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Use of prototype side stream filtration system to control dust levels in a commercial swine farrowing building

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Abstract

Swine meat provides an essential global food source. Due to economies of scale, modern U.S. swine production primarily occurs indoors to maintain an optimal environment across the stages of swine production. Indoor concentrations of dust and contaminant gases in swine production buildings increase in the winter months due to reduced ventilation to optimal building temperature. In this study, an engineering control technology designed to recirculate the air in a swine farrowing room through a mobile air handling unit containing high-efficiency particulate filters was presented. A mobile solution could be easily deployed as an intervention method if an infectious disease outbreak occurs at a swine operation. The performance of this control technology was evaluated following deployment in a production farrowing barn for a period of 6 weeks during the winter in the Midwestern United States. Contaminant concentrations of inhalable dust, respirable dust, and carbon dioxide were measured in the room treated by the prototype system and compared to contaminant concentrations measured in an untreated "control" room. Over 6 weeks, the mean inhalable and respirable dust concentrations observed during the study period for the "treatment" room were 2.61 and 0.14 mg/m^3, respectively, compared to 3.51 and 0.25 mg/m^3, respectively, for the control room. The mobile recirculating ventilation system, operating at a flow rate of 45 m^3/min (5 room air exchanges per hour), reduced the inhalable dust by 25% and respirable dust by 48% as measured with a real-time aerosol monitor, when compared to the control room. In addition, no concentration differences in carbon dioxide and relative humidity between the treatment and the control rooms were observed. Inhalable and respirable concentrations of dust were significantly reduced (p=0.001), which demonstrates an essential improvement of the air quality that may prove beneficial to reduce the burden of disease among both workers and animals.

Keywords

Aerosol; Agriculture; Farrowing; Inhalable Dust; Respirable Dust; Side Stream Ventilation

Disclosure statement

No potential conflict of interest was reported by the author(s).

Introduction

Swine operations provide an essential and global food source, and the U.S. inventory of swine totaled more than 75 million in 2019, with an increase of 12% since 2015 (USDA 2022). Iowa produces more pigs than any other state, with more than 6,200 swine farms producing approximately 48 million pigs in 2019, representing one-third of the nation's inventory (IPPA 2019).

Modern swine production uses a business model designed to raise animals in large enclosed structures to achieve economies of scale (Ramos et al. 2018). Production conditions may generate occupational contaminants (e.g., gases, dust) that could affect worker health (Mitloehner and Calvo 2008). Airborne hazards in swine production include dust, bioaerosols, hydrogen sulfide, carbon dioxide, and ammonia (Thorne et al. 1992; Anthony et al. 2017). Inhalation exposure to hazards may place both animals and farmworkers at risk for disease (McClendon et al. 2015). Although farmworkers must wear respirators for protection, airborne contaminants can cause respiratory disease among pigs and may contribute to animal mortality (Done et al. 2005; Osadebe et al. 2013; Knetter et al. 2014). Historically, pulmonary symptoms, bronchial inflammation, and decreased pulmonary function have been associated with worker inhalation exposure in swine production (Donham et al. 1984; Dosman et al.1988; Schwartz et al.1995; Senthilselvan et al. 1997; Iversen and Dahl 2000). Pathogens, including the influenza virus, can be transmitted via dust and lead to outbreaks and increased pig morbidity and mortality (Ferreira et al. 2017). In addition, piglets inside farrowing production buildings could experience reoccurring influenza infections during the nursing period (Simon-Grifé et al.2012).

During an infectious disease outbreak within swine operations, airborne transmission is an important pathway (Hollenbeck 2016). In animal production buildings, both small (respirable) and larger (inhalable) particles may carry infectious agents. Therefore, controls that reduce aerosol concentrations across all size ranges may reduce disease transmission between animals and improve production goals. Furthermore, zoonotic transmission risks may be reduced by controlling disease transmission via aerosol between workers and animals. As infectious disease outbreaks continue to be problematic for the swine industry, new ventilation control technology designed to reduce dust and aerosols containing microorganisms may prove useful to reduce the animal disease burden in the swine industry.

There are several different occupational exposure standards for airborne particulate matter. The federal Occupational Safety and Health Administration (OSHA) limits exposure to "total dust" (i.e., all particles captured during pump sampling on an open face filter without regard to size) to 15 mg/m^3 and exposure to "respirable dust" (i.e., smaller particles captured using a size-selective cyclone sampler) to 5 mg/m^3 (OSHA 2006). "Total" dust refers to inert nuisance dusts, whether mineral, organic, or dust not otherwise regulated. The inhalable particles include particle sizes up to 100 μm and can deposit in the nasopharynx (upper respiratory tract) or deeper in the lung (ACGIH® 2019). However, measures of "total" dust do not meet a size-selective sampling criterion and may collect particles larger or smaller than the inhalable fraction depending upon the particle size distribution present. In contrast, the American Conference of Governmental Industrial Hygienists limits

exposure to 10 mg/m^3 for inhalable dust and 3 mg/m^3 for respirable dust (ACGIH 2019). However, for area measurements in a general agricultural facility, Donham et al. (1989) recommended occupational exposure concentrations for swine production facilities of 2.4 mg/m^3 for total dust and 0.23 mg/m^3 for respirable dust based on health outcomes during studies measuring multiple air contaminants in swine buildings. Dust from swine production contains biologically active components as well as inert components, which makes the application of OSHA Permissible Exposure Limits (PELs) to swine production work environments more challenging. Previous field studies have reported dust concentrations in swine production facilities ranging from 0.25 to 10 mg/m^3 (total) and 0.01 to 2.13 mg/m^3 (respirable) (Pedersen et al.2000). In addition, inhalable dust was measured among farms in North America and Europe, and concentrations ranged between 1.87 and 2.76 mg/m^3 across multiple stages of production. Specifically, Predicala and Maghirang (2003) measured total and inhalable dust concentrations inside swine facilities and found that concentrations ranged from 0.2 to 5.0 mg/m^3 and 0.3 to 6.6 mg/m^3, respectively, which was similar to what Reynolds et al. 2009 reported. Nonnenmann et al. (2004) measured total dust inside an educational swine production facility and reported concentrations near 2 mg/m^3 during swine grow-finishing. Anthony et al. 2017 performed a study at an educational swine farrowing facility in Iowa and reported winter dust averages of 1.4 mg/m^3 inhalable and 0.23 mg/m^3 respirable. Finally, Alvarado and Predicala (2019) measured respirable dust in swine grow-finish rooms in Saskatoon, Saskatchewan, Canada, and reported concentrations that spanned between 0.19 and 5.0 mg/m^3. Thus, dust concentrations reported in swine production operations are typically below the OSHA PELs. However, health effects associated with lower concentrations have been published (Donham et al. 1984b; Predicala and Maghirang 2003; O'Shaughnessy et al. 2010), likely due to exposures to complex mixtures of dust, bioaerosols including endotoxins, and irritant gases (ammonia) that workers are exposed to simultaneously. Additional information about factors influencing dust concentrations is needed as swine production technology advances, including room design, ventilation, and housing operations, and the effects of dust concentrations on swine and worker health should be considered.

