Assessment of an Aerosol Treatment To Improve Air Quality in a Swine Concentrated Animal Feeding Operation (CAFO)

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Poor air quality within swine concentrated animal feeding operations (CAFOs) poses a threat to workers, the surrounding community, and farm production. Accordingly, the current study was conducted to evaluate a technology for reducing air pollution including particulate matter (PM), viable bacteria, and ammonia within such a facility. The technology consists of an acid−oil−alcohol aerosol applied daily. Its effectiveness was evaluated by comparing air quality from before to after treatment and between treated and untreated sides of a barn separated by an impervious partition. On the untreated side, air quality was typical for a swine CAFO, with mean $PM_{2.5}$ of 0.28 mg/m^3 and PM_{TOT} of 1.5 mg/m^3. The treatment yielded a reduction in PM concentration of 75−90% from before to after treatment. Effectiveness increased with time, application, and particle size (40% reduction for 1 μm and 90% for >10 μm). Airborne bacteria levels (total bacteria, Enterobacteriaceae, and gram-positive cocci) decreased one logarithmic unit after treatment. In contrast, treatment had no effect on ammonia concentrations. These findings demonstrate the effectiveness of an intervention in yielding exposure and emission reductions.

Introduction

Increasing numbers of concentrated animal feeding operations (CAFOs) are being built and operated in rural communities across the United States. From 1982 to 1997, the number of CAFOs grew by 51%, with some of the largest facilities having capacities exceeding 1 million animals (*1*). Since 1978, the number of animals confined per swine operation has increased by 134% (*2*). Along with this growth, there has been increasing concern regarding the adverse effects of these operations on the health of workers, nearby neighbors, livestock, and the environment.

Many of the public health concerns stem from elevated concentrations of respiratory hazards found in swine CAFOs because of their high animal density and enclosed characteristics. These respiratory hazards include chemical and biological (immunogenic and infectious) aerosols (i.e., bio-

aerosols) (*3*, *4*). Among the biological components of these aerosols are molds, bacteria, feed, bedding particles, animal hair, and dried manure. These organic aerosols, combined with inflammatory agents including ammonia and endotoxins, have been associated with the development of respiratory illness among swine workers (*5−8*), the community surrounding the CAFO (*2*, *9*), and the pigs themselves (*10−12*).

Because of the hazardous environment created within CAFOs and the potential airborne releases into the community, research and development in hazard abatement is being actively pursued in order to reduce dust concentrations within CAFOs and dust emissions into the surrounding environment. A number of different strategies have been examined, including air filtration to control emissions (*13*), replacing dry feed with liquid (*14*), generating an electrostatic charge to remove dust particles from the air (*15*), increasing the amount of fat in the animal's feed (*16−18*), and spraying vegetable oil inside the barn (*14*, *16*, *19−22*). Of these approaches, the dispersion of an oil aerosol has shown the greatest promise for reducing indoor dust levels. Oil has been applied at pressures as low as 20 kPa (*22*) and as high as 16 MPa (*21*), with the higher pressures producing smaller-diameter aerosols. The mechanism of particle removal is based on coagulation, where particles are scavenged by the oil aerosol (*23*). This mechanism of removal increases in efficiency with decreased aerosol size. Particle size also has a large influence on aerosol residence time, given that settling velocity increases as the square of the particle diameter. Treatment effect is also dependent on the height of application. Most studies apply close to the floor to optimize the dust suppression effect (*19*, *22*). Other variations include application frequencies and rates. The best results are achieved with one daily application of between 10 and 40 mL/m^2 (*22*). However, these oil aerosol studies have not evaluated indoor levels of ammonia or reductions in airborne bacteria concentrations associated with the dust reductions.

Therefore, the aim of the current study was to evaluate the effectiveness of an oil aerosol formulation in improving swine CAFO indoor air quality. The formulation consists of an oil−acid−alcohol mixture designed to reduce concentrations of particulate matter, microorganisms, and ammonia. This evaluation provides an independent scientific foundation to assess the effectiveness of a treatment designed to improve indoor air quality and reduce air emissions from swine CAFO operations for the protection of worker and community health.

Materials and Methods

Experimental Design. Monitoring was conducted on each of two sides of a tunnel-ventilated swine-finishing CAFO located in the Mid-Atlantic region. The swine house was 25 m wide and 60 m long (Figure 1a), divided lengthwise by a 1.5-m cinder-block wall and a plastic curtain that ran from the wall to the ceiling ridge (Figure 1b). One side was untreated (control side), and the other was treated with the oil-atomization intervention. The effectiveness of treatment was evaluated by simultaneously monitoring the concentration of air contaminants on both sides. Each side housed roughly the same number and age of pigs. During the December sampling, there were 781 and 788 pigs on the control and treatment sides, respectively. Prior to the January sampling, 108 and 95 animals were removed, leaving 673 and 693 on the control and treatment sides, respectively. Accordingly, there were conservative slight animal density

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a) Top view of barn
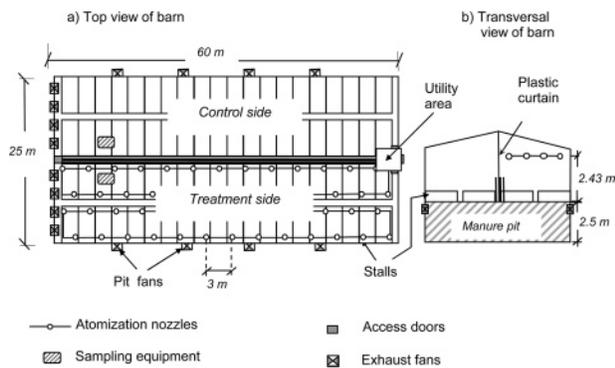
b) Transversal view of barn

FIGURE 1. Schematic of the tunnel ventilated barn and location of access doors, atomization nozzles, sampling stations, and fans: (a) top view, (b) transversal cut. (Not to scale.)

biases of 0.1% and 0.3% during December and January, respectively.

