxin, odors, mesophilic bacteria, and total microbes.

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Figure 1.

Average of the daily midpoint wind speeds for the 10 sampling days at the two study sites measured in the barns and downwind during sampling. The average wind speed inside hoop barns was 0.88 m/s (n=30) while inside the confinement buildings was 0.67 m/s (n=40). Outdoor wind speeds were higher and more variable.

Figure 2.

Concentration of pollutants inhalable inside swine buildings and downwind from the buildings. Fig. 2a. Inhalable endotoxin and particulate matter. Fig. 2b. Culturable bacteria (grown on TSA and R2A media) and culturable fungi (grown on MEA). Fig. 2c. Hydrogen sulfide and odor threshold. Symbols indicated values that are significantly higher than upwind values: *, #, + $p < 0.05$ and **, ##, ++ $p < 0.01$.

Table I

Comparison of unadjusted geometric means of toxicant concentrations inside 3 swine hoop buildings and 4 conventional confinement buildings, each sampled on 10 occasions. P values are shown for paired T-tests comparing hoops and confinements by sampling day.

Toxicant	Hoops N=30	Confinements N=40	P value
	GM (GSD) Range	GM (GSD) Range	
Inhalable Endotoxin, EU/m ³	3250 (4.9) 48–37,700	3100 (5.8) 59–57,800	0.40
Inhalable PM, µg/m ³	1400 (5.9) 10–5470	1910 (2.1) 160–7050	0.39
Hydrogen Sulfide, ppb	19.6 (2.8) 1.0–186	146 (2.3) 15–913	0.004
Odor Threshold, dilution	137 (1.8) 53–440	428 (2.0) 149–1810	0.014
Total Microbes. org/m ³	3.01×10 ⁶ (5.1) 0.02×10 ⁶ –18.0×10 ⁶	1.49×10 ⁶ (4.9) 0.018×10 ⁶ –12.2×10 ⁶	0.012
TSA Mesophilic Bacteria, cfu/m ³	157×10 ⁴ (3.9) 14.8×10 ⁴ –1800×10 ⁴	6.31×10 ⁴ (4.1) 0.21×10 ⁴ –82.4×10 ⁴	0.030
R2A Mesophilic Bacteria, cfu/m ³	85×10 ⁴ (3.6) 4.18×10 ⁴ –1590×10 ⁴	6.48×10 ⁴ (4.7) 0.21×10 ⁴ –82.1×10 ⁴	0.030
MEA Fungi, cfu/m ³	2.83×10 ⁴ (4.0) 0.21×10 ⁴ –42.8×10 ⁴	2.05×10 ⁴ (4.1) 0.21×10 ⁴ –20.9×10 ⁴	0.84

Table II

Comparison of unadjusted geometric mean toxicant concentrations inside swine hoop buildings and conventional confinement buildings compared by season. Bold typeface indicates the highest values.

Barn Type	Season	N	Endotoxin, EU/m ³	Inhalable Particulate, µg/m ³	Odor Threshold, dilutions	Total Microbes, org/m ³ (x 10 ⁶)	TSA Bacteria, cfu/m ³ (x 10 ⁴)
Hoop	Spring	9	3370	1940	90.5	1.34	164
	Summer	15	2070	851	158	4.17	201
	Autumn	6	9490	3470	179	4.44	80
Conventional	Spring	12	4100	2550	607	0.71	8.21
	Summer	20	2640	1220	337	2.28	7.35
	Autumn	8	2980	3570	462	1.57	2.91

Table III

ANOVA reduced models for determinants of in-barn toxicant concentrations. Analyses were performed on log-transformed data. (df = degrees of freedom.)

Endotoxin, EU/m³				
Source	df	Mean Square	F	p value
Intercept	1	3.78	3.71	.059
Barn	1	5.63	5.54	.022
Season	2	5.92	5.82	.005
Temperature	1	3.83	3.76	.058
Number of Pigs	1	2.49	2.45	.124
Barn * Season	2	5.47	5.38	.007
Barn * Temperature	1	4.08	4.02	.050
Barn * Number of Pigs	1	11.34	11.15	.002
Season * Relative Humidity	3	32.12	31.58	.000
Season * Number of Pigs	2	5.01	4.93	.011
Temperature * Number of Pigs	1	3.52	3.46	.069
Error	53	1.02		

Inhalable Particulate, µg/m³				
Source	df	Mean Square	F	p value
Intercept	1	1.04	2.46	.123
Barn	1	1.84	4.34	.043
Season	2	0.84	1.98	.150
Wind	1	3.38	7.98	.007
Temperature	1	1.10	2.60	.114
Number of Pigs	1	1.23	2.90	.095
Barn * Season	2	2.20	5.19	.009
Barn * Wind	1	1.94	4.58	.037
Barn * Temperature	1	1.48	3.48	.068
Barn * Number of Pigs	1	1.61	3.79	.058
Season * Wind	2	1.80	4.25	.020
Season * Relative Humidity	3	3.67	8.66	.000
Season * Number of Pigs	2	1.98	4.68	.014
Temperature * Wind	1	3.99	9.43	.004
Temperature * Number of Pigs	1	1.26	2.98	.091
Error	47	0.42		

Odor Threshold, dilutions				
Source	df	Mean Square	F	p value
Intercept	1	2.13	8.46	.005
Barn	1	2.26	8.97	.004
Season	2	2.18	8.66	.001
Temperature	1	1.84	7.31	.009

Odor Threshold, dilutions

Source	df	Mean Square	F	p value
Number of Pigs	1	1.63	6.46	.014
Barn * Season	2	2.15	8.52	.001
Barn * Temperature	1	2.34	9.27	.003
Season * Number of Pigs	2	2.16	8.57	.001
Temperature * Number of Pigs	1	1.79	7.08	.010
Error	58	0.25		

TSA Mesophilic Bacteria, cfu/m³

Source	df	Mean Square	F	p value
Intercept	1	11.67	13.41	.001
Barn	1	2.76	3.17	.081
Season	2	5.88	6.76	.002
Barn * Number of Pigs	2	5.06	5.82	.005
Season * Wind	3	4.51	5.18	.003
Season * Temperature	3	3.38	3.88	.014
Season * Relative Humidity	3	6.79	7.81	.000
Temperature * Relative Humidity	1	4.32	4.96	.030
Error	54	0.87		

Total Microbes, organisms/m³

Source	df	Mean Square	F	p value
Intercept	1	20.06	16.58	.000
Barn	1	15.24	12.59	.001
Season	2	9.41	7.78	.001
Barn * Season	2	2.84	2.35	.105
Season * Wind	3	2.41	2.00	.125
Season * Temperature	3	22.13	18.29	.000
Season * Relative Humidity	3	5.64	4.66	.006
Error	55	1.21		

Hydrogen Sulfide, ppb

Source	df	Mean Square	F	p value
Intercept	1	4.38	5.91	.018
Barn	1	0.06	0.08	.779
Barn * Number of Pigs	2	2.24	3.02	.056
Relative Humidity * Wind	1	1.65	2.22	.141
Error	65	0.74		

$r^2 = .717$ (adjusted $r^2 = .637$)

$r^2 = .673$ (adjusted $r^2 = .533$)

$r^2 = .723$ (adjusted $r^2 = .670$)

$r^2 = .848$ (adjusted $r^2 = .805$)

$$r^2 = .639 \text{ (adjusted } r^2 = .548)$$

$$r^2 = .608 \text{ (adjusted } r^2 = .584)$$

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