Ventilation control technologies have been evaluated to reduce dust concentrations in swine barns. Van't Klooster et al. (1993) installed a recirculating air filtration system that reduced total dust concentrations by 40% during weaning. Lau et al. (1996) installed two recirculating air filtration systems in a farrowing farm: a fabric filter system decreased the inhalable dust concentrations by 64% and an electrostatic precipitator reduced the inhalable dust concentrations by 66%. Anthony et al. (2017) tested a recirculating ventilation system that used industrial-scale filtration and cyclone control technologies positioned outside a farrowing room on an educational farm, and the filtration control system provided reductions of 44% for inhalable dust and 20% for respirable dust. Wenke et al. (2018), inside grower/finisher rooms in a pig farm, found that three filtration technologies—supplied air with high-velocity filters, displacement ventilation using treated glass wool filters, and rooms with recirculating air filtration units—all achieved similar total dust concentrations, with 0.14 mg/m^3 for the first two methods and 0.12 mg/m^3 for the latter. Finally, in addition to the ventilation control technologies, studies inside grower/finisher rooms in a pig farm have been conducted on atomizing oil and water as another effective dust-mitigating technology,

showing a reduction between 23% and 80% of inhalable and respirable dust (Patterson and Adrizal 2005).

The objective of the current study was to assess the performance of a new experimental mobile recirculating ventilation system to reduce dust concentrations in a commercial swine farrowing building. If an infectious disease outbreak occurs in swine operations, a mobile solution could be a critical immediate interventional response. This study analyzed airborne contaminant concentrations in two farrowing rooms at a single pig farm. The farrowing rooms included industry-standard ventilation systems which only operated on a limited basis due to outdoor temperatures. The recirculating ventilation system was installed in one of these two farrowing rooms. The fans in the farrowing rooms were temperature controlled and did not operate during the study due to the low outdoor temperatures. The experimental air handling unit (AHU) for air treatment was designed to implement a filtration system and an ultraviolet C-band (UVC) germicidal array. However, this study evaluates the effectiveness of the system at reducing dust concentrations using filtration only. This experiment was necessary to confirm that system airflow rates targeting five air exchanges per hour were effective at controlling dust concentrations in swine farrowing production (Park et al. 2013). Future studies will evaluate the combined effects of filtration and UVC microbial disinfection technology on dust and bioaerosol concentrations and the effectiveness of UVC germicidal action on airborne bioaerosols in swine production.

Methods

Site description

A swine farrowing operation in the Midwestern United States was recruited to test a prototype air ventilation system from November 2017 to February 2018. The test site was constructed in 2007 and consisted of a farrowing building containing 12 side-by-side farrowing rooms, and each farrowing room contained 12 stalls. Two farrowing rooms adjacent to one another were used to conduct the study (Figure 1). Both rooms were 31.4 m by 6.7 m and contained 28 farrowing crates distributed in two rows. Each crate was 2.7 m by 0.65 m. Both rooms were equipped with a thermostat and humidistat, which controlled an L.B. White (Guardian) heater with a 17.58 kW capacity, mounted near the ceiling. Additionally, a radial exhaust fan and a window were located on the outside wall in each room. Under each room was a shallow gravity drain pit, with pit fans operating continuously to exhaust pit air. Three negative pressure-activated ceiling louvers (RayDot Industries, Cokato, MN) were located above the central aisle and were closed during the sampling period. Each room was equipped with a 1.22 m deep manure gravity drain pit. Identical pit fans in each room remained operational throughout the study, as was common practice to prevent the built-up manure gas in the rooms because it can cause explosive atmospheres. In the farrowing building, one of the farrowing rooms was designated the “treatment room” (TR), where ducts were installed for the experimental recirculating ventilation system located outdoors in an enclosed trailer, detailed below, that filtered the air that was then returned to the TR. An adjacent farrowing room was designated the “control room” (CR), where no additional air filtration was provided beyond normal room ventilation (radial exhaust fans, ceiling louvers) following typical in winter operation criteria. The new

experimental mobile recirculating ventilation system operated as designed for commercial swine production throughout this study.

Engineering control method

A recirculating ventilation system was designed and installed to remove air from a farrowing room via two 16-inch ducts, deliver it to a treatment trailer positioned outside the room, then return the treated air along the inside length of the room at ceiling height. Figure 1 presents the schematic of the system, Figure 2 illustrates the deployment via photographs, and Figure 3illustrates the AHU.

The AHU was constructed using an enclosed trailer (Cargo Express, EX series, Middlebury, IN) as a mobile platform and was positioned outside the TR with ductwork connecting to the test room (Figure 2A). The AHU was 3.7 m long, 1.7 m wide, and 1.8 m high (Figure 3). A centrifugal fan (Class L, 150 BCVR, 26-51 m^3/min., 374 Pa SP, Twin City Fan & Blower, Minneapolis, MN) was positioned inside the trailer to pull air from the test room, pass it through multiple filters, and then pass through a plenum area designed for future UVC disinfection studies.

The air filtration system consisted of four Minimum Efficiency Reporting Values (MERV) 8 pre-filters (Part No. 0474505, CLARCOR Inc., Franklin, TN), followed by four MERV 16 SLIMBOX-6 filters (Part No. 1124086, CLARCOR Inc.). The MERV 8 should capture dust at 85% efficiency or greater for particles 3 to 10 μm in size, and the MERV 16 filters should capture dust at 75% efficiency or greater for particles 0.3 to 1.0 μm in size (ASHRAE 2007). The total efficiency of stacked filters was 95%, 96%, and 98.5% efficient for 0.3–1, 1–3, and 3–10 um sizes, respectively (ASHRAE 2007). The MERV filters were positioned inside a housing unit (CLARCOR, Model 4000-P Ag Housing 4-Filter, Part No. 1196352, Jeffersonville, IN), which was positioned at the entrance of the AHU.

Treated air then passed through the fan and was returned to the building and distributed throughout the room via a flexible supply duct (Powerflow Design Fabric, Air Distribution Concepts, Delavan, WI), which was installed on the ceiling, at the center of the room (Figure 1B). The supply duct contained two rows of holes (⌀ = 2.54 cm) every 15 cm along its length that traversed the length of the farrowing room to maximize the even distribution of the treated air. Inside the TR, the window at the outside wall was replaced with an airtight barrier to connect the exhaust and return air ducts between the room and the AHU (Figure 2B). The 16-inch ducts into and out of the AHU were insulated and wrapped with a plastic barrier to minimize heat losses and condensation in the system.