The central partition divides the house into two separate sides of the same size (12.5×60 m). Each side contains two rows divided by a central aisle (0.91 m), with 20 pens per row. Each pen is 3×5.6 m, is equipped with automatic self-feeders and drinkers, and was designed for an occupancy of 25 pigs per pen. The barn has fully slatted wooden floors atop a 2.5-m-deep concrete manure pit. Pigs arrive when they are 5–6 weeks old (16–18 kg) and are exclusively housed within the barn for 14–18 weeks until they reach a slaughter weight of 113 kg. The barn was reported to have been spray-washed before the pigs arrived. The underlying pit had been emptied approximately 6 months prior to the December sampling. At the time of sampling, the pit was near capacity, i.e., within 10 cm of maximum capacity. No cleaning is conducted during the time that the barn is occupied.

Ventilation on each side of the barn is independently controlled by a combination of wall and pit fans (see Figure 1). Four exhaust pit fans are positioned on each side of the barn and are run constantly, with their speed thermostatically controlled. Exhaust ventilation provided by the pit fans is supplemented by four thermostatically controlled wall fans positioned on the south end of each side of the barn. During the winter, two 36-in. wall fans would periodically turn on depending on temperature within the barn. Makeup air during the winter season is provided exclusively by ceiling baffles (12 in. $\times$ 96 in.). During summer months, additional makeup air is provided by a retractable curtain at the north end of the barn. Temperature is regulated by a stepwise thermostat that controls the house fans and heaters to maintain a programmed temperature (21 °C) in the barn. The exchange rate is primarily determined by the wall fans during the summer and the pit fans during the winter. During our sampling days, all pit fans were on, and only one end fan was turned on intermittently for a typical exchange rate of 5000 cfm per side.

Description of Atomization Intervention. Treatment consisted of a formulation comprising proprietary proportions of corn oil, adipic acid, ethyl alcohol, eucalyptus, and water (Atomization Solution Number 5 by Custom Formulated Blenders, Bristol, IN). The formulation was developed to reduce airborne particulate matter and ammonia through short- and long-term mechanisms. The short-term mechanisms include kinematic coagulation (23) and deposition. Long-term reductions occur through the suppression of dust resuspension. Adipic acid was added to neutralize gaseous ammonia. Alcohol helps dry the atomized aerosol and serves as an adjuvant so that formulation components are well mixed. This final formulation is atomized for 45 s once a day at a pressure of 235 psi (1620 kPa) and a rate of 45 mL/m². The nozzles are located 2.43 m from the floor on 3-m centers

(Figure 1) for complete coverage of the treated area and were designed to produce an aerosol 1–10 μm in diameter under conditions of this formulation and pressure. Atomization rate and application times were established empirically by the manufacturer. It is not within the scope of this study to evaluate specific application procedures, but rather the overall methodology.

General Sampling Strategy. Air monitoring was simultaneously conducted on both sides of the barn for particles, bioaerosols, and ammonia on two separate days (December 9 and January 5) during the winter of 2003/2004. On each day, sampling was conducted over two 3-h intervals for a total of eight sampling intervals (2 sides $\times$ 2 days/side $\times$ 2 intervals/day). The first sampling interval of the day occurred in the morning and preceded application of the oil aerosol treatment. The second sampling interval occurred in the afternoon immediately following the aerosol treatment. This design provided the means to examine both the long- and short-term effectiveness of treatment. The short-term effectiveness was evaluated by examining changes within a day from pre- to post treatment. The long-term effectiveness was evaluated as the change in airborne concentrations from December 9 to January 5 after 27 days of daily treatment. Sampling was conducted at a time when the pigs were near their slaughter age (approximately 18 weeks) and weight (approximately 250 lbs).

Samplers were placed on tables (approximately 1.5 m from the ground) within empty stalls 2 m from the central wall and toward the end of the barn where the exhaust fans are located (see Figure 1). Duplicate side-by-side sampling was conducted for each integrated sampling method (gravimetric PM, bioaerosols, and ammonia).

Particle mass and count concentrations were evaluated using a combination of integrated and direct-reading instruments. Integrated sampling was used to assess particle mass concentrations across three size fractions: total PM (PM_{TOT}) ($d_{50\%} < 100$ μm, where $d_{50\%}$ is the particle diameter that has a 50% collection efficiency), PM_{10} or thoracic ($d_{50\%} < 10$ μm), and $PM_{2.5}$ or fine ($d_{50\%} < 2.5$ μm). Two different nephelometers were used to provide direct-reading particle mass (nominally d $\leq$ 10 μm) and count concentration (six sizes from 0.3 to >10 μm).

Integrated sampling for PM_{TOT} was determined according to National Institute of Occupational Safety and Health (NIOSH) method 0500 (24). Samples were collected over 3 h at 2 L per minute (lpm). PM_{10} and $PM_{2.5}$ mass concentrations were measured at 4 lpm using Personal Environmental Monitors (PEMs) (models 761-200A and 761-203A, respectively, MSP Corporation, Shoreview, MN) loaded with 37-mm Teflo filters (225-1709, SKC Inc., Eighty Four, PA). A single 29 lpm vacuum pump (VP0435A-V1029-D1-0511, MEDO USA Inc., Hanover Park, IL) attached to a four-way adjustable flow manifold (55-007973, R&P, Albany, NY) was used to draw air though both PEM samplers as well as their side-by-side duplicates. An identical pump and adjustable flow manifold was used for PM_{TOT} sampling. Inlet airflows were set at the beginning of sampling and checked at the end of sampling with a primary standard electronic flow calibrator (DC 2M, BIOS International, Butler, NJ). Mass concentrations were determined from the averages of the flows measured at the beginning and end of sampling.

Gravimetric analysis was conducted according to 40CFR50 appendix L (25) using a microbalance (MT5, Mettler-Toledo, Columbus, OH) that had microgram-level mass resolution. The balance was located within a humidity-controlled dedicated facility. The mass measurement methods described by Lawless and Rodes 1999 were applied (26).

Time-resolved particle mass was assessed with two DataRam nephelometers (pDR-1000AN, Thermo-MIE, Franklin, MA) and two size-selective laser particle counters (CI-

500, Climet Instruments, Redlands, CA), one on each side of the barn. The laser particle counters were retrofitted by the manufacturer to provide counts across the following bin sizes: 0.3−0.5, 0.5−1.0, 1.0−2.5, 2.5−5.0, 5.0−10, and >10 μm. Instrument clocks were synchronized, and the instruments were programmed to record measurements every 1 min for the DataRam and every 10 min for the CI-500. To assess instrument bias, samplers were run side-by-side before and after sampling. Reported results have been adjusted for instrument differences.

Bioaerosol sampling was conducted using all-glass liquid impingers (AGI-30, Ace Glass, Vineland, NJ), according to recommended methods (27−29). Each impinger was autoclaved and filled with 20 mL of sterile phosphate buffered saline (PBS) solution. Flow through the impingers (12.5 lpm) was achieved with a 40 lpm pump (ABS-II-S, BGI Waltham, MA) and checked before and after sampling with an electronic flow calibrator. Samplers ran for 30 min on the first sampling day. This is the maximum time suggested to maintain collection efficiency (29). On the second sampling day, to increase the volume of air sampled without compromising sampling efficiency, liquid was replenished after 30 min, and the samplers ran for a total of 1 h. Sterile pipets were used to replenish liquid (using sterile distilled deionized water, to avoid increasing salinity). Impingers were stored and transported at 4 °C.

Samples were transported back to the laboratory within 3 h of the last collected sample. After the volume of the impinger fluid had been measured, it was diluted and filtered in order to obtain a countable number of colonies. Three 10-fold dilutions were plated (100 μL/plate) in duplicate on tryptic soy agar (TSA) and McConkey's, mE, and Sabouraud agars. Colonies growing on TSA were classified as total viable bacteria (TVB). McConkey's agar was used as a selective medium for the isolation of gram-negative bacilli that comprise the family Enterobacteriaceae. The Enterobacteriaceae is the largest and most heterogeneous family of clinically important gram-negative bacilli. Potential human pathogens in this family include *Escherichia*, *Shigella*, *Salmonella*, and *Yersinia* to name a few (30). Throughout the rest of the paper, isolates cultured on McConkey's agar will be referred to as Enterobacteriaceae. mE agar was used as a selective medium for the isolation of *Enterococcus* spp., gram-positive cocci that are not only members of the normal intestinal flora of animals and humans but also opportunistic pathogens. After incubation on mE agar for 48 h at 41 °C, representative pink to red colonies [indicative of enterococci (31)] were initially stored and later speciated as reported elsewhere (32). Thirty-four percent of the isolates were confirmed as *Enterococcus* spp., 32% were classified as *Staphylococcus* spp., 33% as *Streptococcus* spp., and <1% as *Micrococcus* spp., all of them gram-positive cocci associated with human infections and therefore of health concern. Consequently, bacteria collected on mE agar are referred to throughout the rest of the paper as gram-positive cocci. Sabouraud agar (with 25 μg/mL antibacterial gentamicin) was used for isolation of mold and fungi. Plates were incubated at temperatures and times designated to select the organisms of interest: TSA and McConkey plates at 36 °C for 24 h, mE plates at 41 °C for 48 h, and Sabouraud plates at 28 °C for 24 h. If no noticeable growth was detected after 15 h, 5 mL of the impinger fluid was analyzed using a membrane filtration technique (33). Negative control plates were made of the replenishing fluid and the dilution liquid. Because the focus of this study was to evaluate the effectiveness of the intervention on bioaerosols in general, the cultured organisms were not further characterized to the species level for this study.

Ammonia sampling was performed using passive colorimetric tubes (Dräger color diffusion tubes, SKC #800-01301) (34, 35). Sampling was begun by breaking the glass tip of the tubes. The time, date, and location were recorded. At the end of the sampling period, the levels registered on the tubes were recorded along with time. Results were obtained by dividing the reading on the tube (in ppm/h) by the number of hours sampled.

Statistical Analysis. Percent reductions for both the integrated particle mass and bioaerosol concentrations were calculated using eq 1

$$\% \, R_{ijk} = [(C_{cb1} - C_{ijk})/C_{cb1}] \times 100 \qquad (1)$$

where R_{ijk} is the reduction observed on the ith side of the barn at the jth time (before or after treatment) on the kth day, C_{cb1} is the concentration on the control side before treatment on the first day, and C_{ijk} is the concentration on the ith side at the jth time on the kth day. For this calculation, the baseline control values were based on the values obtained during the first day on the control side of the barn before treatment. However, because PM_{TOT} was lost during this sampling period, its percent reduction was based on the January pretreatment levels. Because of the small sample numbers, statistically significant differences by sampling period were evaluated using the Kruskal−Wallis test (36). This nonparametric alternative to the one-way ANOVA was used to compare both control to intervention and before to after treatment.