After air passed through the treatment unit's filters, it entered the return plenum (Figure 3) before being exhausted from the AHU by the fan and returned to the TR. The return plenum was designed to house UV germicidal lamps for later disinfection studies. At the end of the return plenum, the centrifugal fan moved air through the system and returned it to the building through a 16" diameter duct, where the filtered air passed through the supply duct for distribution throughout the TR. The system supplied 45 m^3/min of filtered air to meet the five room air exchanges per hour (ACH) criteria recommended by Anthony et al. (2014) and was operated continuously throughout the study period. The researchers showed that

inhalable dust decreased from 1.3 mg/m^3 at 0.6 ACH to 0.5 mg/m^3 at 5 ACH. However, in case of an outbreak, higher air flows might be required for a temporary period.

Sampling methods

Analogous to Anthony et al. (2015) measurements were collected at three fixed locations in both the TR and CR over 24 hr, with 13 sampling events covering the 6.5-week test period. Measurements were collected at three locations for both rooms, as shown in Figure 1. At each of the six locations, measurement equipment hung 1.5 m off the floor (Figure 4). Table 1 identifies equipment used to measure concentrations of dust (i.e., inhalable, respirable) and carbon dioxide (CO_2), relative humidity (% RH), and temperature (°C) throughout the study. Inhalable dust was measured using an IOM sampler operated with a 25-mm PVC filter at a flow rate of 2 Lpm. The respirable dust was measured using a BGI GK2.69 Cyclone (4 μm 50% cutpoint) operated with a 37-mm PVC filter at 4 Lpm. A real-time aerosol monitor (pDR-1200, ThermoFisher Scientific., Waltham, MA) with attached respirable cyclone and filter (BGI GK2.69, Mesa Labs, Lakewood, CO) was also used at the center of the TR and CR to measure changes in respirable dust concentrations during deployment. The pDR real-time aerosol measurements were gravimetrically corrected using the respirable filter measurement accompanied by the monitor. Gravimetric dust concentrations were calculated using the filter mass difference, before and after sampling, and dividing it by the product of the mean pump flow rate and the total sampling time that the pump operated. Lab and field blanks were used to correct for error following standard protocols (NIOSH 2003). The filter corrected real-time pDR measurements will be referred to as pDR respirable dust from this point forward, compared to the discrete inhalable and respirable measurements. A 110-V wall outlet powered all pumps and real-time instruments during the measurements.

The samplers were placed at the height of a worker's breathing zone and as far as possible from the supply duct. It is possible that the samplers underrepresented room dust concentrations, given the proximity of the supply air. Additionally, to reduce the impact of error due to sampler location, triplicate samples were taken, and a room mean was calculated. Anthony et al. (Citation 2015) performed inhalable and respirable air sampling by distributing the dust air samplers at six locations throughout a farrowing room. No spatial significance was found for the inhalable dust when the building's ventilation system was on or off, and no spatial significance was found for the respirable dust concentrations when the ventilation system was off. For the respirable dust when the ventilation was on, Anthony et al. (Citation 2015) attributed the spatial differences to the crate's headcount and the fresh air from the AHU at one location in the room compared to other locations further from the entrance of the room.

Dust samples (inhalable, respirable, and pDR-1200 cyclone filter) were collected and analyzed gravimetrically in house. Flowrates for the respirable and inhalable dust samples were calibrated pre- and post-sampling using a calibration device (Defender 500, Mesa Labs, Lakewood, CO). Dust media were prepared in a stable balance room, desiccated for 7 days, then re-equilibrated to laboratory conditions for 24 hr before pre- and post-sampling weighing. A MT5 Mettler balance (Toledo, Columbus, OH) was used to obtain

pre- and post-filter weights. One field blank for each sampler type was collected during each monitoring event, and one inhalable and respirable laboratory blank were used.

Direct-reading monitors were used to obtain 24-h carbon dioxide and to spot check dust concentrations with particle sizes ranging between 0.1 and 35 μm going into and returning out of the filtration unit. A zero- and span-check (5,000 ppm, CO_2) were performed before and after each sample event for the CO_2 monitors. The DustTrak II (Model 8534, TSI, Shoreview, MN) was used in the TR to measure the air going to and from the AHU by sampling the inlet and outlet duct airways inside the TR. These samples were collected at the start and end of each 24-h sample event with a 3-min sampling frequency. All real-time monitors were collocated on-site for 5 minutes before deployment and after retrieval to quantify sensor differences separately from true room differences.

The study began once sows were placed in the farrowing rooms. We sampled for 13 of the 28-day farrowing cycle. Data collection started on December 29, 2017, and was completed on February 12, 2018. Data were collected twice a week during the farrowing period. The measurement equipment was deployed for 24 h, where deployment was done on one day (Monday and Wednesday), and retrieval was done on other days (Tuesday and Thursday). The number of sows and piglets was recorded in each room during each visit to the farm (i.e., equipment deployment or retrieval). Outdoor temperature data were used from a meteorological monitoring station located 5.6 km from the study site (WeatherUnderground 2018).

Data analysis

For each 24-h sample period and for each room, arithmetic means and standard deviations were computed for each contaminant concentration. The inhalable and respirable mass concentrations represent 24-h measurements for each room.

To compare concentrations between rooms, the normality of 24-hr concentration averages over the study period was tested using Shapiro-Wilks test. If the Shapiro-Wilks identified non-normal data ($p < 0.05$), a nonparametric Levene's test and Wilcoxon test were performed for comparison studies. Otherwise, a parametric Levene's test and *t*-test were performed. In addition, to compare contaminant concentrations between the TR and CR, the equality of variances (i.e., Levene) was tested for the 24-hr average concentrations for the gravimetric and real-time measurements. Finally, multiple linear regression, using backward elimination ($p < 0.05$), was used to determine which production variables (i.e., animal occupancy, outdoor daily average temperature) could help estimate contaminant concentration in the TR and CR. Animal occupancy may be associated with dust concentrations due to swine feeding, dander, or daily activities. In addition to the number of sows and piglets, daily average outdoor temperatures may affect dust or CO_2 concentrations due to extremely low temperatures reducing ventilation and increasing heating system use. The same analyses were used to assess the normality of treated (supply plenum) and untreated (return plenum) dust measurements and to assess significant differences. A criterion of $\alpha = 0.05$ was used to interpret the statistical significance.

Results

Prior to the experiment, preliminary inhalable dust and respirable dust sampling was conducted during a single day and observed 3.43 mg/m^3 and 0.15 mg/m^3 in the control room and 3.49 mg/m^3 and 0.31 mg/m^3 in the treatment room, respectively. The number of sows and piglets was observed across five available farrowing rooms at the commercial farm on multiple days. We observed that the number or sizes of animals were significantly different based on the room, which may explain differences in respirable dust concentrations between the TR and CR.