Instrument bias between nephelometers (determined by side-by-side sampling before and after each sampling day) was corrected using regression analysis. Once nephelometric data were adjusted for instrument differences, a ratio of mist to control values was obtained for each data point. The interval associated with application of the oil−alcohol aerosol (approximately 10 min) was excluded from this analysis. These ratios were found to be log-normally distributed. Their logarithmic transform was tested using the Shapiro−Wilk test for normality and found to be normally distributed (p > 0.05), making their means suitable for testing by the Student's t-test. The effect of the intervention was evaluated using paired t-tests by comparing the means of the ratios from before to after treatment. A nonpaired t-test was used to test for differences in air pollution mean concentrations between the control and treatment sides. Percent reduction was obtained using the average on the control side before treatment as the 100% reference as in eq 1. The coefficient of variation (CV) was determined for each sample type and monitoring period based on duplicate side-by-side sampling. As a measure of the overall measurement reproducibility, we report the mean CV across all sampling periods. All statistical analyses were performed using STATA (Stata Corporation, College Station, TX). A p value of ≤0.05 was considered significant.

Results

The integrated air monitoring results by side of the barn and time relative to treatment are summarized in Table 1. On the basis of a comparison between sides of the barn for each sampling period, the treatment was associated with a significant reduction (p < 0.05) in PM across all three size fractions. The treatment was also associated with a significant reduction (p < 0.05) in bioaerosols (except fungi), on the basis of comparisons both between sides of the barn and before to after treatment. No significant difference was observed for ammonia. Treatment and control sides were analyzed separately before treatment because of a test atomization the preceding day on the treatment side, which had a noticeable effect on the baseline.

Data quality was assured by having side-by-side duplicates of every PM, bioaerosol, and ammonia measurement, as well as field and laboratory blanks. Coefficients of variation for

TABLE 1. Comparison of Integrated PM and Ammonia Concentrations between Treatment and Control Sides of a Swine CAFO Measured on 2 Days during the Winter of 2003/2004[a,b]

contaminant (units)	control side (C)		treatment side (T)		C vs T p value	CV[c] (%)
	before	after	before	after		
$PM_{2.5}$ (mg/m^3)	0.294 (0.189−0.439)	0.262 (0.136−0.385)	0.085 (0.01−0.161)	0.047[d] (0.018−0.126)	0.02	60
PM_{10} (mg/m^3)	0.848 (0.752−1.010)	0.911 (0.855−1.005)	0.256 (0.216−0.299)	0.150[d] (0.066−0.266)	0.02	10
PM_{TOT}[e] (mg/m^3)	1.576 (1.571−1.580)	1.446 (1.431−1.461)	0.627 (0.579−0.676)	0.259[d] (0.250−0.269)	0.02	7
ammonia (ppm)	37 (34−40)	37 (34−40)	35 (30−40)	34 (28−40)	0.22	13

[a] Statistical significance was evaluated using Kruskall−Wallis tests. [b] Values reported as averages, followed by ranges (in parentheses). $n = 4$ except for PM_{TOT} before, for which $n = 2$. [c] Coefficient of variation (CV) = mean value of side-by-side duplicates across all sampling periods. [d] Statistically significant reduction on the treatment compared to the control side. [e] December data was lost. Only January data included in analysis.
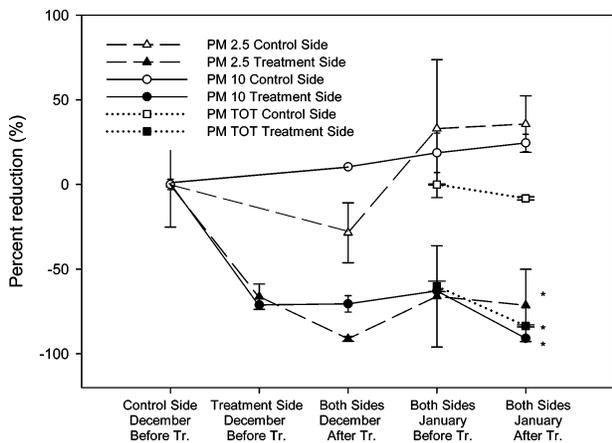

FIGURE 2. Percent reductions in particulate matter related to treatment. Based on first-day measured concentration before treatment on the control side. (Data for PM_{TOT} in December were lost. Calculations are compared to the control side in January.) Statistical differences were evaluated by sampling period using the Kruskall−Wallis test.

PM are reported in Table 1 and fall within 30%, except for $PM_{2.5}$ (60%). CVs for bioaerosols were 36% for gram-positive cocci, 66% for Enterobacteriaceae, 15% for TVB, and 24% for fungi.

The percent changes in both short- and long-term airborne particulate matter are illustrated in Figure 2. A reduction trend is observed for all size fractions on the treatment side relative to the control side. For the January data (second sampling day), short-term reductions of 15%, 75%, and 58% were observed from before to after treatment for $PM_{2.5}$, PM_{10}, and PM_{TOT}, respectively. The long-term effect (determined after one month of daily treatment) showed a similar but enhanced profile of reduction: 71% for $PM_{2.5}$ and 91% for PM_{10} when compared to December and 82% for PM_{TOT} when compared to the control side (because of missing data in December). Error bars represent data ranges.

The time-resolved size-selective monitoring (CI-500) was consistent with integrated sampling methods in revealing a significant ($p < 0.05$) treatment effect across all particle size ranges except the 0.3−0.5-μm range. Furthermore, these data indicate that the treatment effect increased with particle size (Figure 3) such that no reduction was observed for 0.3−0.5-μm particles, whereas a 39% reduction was observed for the 0.5−1-μm size bin, and 81%, 82%, 88%, and 89% reductions, respectively, were observed for the consecutive size bins.