The TR ventilation system functioned as installed, exhibited no pressure drop, and was not disrupted by the installation and use of the recirculating air ventilation system that only recirculated the air with the AHU, where no air was removed or added, and the pit fan provided exhaust air, which was not treated. In addition, the pressure drop in the trailer filters changed during the experiments from 50 to 170 Pa. However, the increase in pressure drop in the filters did not affect the pressure balance within the building, where the RayDot ceiling louvers remained closed for the entire duration of the study. In addition, the system airflow was measured at various times during the study and did not change. However, for longer-term installations, pressure drop across the filter bank should be tested regularly using a pressure manometer.

Dust concentrations were significantly lower ($p \leq 0.05$) in the TR compared to the CR (Table 2). Comparing the TR and CR, the mean inhalable dust and pDR respirable dust concentration reductions were 25% and 48%, respectively. The respirable dust concentrations were under OSHA's 8-hr TWA PEL for respirable "nuisance" dust (i.e., 5 mg/m^3). The concentrations of inhalable dust we observed were less than the OSHA's 15 mg/m^3 8-hr TWA PEL for total dust. No significant differences in concentrations of CO_2 and relative humidity between the TR and CR were observed. Throughout the study, three inhalable dust measurements were not collected due to technical error.

Inhalable dust concentrations were not normally distributed (Shapiro-Wilk $p = 0.003$) and the concentrations between TR and CR were significantly different (Table 2). The nonparametric Levene's test verified that the inhalable measurements for the rooms did not have equal variances ($p = 0.001$). Similarly, a parametric Levene's test was used to verify the homogeneity of variances between samples and verified that the variances ($p < 0.05$) in the measurements were not equal between the TR and CR for respirable dust, pDR respirable dust, and CO_2. A Wilcoxon test demonstrated that the inhalable dust concentrations in the TR were significantly different ($p < 0.001$) than the CR measurements.

Dust concentration measurements within the return plenum and supply plenum were significantly different ($p = 0.001$) and normally distributed (Table 3). In addition, the results of the Levene's test indicate that observed variance between contaminant concentrations in the supply plenum and return plenum for the TR are not equal ($p = 0.001$).

The 24-hr average measurements for the inhalable dust, respirable dust, pDR respirable dust, and CO_2 measurements are shown in Figure 5. The AHU provided a 25%, 44%, and 48% reduction between the TR and the CR for the inhalable dust, respirable dust, and pDR

respirable dust measurements, respectively. The range of piglets in the TR and CR was similar (2 to 353) over the project period, and the number of sows in the rooms were 27 (TR) and 28 (CR). The outdoor daily average temperature range was between −17 and 6 °C.

Linear regression results suggest that for the TR, only the number of piglets significantly ($p < 0.001$) affected the concentrations of the inhalable dust, respirable dust, and pDR respirable dust concentrations. Also, the number of sows and piglets and the range of outdoor temperatures significantly affected the CO_2 room concentrations. Therefore, the following relationships were identified

$$\text{Inhalable dust(mg/m3)} = 13.00 \times 10 - 3 \times \text{Piglet} + 336.00 \times 10 - 3(\text{R2} = 0.63) \quad (1)$$

$$\text{Respirable dust(mg/m3)} = 0.10 \times 10 - 3 \times \text{Piglet} + 84.00 \times 10 - 3(\text{R2} = 0.23) \quad (2)$$

$$\text{PDR respirable dust(mg/m3)} = 1.00 \times 10 - 3 \times \text{Piglet} + 16.00 \times 10 - 3(\text{R2} = 0.42) \quad (3)$$

$$\text{CO2(ppm)} = 2384.00 + 3.40 \times \text{Piglet} - 95.00 \times \text{Temp}(\text{R2} = 0.78) \quad (4)$$

where *Piglet* is the daily count of piglets in the room (range: 0 to 354), *Sow* is the daily count of sows in the room (range: 27 to 28), and *Temp* is the he daily outside temperature (°C; range: −17 °C to 6 °C).

Finally, the linear regression results suggests that only the number of piglets significantly affects the DustTrak II exhaust air measurements:

$$\text{DustTrak(mg/m3)} = 1.00 \times 10 - 3 \times \text{Piglet} + 1.20(\text{R2} = 0.13) \quad (5)$$

For the CR, the linear regression results suggest that the number of piglets significantly ($p < 0.001$) affects the concentrations of the inhalable dust and respirable dust concentrations. In addition, the number of piglets and outdoor temperature affects the pDR respirable dust concentrations, and only the outdoor temperature affects the CO_2 room concentrations. Therefore, the following relationships were identified as:

$$\text{Inhalable dust(mg/m3)} = 12.00 \times 10^{-3} \times \text{Piglet} + 0.29.(\text{R}^2 = 0.73) \quad (6)$$

$$\text{Respirable dust(mg/m3)} = 1.00 \times 10^{-3} \times \text{Piglet} + 0.36.(R^2 = 0.66) \quad (7)$$

$$\text{PDR respirable dust(mg/m3)} = 1.00 \times 10 - 3 \times \text{Piglet} - 8.00 \times 10^{-3} \times \text{Temp} - 30.00 \times 10 - 3(R^2 = 0.75) \quad (8)$$

The Sow and Piglet count range were the same presented in the TR. The linear relationship assumption between the CO_2 concentrations and the number of piglets was not valid, where only the effects of the outdoor temperature were linearly correlated with the CO_2 concentrations. Therefore, no CO_2 linear regression model was included for the CR.

Discussion

The inhalable and respirable dust concentrations in the TR were lower compared to the CR. These observations demonstrate that the prototype AHU with an airflow rate (i.e., 45 m^3/min) targeting five room air exchanges per hour is effective at reducing dust concentrations in commercial swine farrowing. Therefore, based on the room exchanges and average sow of 28 in each room, the air exchange per sow for the TR and CR was ~2 m^3/min/sow. Also, no significant difference in CO_2 concentrations between the TR and CR was observed because the ventilation was nearly similar. Therefore, CO_2 will not increase as a result of using the recirculating system as it does not generate CO_2. Given the effectiveness of the AHU at reducing indoor dust concentrations, the UV bioaerosol treatment system can be designed for system flow rates observed to be effective for disinfection of bioaerosols in this experiment (i.e., 45 m^3/min targeting five ACH).

The 24-hr average daily measurements for the inhalable dust, respirable dust, pDR respirable dust concentrations measured at the study site were well below OSHA 8-hr TWA PEL of 15 mg/m^3 for total dust and 5 mg/m^3 for respirable dust. However, in the CR, the inhalable dust and respirable dust measurements exceeded recommended exposure concentrations specified by Donham et al. (1984). Inhalable dust concentrations were the highest when there were 200 or more piglets in the room. The respirable dust measurements for the TR were below recommended exposure concentrations of 0.23 mg/m^3, except for day 13. Additionally, respirable dust concentrations were nearly double in the CR compared to the TR (Table 2), demonstrating effective control. The respirable dust and pDR respirable dust concentrations were comparable, suggesting that the middle of the room can be represented by one of these locations, but these values do not necessary represent the average respirable dust concentrations of the room. Reeve et al. (2013) performed respirable air sampling at seven locations throughout a farrowing room and concluded that multiple fixed stations are representative of determining room contaminant concentrations.