In contrast to the other monitoring approaches, the MIE nephelometer gave mixed results as to the effect of treatment. No significant ($p > 0.05$) effect was detected on the first sampling day when comparing treatment to control or before
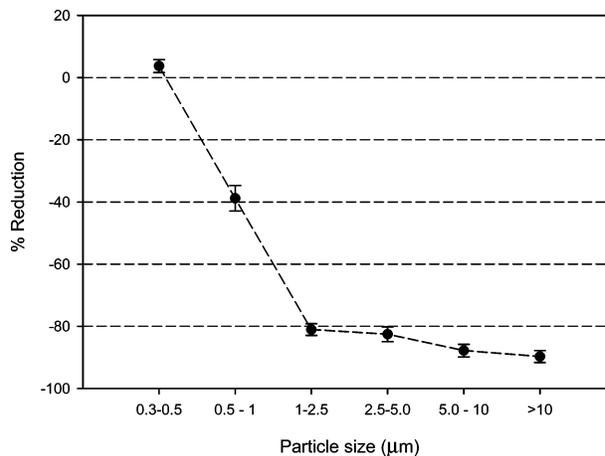

FIGURE 3. Particle-size-dependent treatment effect. Percent reduction is relative to control side (December data only).
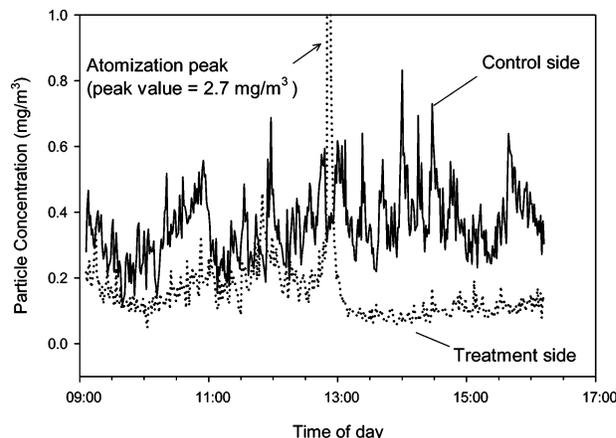

FIGURE 4. PM concentrations measured with the DataRam nephelometer (1-min resolution). Concentration profile by side of barn for January sampling.

to after treatment (data not shown). On the second sampling day, however, a statistically significant reduction was observed on the treatment side after atomization. Furthermore, there was a statistically significant difference between the control and treatment sides before atomization, suggesting long-term effects of daily treatment. This reduction can also be observed in Figure 4, where all data points for the second sampling day are plotted. The atomization PM-associated peak can be distinguished clearly, as well as the reduction after treatment.

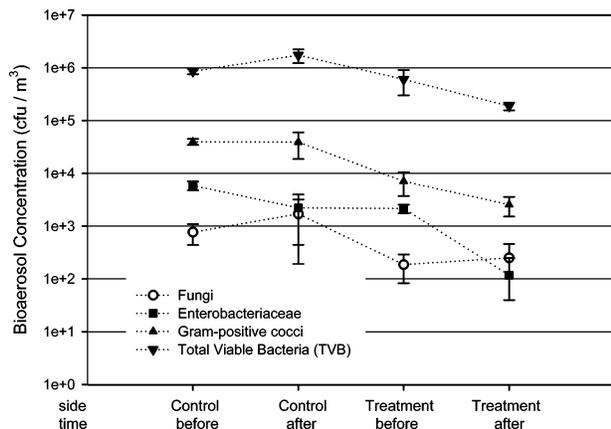Concentrations of bioaerosols sampled in January including TVB, gram-positive cocci, and Enterobacteriaceae,

FIGURE 5. Bioaerosol concentration by side of barn and time relative to treatment. Only January data are included for analysis because of missing values in December.

were significantly reduced ($p < 0.05$) when comparing either before to after treatment (Figure 5) or sides of the barn. For fungi, there was a statistically significant difference ($p < 0.05$) between the control and treatment sides but no statistically significant difference ($p > 0.05$) between before and after treatment. Data for December were below the limit of detection for most bioaerosols. Consequently, we doubled the sampling volume for the second sampling day. December data were not included in the analysis. Short-term reductions (comparing before to after treatment) were 68% (0.4 log) for TVB, 63% (0.3 log) for gram-positive cocci, 94% (1.2 logs) for Enterobacteriaceae, and no reduction for fungi. Long-term reductions (comparing treatment to control side) were greater, with 90% (1 log) for TVB, 93% (1.1 log) for gram-positive cocci, 94% (1.2 log) for Enterobacteriaceae, and 85% (0.75 log) for fungi.

Ammonia concentrations averaging 37 ppm were recorded on the first sampling day and 35 ppm on the second day (Table 1). There was no observed effect before and after treatment or between sides. Colorimetric tubes do not have a high resolution, but duplicates showed agreement within 15%.

Discussion and Conclusions

As concern grows over the public health and environmental impacts of producing large numbers of animals at CAFOs, there is a need for the development and testing of technologies that mitigate their impact. A variety of approaches have been developed and tested for improving CAFO air quality and reducing emissions (5, 14). Of these, the application of an oil aerosol has shown to be one of the most promising (17−22). However, none of the published oil-based reduction systems have addressed the reduction of ammonia concentrations or measured the impacts on biological aerosols. The current study was designed and conducted to evaluate an oil aerosol application that is unique in two ways. First, the oil is in a water formulation that includes alcohol, adipic acid, and eucalyptus to dry and help mix the atomized aerosol, neutralize gaseous ammonia, and provide a pleasant odor, respectively. Second, the oil formulation is applied under high pressure, potentially yielding micron-sized charged particles that will likely be more efficient in particle removal through electrostatic attraction and coagulation.