Peak dust concentrations measured in this study were higher compared to measurements conducted in other similar studies. Specifically, in the TR the maximum inhalable and respirable concentrations were 3.86 and 0.3 mg/m^3, respectively, compared to 1.4 and

0.26 mg/m^3, observed by Anthony et al. (2015). Similarly, Lau et al. (1996) reported that the maximum inhalable concentration of 1.5 mg/m^3 in a room being treated with a filtration system. These differences could be due to the different filtration methods used in the ventilation systems and perhaps the higher air exchange per sow of 2 m^3/min/sow in this study compared to 1.5 m^3/min/sow in Anthony et al. (2015). In addition, similar to what Anthony et al. (2015) observed, the crates were designed for limited sow mobility (i.e., only standing and laying down) to protect the piglets. Anthony et al. (2015) used a shaker dust collector and achieved a larger reduction in inhalable dust concentrations (33%) and a comparable reduction in respirable dust (41%) using a room ACH of five. Lau et al.1996 used two recirculating air filtration systems to achieve a larger reduction in inhalable dust (64%), compared to this study. Anthony et al. (2015) conducted their study on an educational swine farm, which may have different dust generation characteristics compared to the commercial swine barn used in this study. Lau et al. (1996) had a room ACH of 20, which may explain the higher observed reduction in inhalable dust concentrations as their targeted ACH was four times what was used in this study.

For the 13-day measurement cycle, the TR had 3 days with an average reduction of 352 ppm in CO_2, compared to 10 days with an average increase of 426 ppm in CO_2 concentrations. In contrast, the air treatment system described in Anthony et al. (2015) resulted in a maximum increase in CO_2concentration of 100 ppm. This observation could be due to the study site having a higher air exchange per sow of 2 m^3/min/sow compared to 1.5 m^3/min/sow in Anthony et al. (2015). In addition, the changes in CO_2 concentrations could have been due to a building leakage when installing the AHU in which the pressure changes could result in increased building leakage leading to reduced CO_2 measurements. In contrast, Wenke et al. (2018) reported a 300 ppm lower CO_2 concentration in the TR during their study compared to what was observed in their CR. However, in this study, there was an average of 788 pigs inside the TR compared to 825 in the CR, which suggests that observed differences in CO_2 across studies shown in Table 4 is likely due to the number of pigs in the rooms.

For the linear regression models, number of piglets in the room explained a significant proportion of the variability of dust concentrations in the farrowing rooms. This observed relationship was expected and reported elsewhere (Anthony et al.2015, 2017). In this study, inhalable dust concentrations in the TR and CR were lower than 1 mg/m^3 on the first day of the experiment when no piglets were in the room, compared to 3 mg/m^3 and 7.5 mg/m^3 for the TR and CR, respectively, on day 10 when the number of piglets was 353. A similar association was observed between the number of pigs and respirable dust concentrations, however, was not as apparent. For example, respirable dust concentrations were only slightly higher in the TR compared to the CR for day 5. Increasing CO_2 concentrations were associated with decreasing outdoor temperature. However, the linear relationship assumption between the CO_2concentrations and number of piglets was only valid for the TR. Differences in CO_2 concentrations may be due to other uncharacterized factors (e.g., heater use, pit conditions). In comparison to this study, linear regression models, Anthony et al. (2017) found a significant linear correlation between piglets and inhalable concentrations, but Anthony et al. (2017) did not find an association between piglets and respirable dust concentrations. Which could have been due to the smaller number of pigs (7–18) in the swine educational farrowing facility compared to the commercial farrowing facility (788–

825) used in this study. Future ventilation technology could be programmed to adjust airflow rates according to real-time dust concentrations or number and size of the pigs in the room.

Study Limitations

Real-time instruments may experience sensor drift due to extended sampling. To address this problem, instruments were collocated both before and after deployment. Carbon dioxide and real-time aerosol monitors were adjusted if the concentrations differed by 100 ppm and 10% for dust, respectively. In addition, this study was performed in two farrowing rooms on one commercial production swine farm. Therefore, the generalization of the results from this study to other swine barns is challenging given building design variability. However, the locations used for this study represented modern commercial swine farrowing practices that are similar across the United States. In addition, performing one-day measurements of the inhalable and respirable concentrations in each room prior to the start of the study might not have been sufficient to characterize the similarity of the rooms. Although challenging given study resources, the rooms could have been characterized over multiple days across several weeks prior to installing the prototype ventilation system to ensure the similarity in the rooms.

Workers spend more time in farrowing rooms than in other stages of production (i.e., performing pig care, vaccinations, tail docking etc.) (Anthony et al. Citation 2015). Therefore, sampling was performed near the walkways in farrowing rooms to represent workplace exposure, but as far from the supply air duct as possible. It is possible that the samplers underrepresented room dust concentrations, given the proximity of the supply air. However, as the workers spend most of their time in the walkway, this was the correct location to estimate worker exposure. It is unlikely that the samplers would have been in a micro-plume of treated air due to the proximity of the air supply holes in the duct. The goal of the study was to assess the performance of a new experimental mobile recirculating ventilation system to reduce dust concentrations in a commercial swine farrowing building and determine whether increased filtration would improve the environment for the animals and workers. Demonstrating the cost-effectiveness of the system was not the goal of this study. Ongoing research demonstrates the effectiveness of the ventilation system with additional technology (i.e., UVC light) that has been added to target problematic pathogens. In addition, ongoing funded work focuses on cost-benefit analysis of prototype ventilation systems in commercial production.

Conclusions

The ability of an AHU utilizing filtration and five ACH to reduce dust concentrations inside a commercial swine farrowing room was evaluated. The filtration system operated at 45 m^3/min and reduced the average room concentrations of inhalable and pDR respirable dust by 25% and 48%, respectively. The observed differences in dust concentrations across TR and CR were statistically significant. This work was the first study conducted in the United States to reduce inhalable and respirable dust concentrations in a commercial swine barn using a matched TR and CR design. These results represent the first study in a series of experiments evaluating a mobile AHU designed for dust reduction. Future