Acceptance of the oil-atomization technology for control of indoor air hazards and emissions will depend on practical considerations including cost. The projected cost of installation varies between $5,500 and $10,000 per barn, depending on the numbers of houses and the availability of an existing room or the need to build one to house the control panels and solution tank. The atomization solution costs $0.0011

per sq ft ($9.25/day for the barn under study). The pumping and mixing system only runs for 16 min a day (15 min of mixing and 45 s of spraying), so the electrical costs are minimal.

The atomization treatment was conducted within a swine CAFO during the winter months when the hogs were close to slaughter age (15−18 weeks). These conditions represent a near-worst-case scenario for air quality within a CAFO because of decreased ventilation and increased animal density (37, 38). The observed levels in the control side (Table 1) were consistent with ranges that have been reported in other similar facilities (5, 38−40), with PM_{TOT} of $1-7$ mg/m^3, $PM_{2.5}$ of $0.1-1$ mg/m^3, TVB of 10^5-10^6 cfu/m^3, and ammonia of $5-40$ ppm. The atomization treatment examined in this study was effective in significantly reducing particulate matter and bioaerosols, but not ammonia concentrations, inside the barn.

Using a combination of methods measuring PM of differing size classification and time resolution, a consistent treatment-related reduction in PM levels was observed. The effects of treatment observed in the current study are similar to those reported in recent studies that have evaluated different atomization methods by modifying the droplet size (20); the oil type (19); and the frequency, dose, and duration of oil application (21, 22). All of these studies have shown a statistically significant reduction in dust of up to 76%. Furthermore, the present results indicate that the treatment effect is enhanced for increasing particle sizes. This particle size effect is likely due to suppression of resuspension being more effective for larger sizes.

PM concentrations were reduced by $75-90\%$ for $PM_{2.5}$, PM_{10}, and PM_{TOT} after 1 month of daily treatment (Figure 2 and Table 1). These reductions were statistically significant ($p < 0.05$) and were consistent for both integrated and direct-reading measurements. The reduction effect increased with particle size (Figure 3) and was cumulative, i.e., reductions increased after more than one application (Figure 2). The lack of an observed effect on the first day with the MIE nephelometer can be explained by this instrument's more sensitive response to particles less than 2 μm in diameter, given that we observed only a small treatment effect for particles in this size range (41). Also, photometers are sensitive to the high-humidity conditions that exist in CAFOs during winter, and the increase in average particle size associated with condensation might have affected the instrument's sensitivity (42).

There are no threshold or permissible exposure limits for CAFO dust. However, Donham et al. (3) published dose−response relationship studies suggesting health-related limits below which no effect is observed. The oil aerosol treatment evaluated in this study was effective in decreasing PM levels from 0.3 mg/m^3 to below the recommended health guidelines of 0.23 mg/m^3 for respirable PM ($PM_{2.5}$). (PM_{TOT} was below the recommended limit even before treatment, and there are no guidelines for PM_{10}.)

This study is unique in its assessment of the effect of an oil treatment on bioaerosol levels. The samplers used (all-glass impingers) are the samplers most widely used in bioaerosol sampling of animal facilities (37, 40, 43). Bioaerosol results (TVB, gram-positive cocci, and Enterobacteriaceae) were consistent with PM results, i.e., short-term reductions were smaller than long-term reductions, with the latter close to 1 log (>90%), and the results were statistically significant. However, although the treatment effect was statistically significant, the biological and public-health significance is less clear. There is no evidence to suggest that a 1-log reduction in airborne bacteria will yield a health benefit. For example, TVB concentrations exceeded the recommended level of 10^5 cfu/m^3 (5) even after treatment, and no recommended limits are established for airborne concentrations

of specific organisms, such as Enterobacteriaceae, gram-positive cocci, or fungi. In addition, a study that was conducted in collaboration with this investigation found that 98% of the airborne *Enterococcus* spp., *Streptococcus* spp., and *Staphylococcus* spp. collected from this swine facility were resistant to multiple antibiotics (*32*). Reducing the concentration of airborne multidrug-resistant bacteria by only 1 log (when original concentrations are high) is unlikely to alter either potential health outcomes or the dissemination of antibiotic resistance genes when an individual is exposed to antibiotic-resistant bacterial isolates. Therefore, although the oil treatment was effective in reducing indoor concentrations, levels are still likely to exceed health thresholds.

Ammonia concentrations exceeded occupational threshold limit values (ACGIH TLV = 25 ppm) and far exceeded the health-based suggested limit of 7 ppm for swine houses (*5*). Our results, based on passive colorimetric detector tubes, suggest that the treatment had no detectable effect. Although this method of monitoring is relatively imprecise in comparison to active sampling coupled with laboratory analysis, we observed a mean 13% coefficient of variation for side-by-side duplicate samples. This level of precision suggests that the method was able to detect relatively small differences in ammonia concentration between sides of the barn. The oil-atomization treatment is believed to yield reductions in ammonia by acid neutralization of both gaseous and particle-bound forms. Further changes to the formulation are being considered to increase the acid content, thereby increasing the ammonia neutralization potential.

In conclusion, the current study adds to a growing body of literature demonstrating the effectiveness of oil atomization in reducing airborne PM levels within CAFOs. It logically follows that reductions indoors will yield proportional reductions in PM levels emitted into the surrounding community. It is likely that continued advances will be made in the formulation and/or method of application to further enhance the effect of treatment. Further research is needed to investigate seasonal variability of treatment effectiveness. The availability of such technologies holds promise for reducing worker and community exposures to PM. Furthermore, because CAFOs can potentially fall within the definition of a stationary source under the Clean Air Act, the U.S. EPA and state governments have the authority to require that CAFOs measure and control their emissions. The treatment evaluated in this study could help bring a CAFO in compliance for PM standards. Nonetheless, the application of the oil-atomization technology examined in this study had no effect on ammonia concentrations, and the statistically significant reductions observed for airborne bacteria are unlikely to be biologically significant for swine workers and others exposed to air originating in swine CAFOs. Thus, although oil atomization can address a portion of the air-quality and public-health problems associated with swine CAFOs, it is prudent that additional strategies be investigated to mitigate the public-health and environmental-health effects associated with swine production. These strategies could include the incorporation of improved hygienic practices within swine CAFOs, as well as the continued exploration of alternative swine production methods, such as hoop housing systems and deep-bedded systems, as viable swine production approaches in the United States.

Acknowledgments

Literature Cited

(1) U.S. Environmental Protection Agency (U.S. EPA). EPA Newsroom. EPA and Agriculture Working Together to Improve America's Waters. Available at http://www.epa.gov/epahome/headline_121602.htm, 2002 (accessed May 2004).

(2) Wing, S.; Wolf, S. Intensive livestock operations, health, and quality of life among eastern North Carolina residents. *Environ. Health Perspect.* **2000**, *108*, 233−238.

(3) Donham, K. J.; Reynolds, S. J.; Whitten, P.; Merchant, J. A.; Burmeister, L.; Popendorf, W. J. Respiratory Dysfunction in Swine Production Facility Workers−Dose−Response Relationships of Environmental Exposures and Pulmonary Function. *Am. J. Ind. Med.* **1995**, *27*, 405−418.

(4) Takai, H.; Pedersen, S.; Johnsen, J. O.; Metz, J. H. M.; Koerkamp, P. W. G. G.; Uenk, G. H.; Phillips, V. R.; Holden, M. R.; Sneath, R. W.; Short, J. L.; White, R. P.; Hartung, J.; Seedorf, J.; Schroder, M.; Linkert, K. H.; Wathes, C. M. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agric. Eng. Res.* **1998**, *70*, 59−77.

(5) Donham, K. J. The concentration of swine production−Effects on swine health, productivity, human health, and the environment. *Vet. Clin. North Am.−Food Anim. Pract.* **2000**, *16*, 559−597.

(6) Radon, K.; Monso, E.; Weber, C.; Danuser, B.; Iversen, M.; Opravil, U.; Donham, K.; Hartung, J.; Pedersen, S.; Garz, S.; Blainey, D.; Rabe, U.; Nowak, D. Prevalence and risk factors for airway diseases in farmers−Summary of results of the European Farmers' Project. *Ann. Agric. Environ. Med.* **2002**, *9*, 207−213.

(7) Von Essen, S.; Donham, K. Illness and injury in animal confinement workers. *Occup. Med.−State of the Art Rev.* **1999**, *14*, 337−350.

(8) Zhiping, W.; Malmberg, P.; Larsson, B.-M. Exposure to bacteria in swine-house dust and acute inflamatory reactions in humans. *Am. J. Respir. Crit. Care Med.* **1996**, *154*, 1261−1266.

(9) Cole, D.; Todd, L.; Wing, S. Concentrated swine feeding operations and public health: A review of occupational and community health effects. *Environ. Health Perspect.* **2000**, *108*, 685−699.

(10) Stärk, K. D. C. The Role of Infectious Aerosols in Disease Transmission in Pigs. *Vet. J.* **1999**, *158* (3), 164−181.

(11) Donham, K. J. Association of Environmental Air Contaminants with Disease and Productivity in Swine. *Am. J. Vet. Res.* **1991**, *52*, 1723−1730.

(12) Sutton, A. L.; Malayer, J. R.; Diekman, M. A.; Kelly, D. T.; Jones, D. D.; Long, G. G. Effects of Manure Management and Building Environments on Swine Health and Productivity. *Trans. ASAE* **1987**, *30*, 1764−1771.

(13) Martens, W.; Martinec, M.; Zapirain, R.; Stark, M.; Hartung, E.; Palmgren, U. Reduction potential of microbial, odour and ammonia emissions from a pig facility by biofilters. *Int. J. Hyg. Environ. Health* **2001**, *203*, 335−345.

(14) Takai, H.; Pedersen, S. A comparison study of different dust control methods in pig buildings. *Appl. Eng. Agric.* **2000**, *16*, 269−277.

(15) Richardson, L. J.; Hofacre, C. L.; Mitchell, B. W.; Wilson, J. L. Effect of electrostatic space charge on reduction of airborne transmission of Salmonella and other bacteria in broiler breeders in production and their progeny. *Avian Dis.* **2003**, *47*, 1352−1361.

(16) Pedersen, S.; Nonnenmann, M. W; Rautiainen, R. H.; Demmers, T. G.; Banhazi, T.; Lyngbye, M. Dust in pig buildings. *J. Agric. Saf. Health* **2000**, *6*, 261−274.

(17) Takai, H.; Jacobson, L. D.; Pedersen, S. Reduction of dust concentration and exposure in pig buildings by adding animal fat in feed. *J. Agric. Eng. Res.* **1996**, *63*, 113−120.

(18) Mankell, K. O.; Janni, K. A.; Walker, R. D.; Wilson, M. E.; Pettigrew, J. E.; Jacobson, L. D.; Wilcke, W. F. Dust suppression in swine feed using soybean oil. *J. Anim. Sci.* **1995**, *73*, 981−985.

(19) Nonnenmann, M. W.; Donham, K. J.; Rautiainen, R. H.; O'Shaughnessy, P. T.; Burmeister, L. F.; Reynolds, S. J. Vegetable oil sprinkling as a dust reduction method in swine confinement. *J. Agric. Saf. Health* **2004**, *10*, 7−15.

(20) Pedersen, S. Reduction of aerial dust in pig houses. *Dtsch. Tierarztl. Wochenschr.* **1998**, *105*, 247−250.