studies will evaluate the mobile AHU for reducing dust and bioaerosol concentrations using filtration and UVC technology. Understanding the effectiveness of the engineering control technology's intended to reduce worker and animal exposures to dust and bioaerosols will drive technology development to protect both worker and animal health in swine production.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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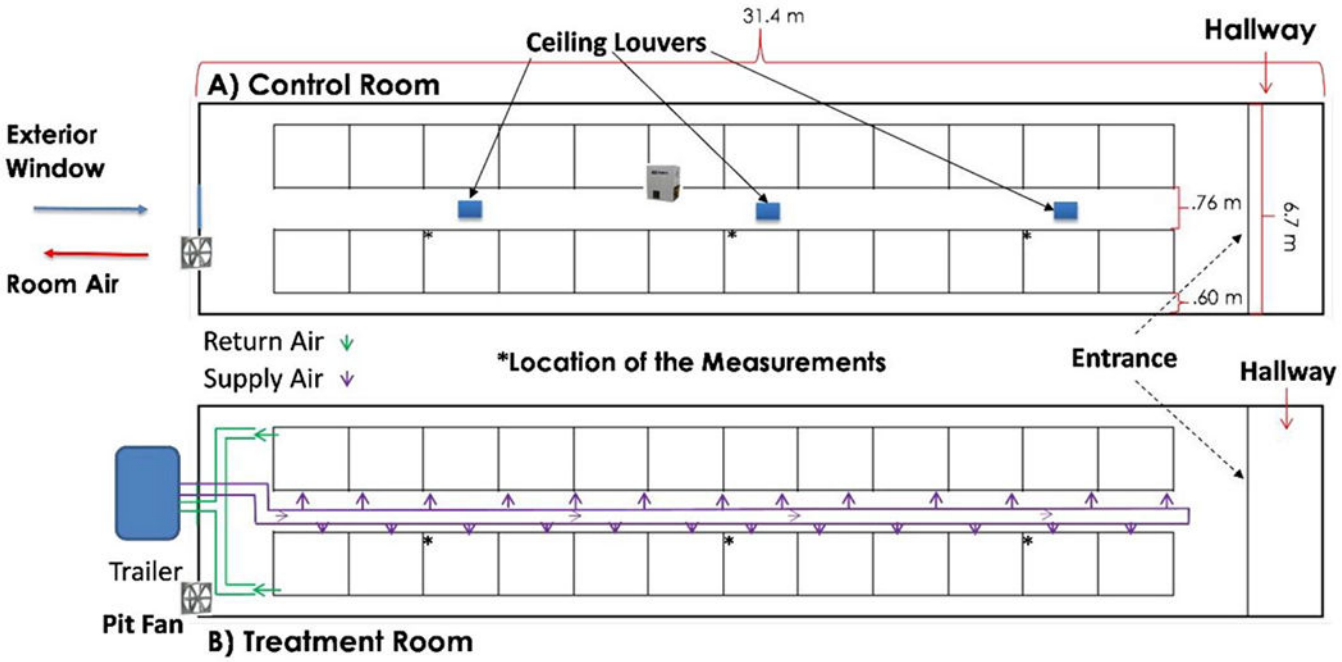

Figure 1.

Layout for (A) control room and (B) treatment room layout showing the mobile air handling unit and duct system installed outside the treatment room, the ceiling louvers, radial fans, entrance, and the location of the measurements. This figure does not represent a floor plan but is only intended to provide a simple schematic of both rooms.

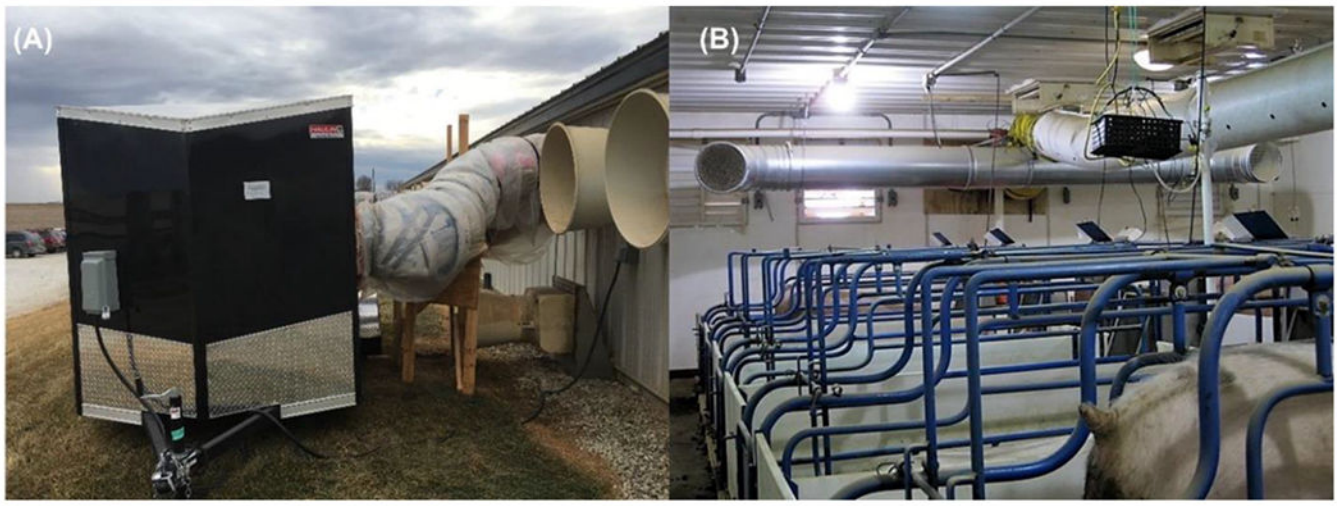

Figure 2.
Ductwork installed in the treatment room: (A) outside attached to air handling unit and (B) inside the treatment room.