(21) Takai, H.; Moller, F.; Iversen, M.; Jorsal, S. E.; Bille-Hansen, V. Dust control in pig houses by spraying rapeseed oil. *Trans. ASAE* **1995**, *38*, 1513−1518.

(22) Zhang, Y.; Tanaka, A.; Barber, E. M.; Feddes, J. J. R. Effects of Frequency and Quantity of Sprinkling Canola Oil on Dust Reduction in Swine Buildings. *Trans. ASAE* **1996**, *39* (3), 1077−1081.

(23) Hinds, W. C. *Aerosol Technology. Properties, Behavior, and Measurement of Airborne Particles*; Wiley & Sons: New York, 1982.

(24) *NIOSH Manual of Analytical Methods*, 4th ed.; Publication No. 94-113; Centers for Disease Control and Prevention, U.S. Department of Health and Human Services: Cincinnati, OH, 1994.

(25) U.S. Environmental Protection Agency (U.S. EPA). National Primary and Secondary Ambient Air Quality Standards: Reference Method for the Determination of Fine Particulate Matter as PM in the Atmosphere. *Fed. Reg. 40CFR50 App L*, 1998.

(26) Lawless, P. A.; Rodes, C. E. Maximizing data quality in the gravimetric analysis of personal exposure sample filters. *J. Air Waste Manag. Assoc.* **1999**, *49*, 1039−1049.

(27) Henningson, E. W.; Ahlberg, M. S. Evaluation of Microbiological Aerosol Samplers—A Review. *J. Aerosol Sci.* **1994**, *25*, 1459−1492.

(28) Jensen, P. A.; Todd, W. F.; Davis, G. N.; Scarpino, P. V. Evaluation of 8 Bioaerosol Samplers Challenged with Aerosols of Free Bacteria. *Am. Ind. Hyg. Assoc. J.* **1992**, *53*, 660−667.

(29) Lin, X. J.; Willeke, K.; Ulevicius, V.; Grinshpun, S. A. Effect of sampling time on the collection efficiency of all-glass impingers. *Am. Ind. Hyg. Assoc. J.* **1997**, *58*, 480−488.

(30) Murray, P. R.; Baron, E. J.; Jorgensen, J. H.; Pfaller, M. A.; Yolken, R. H. *Manual of Clinical Microbiology*, 8th ed.; American Society for Microbiology Press: Washington, DC, 2003.

(31) *Improved Enumeration Methods for the Recreational Water Quality Indicators: Enterococci and Escherichia coli*; Report EPA/821/R-97/004; U.S. Environmental Protection Agency: Washington, DC, 2000.

(32) Chapin, A.; Rule, A.; Gibson, K.; Buckley, T.; Schwab, K. 2004. Airborne Multi-drug Resistant Bacteria Isolated from a Concentrated Swine Feeding Operation. *Environ. Health Perspect.* **2005**, *113* (2), 137−142.

(33) Eaton, A. *Standard Methods for the Examination of Water and Waste Water*; APHA/AWWA/WEF: Washington, DC, 1995.

(34) Siefert, R. L.; Scudlark, J. R.; Potter, A. G.; Simonsen, K. A.; Savidge, K. B. Characterization of atmospheric ammonia emissions from a commercial chicken house on the Delmarve peninsula. *Environ. Sci. Technol.* **2004**, *38*, 2769−2778.

(35) Thoni, L.; Seitler, E.; Blatter, A.; Neftel, A. A passive sampling method to determine ammonia in ambient air. *J. Environ. Monit.* **2003**, *5*, 96−99.

(36) Rosner, B. A. *Fundamentals of Biostatistics*, 5th ed.; Duxbury Press: Belmont, CA, 2000.

(37) Cormier, Y.; Israel-Assayag, E.; Racine, G.; Duchaine, C. Farming practices and the respiratory health risks of swine confinement buildings. *Eur. Resp. J.* **2000**, *15*, 560−565.

(38) Duchaine, C.; Grimard, Y.; Cormier, Y. Influence of building maintenance, environmental factors, and seasons on airborne contaminants of swine confinement buildings. *Am. Ind. Hyg. Assoc. J.* **2000**, *61*, 56−63.

(39) Predicala, B.; Urban, J.; Maghirang, R.; Jerez, S.; Goodband, R. Assessment of Bioaerosols in Swine Barns by Filtration and Impaction. *Curr. Microbiol.* **2002**, *44*, 136−40.

(40) Hinz, T.; Linke, S. A comprehensive experimental study of aerial pollutants in and emissions from livestock buildings. Part 1. Methods. *J. Agric. Eng. Res.* **1998**, *70*, 111−118.

(41) O'Shaughnessy, P. T.; Achutan, C.; Karsten, A. W. Temporal Variation of Indoor Air Quality in an Enclosed Swine Confinement Building. *J. Agric. Saf. Health.* **2002** Nov; *8* (4), 349−64.

(42) Ramachandran, G.; Adgate, J.; Pratt, G.; Sexton, K. Characterizing Indoor and Outdoor 15 min Average $PM_{2.5}$ Concentrations in Urban Neighborhoods. *Aerosol Sci. Technol.* **2003**, *37* (1), 33−45.

(43) Thorne, P. S.; Kiekhaefer, M. S.; Whitten, P.; Donham, K. J. Comparison of Bioaerosol Sampling Methods in Barns Housing Swine. *Appl. Environ. Microbiol.* **1992**, *58*, 2543−2551.

(44) Middendorf, P. J.; Lehocky, A.; Williams, P. Evaluation and field calibration of the Miniram PDM-3 aerosol monitor for measuring respirable and total coal dust. *Am. Ind. Hyg. Assoc. J.* **1999**, *60* (4), 502−11.