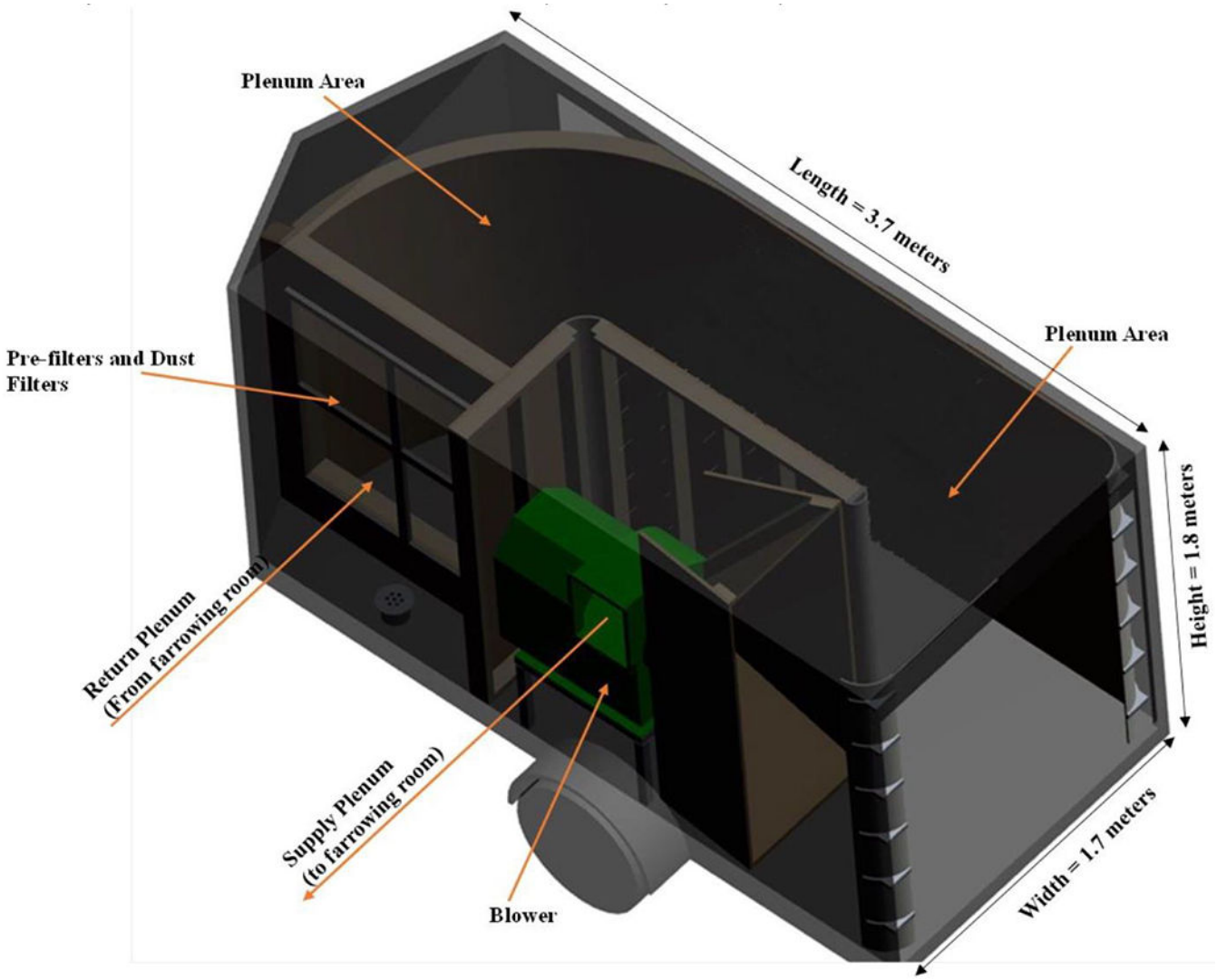

Figure 3.
Mobile recirculating ventilation system designed to incorporate filtration for dust control and a plenum area for bioaerosol control (future experiment).

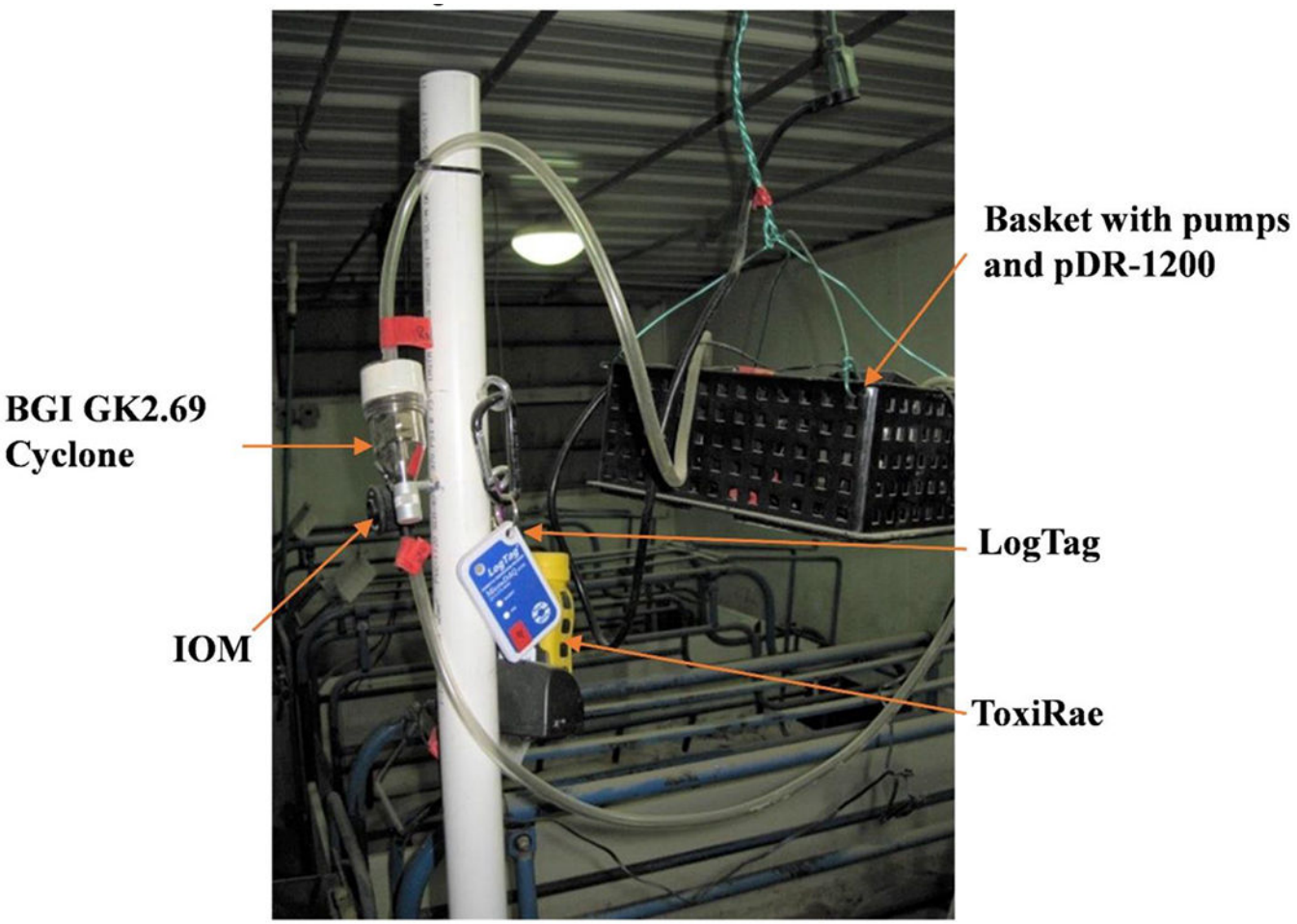

Figure 4.
Inhalable dust (IOM), respirable dust (BGI cyclone), direct reading respirable dust (pDR-1200) and carbon dioxide (ToxiRae), indoor temperature and relative humidity (LogTag) data collection in swine farrowing rooms.

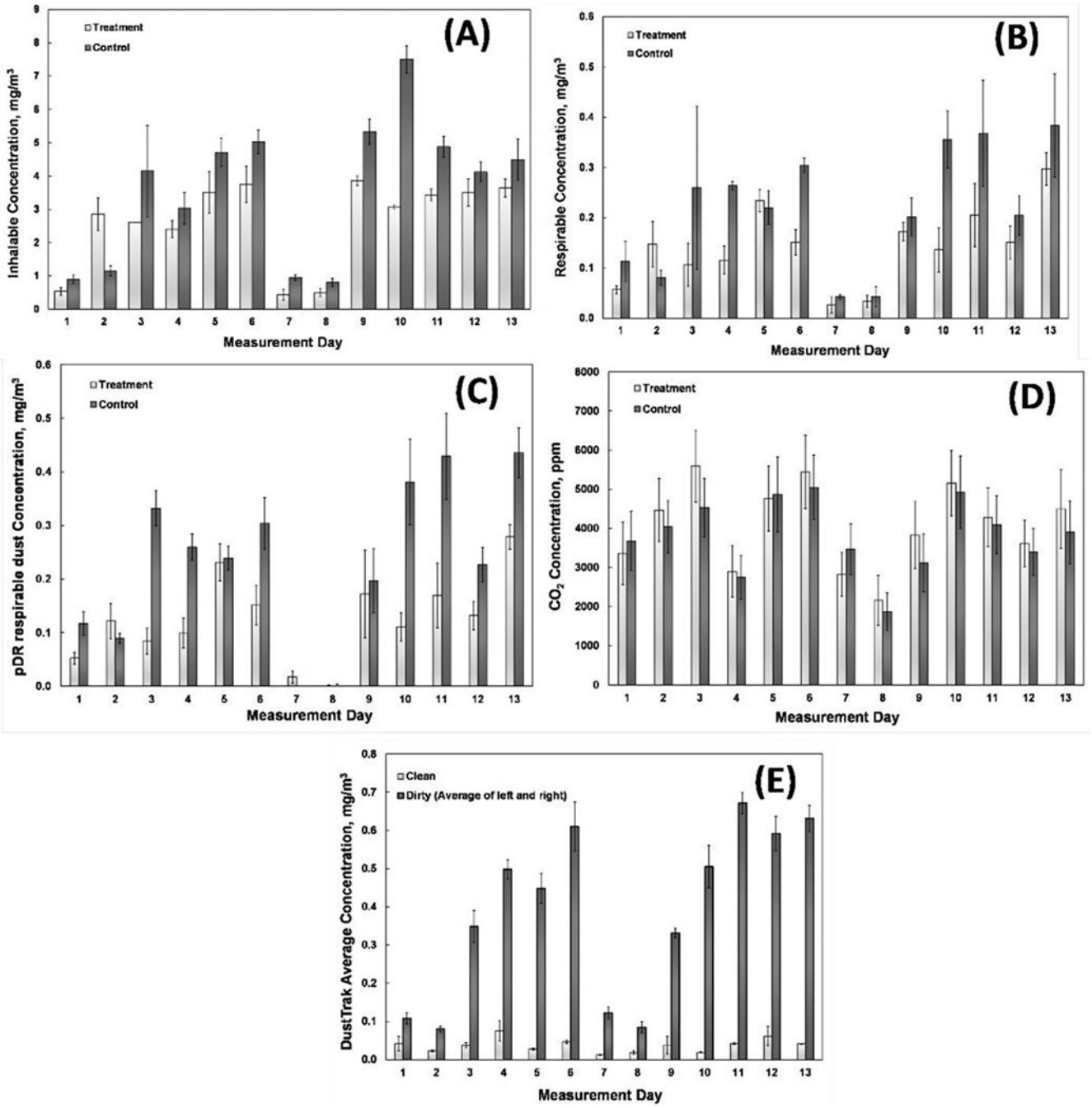

Figure 5.

The 24-hr average concentrations inhalable dust (A), respirable dust (B), pDR respirable dust (C), and CO_2 (D) in swine farrowing treatment room (TR) and control room (CR). Recirculating ventilation system exhaust air and reentry dust concentrations for the TR (E). The y-axis error bars represent the standard deviation in the measurements among the three sampling locations in the TR and CR.

Table 1.

Monitoring equipment used for quantitative evaluation.

Exposure, units	Device	Measurement type	Operation
Inhalable dust, mg/m^3	IOM-plastic internal cassette with 25-mm PVC filter (5-mm pore size) operated with PCXR4 pumps using AC power (SKC, Eighty Four, PA)	24-hr gravimetric	2 Lpm
Respirable dust, mg/m^3	BGI GK2.69 Cyclone (4-μm 50% cutpoint, Thermo-Electron Corp, Waltham, MA) with 37-mm PVC filter (5-μm pore size) operated with PCXR4 pumps using AC power	24-hr gravimetric	4.2 Lpm
pDR respirable dust, mg/m^3	pDR-1200 (Thermo-Electron Corp, Waltham, MA) with BGI GK2.69 Cyclone (4-μm 50% cutpoint) and 37-mm PVC filter (5-μm pore size)	Real-time	4.2 Lpm, 60-sec logging interval
Carbon dioxide, ppm	ToxiRae (Rae Systems, San Jose, CA)	Real-time	60-sec logging interval
Temperature, °C humidity, %	LogTag HAXO-8 (MicroDAQ, Contoocook, NH)	Real-time	60-sec logging interval
Short-term dust concentrations in duct, mg/m^3	DustTrak II Model 8534 (TSI Inc, Shoreview, MN)	Real-time	15-sec logging interval

Table 2.

Mean (standard deviation) exposure concentrations and sample number (*N*) in swine farrowing.

	24-hr mean (SD) from three locations for each room		Parametric test, p-value		Nonparametric test, p-value	
Exposure	**Treatment**	**Control**	**Levene**	**Two sample t-test**	**Levene**	**Wilcoxon**
Inhalable dust (gravimetric) mg/m^3	2.61(1.33)[B] N =36	3.50 (2.04) N=38	0.002	0.002	0.001	<0.001
Respirable dust (gravimetric) mg/m^3	*0.14 (0.07)*[A] N=39	*0.25 (0.12)* N= 39	0.001	<0.001	-	-
PDR respirable dust (pDR) mg/m3	*0.12 (0.08)* N=13	*0.23 (0.14)* N=13	0.04	0.03	-	-
CO_2, ppm	*4068 (1041)* N=39	*3822 (917)* N=39	0.3	0.3	-	-

[A] Italics indicates that data were not normally distributed.

[B] Normally distributed.

Table 3.

Mean (standard deviation) and sample count (*N*) of dust measured by the DustTrak II at the exhaust air and reentry air in the treatment room in swine farrowing.

	Measurements		Parametric Tests	
Exposure	**Reentry air**	**Exhaust air**	**Levene**	**Two-sample t-test**
DustTrak II mg/m^3	0.04 (0.017) * N=13	0.39 (0.22) * N=13	0.001	0.001

* Normally distributed

Table 4.

Average increase/reduction in CO_2 concentrations between studies.

Study	Average CO_2 (ppm) change in TR compared to CR	Increase/reduction
This study: 3 out of 13 days	352	Reduction
This study: 10 out of 13 days	426	Increase
Anthony T. R. et al. (2015)	100	Increase
Wenke et al. (2018)	300	Reduction