Methane and Carbon Dioxide Emission from Two Pig Finishing Barns

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Agricultural activities are an important source of greenhouse gases. However, comprehensive, long-term, and high-quality measurement data of these gases are lacking. This article presents a field study of CH_4 and CO_2 emission from two 1100-head mechanically ventilated pig (*Sus scrofa*) finishing barns (B1 and B2) with shallow manure flushing systems and propane space heaters from August 2002 to July 2003 in northern Missouri. Barn 2 was treated with soybean oil sprinkling, misting essential oils, and misting essential oils with water to reduce air pollutant emissions. Only days with CDFB (complete-data-full-barn), defined as >80% of valid data during a day with >80% pigs in the barns, were used. The CH_4 average daily mean (ADM) emission rates were 36.2 ± 2.0 g/d AU (ADM ± 95% confidence interval; animal unit = 500 kg live mass) from B1 (CDFB days = 134) and 28.8 ± 1.8 g/d AU from B2 (CDFB days = 131). The CO_2 ADM emission rates were 17.5 ± 0.8 kg/d AU from B1 (CDFB days = 146) and 14.2 ± 0.6 kg/d AU from B2 (CDFB days = 137). The treated barn reduced CH_4 emission by 20% ($P < 0.01$) and CO_2 emission by 19% ($P < 0.01$). The CH_4 and CO_2 released from the flushing lagoon effluent were equivalent to 9.8 and 4.1% of the CDFB CH_4 and CO_2 emissions, respectively. The emission data were compared with the literature, and the characteristics of CH_4 and CO_2 concentrations and emissions were discussed.

Greenhouse gas emissions have been one of the major environmental protection concerns because they are related to global climate changes. In 2005 the agricultural sector in the United States was responsible for emissions of 536.3 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 7.4% of total U.S. greenhouse gas emissions. Methane and N_2O were the primary greenhouse gases emitted by agricultural activities (USEPA, 2007). Similarly, the agricultural sector in Canada contributes about 8% of greenhouse gas emissions in that country (Kebreab et al., 2006).

Recent inventories suggested that livestock manure makes a significant contribution to global CH_4 emissions (Moller et al., 2004). Of the anthropogenic greenhouse gas emissions in Denmark, animal manure contributes an estimated 40% of CH_4 and 20% of N_2O (Sommer and Moller, 2000). The annual emission of CH_4 from stored animal manure in Denmark is estimated to be 28, 000 Mg (Husted, 1994). As a consequence, greenhouse gas emissions can potentially become a limiting factor in the development and sustainability of livestock production (Su et al., 2003). There are only a few journal publications so far that have studied CH_4 emissions from pig barns, and most of them were based on short-term or discrete measurements (Osada et al., 1998; Delcourt et al., 2001; Nicks et al., 2003; Su et al., 2003; Nicks et al., 2004; Amon et al., 2007; Dong et al., 2007).

Carbon dioxide from livestock is not listed as an important greenhouse gas source by the USEPA and the Intergovernmental Panel on Climate Change. However, CO_2 is one of the toxic gases of concern related to the health risks of exposure for people living in the surrounding areas (Heederik et al., 2007). It was also used as a tracer gas for ventilation estimation in pig houses (Blanes and Pedersen, 2005). Only a few publications reported CO_2 emission from pig barns under field conditions. There are three sources of CO_2 from pig barns. In addition to the exhalation of animals (Ni et al., 1999a) and release from manure (Ni et al., 1999b), combustion space heaters using propane or natural gas also emit CO_2. The daily CO_2 emission during a 6-d study at constant airflow rate averaged between 81 and 120 g/h per pig and included diel variations from

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Abbreviations: ADM, average daily mean; AU, animal unit, equals 500 kg live mass; CD, complete data, defined as > 80% of valid data during a day for a single measurement; CDFB, complete-data-full-barn day, defined as > 80% of valid data during a day with > 80% pigs in the barns; DAC, data acquisition and control; RH, relative humidity.

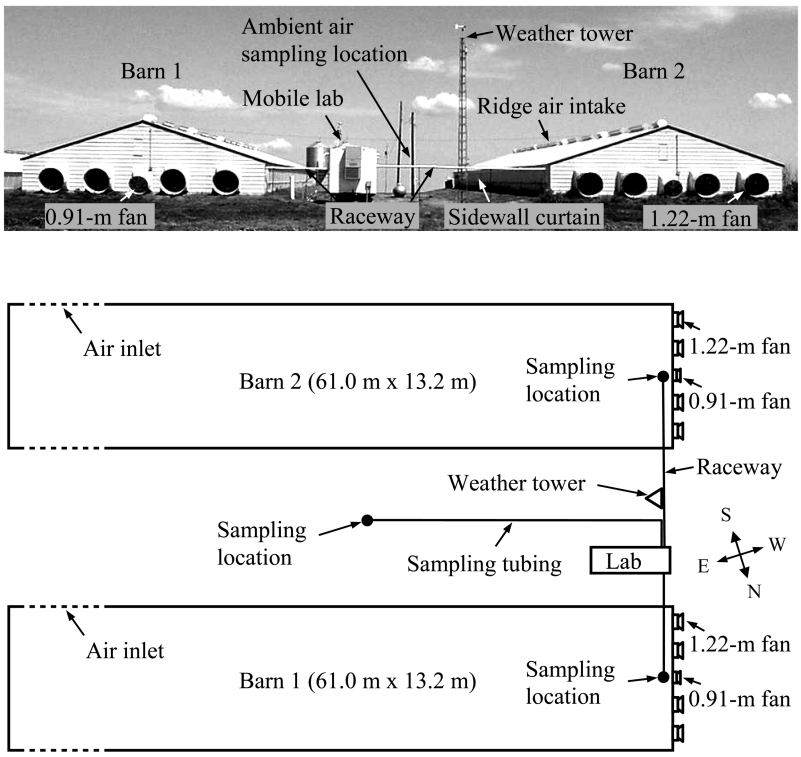

Fig. 1. West side view (top) and floor plan (bottom) of the two barns.

61 to 249% of the mean. Emission of CO_2 was correlated to the barn air temperature and animal activity (Jeppsson, 2002).

Although an increasing number of investigations into greenhouse gases from animal industry have been conducted, the emission factor data vary (Osada et al., 1998). The variance is observed because the studies typically represent short-term measurements and a limited number of emission circumstances, which could be substantially different geographically, climatically, seasonally, and in terms of emission sources and farm practices. Temporal variations of gas emission may not be detected in short duration measurements or low-frequency sampling. Laboratory studies, although more controllable, might result in data that are significantly different from data obtained under field conditions. Some published estimation and modeling approaches for greenhouse gas emissions from agricultural sources have not been validated against measured data due to the scarcity of year-round studies (Park et al., 2006). Therefore, continuous, long-term, and high-quality measurements are needed to obtain accurate and unbiased data for properly assessing the quantity and characteristics of greenhouse gas emissions (Jungbluth et al., 2001).

Vegetable oil sprinkling and essential oil misting have been studied as mitigation techniques to reduce dust, odor, gases, and airborne bacteria at animal buildings (Zhang et al., 1996; Pahl et al., 2002; Nonnenmann et al., 2004; Varel et al., 2004, 2006; Rule et al., 2005; Kim et al., 2006). However, their effects on reducing gas emissions were inconsistent. More investigations are needed to evaluate these methods.

The objective of this paper is to report quantities and characteristics of CH_4 and CO_2 emissions and to assess the effect of oil treatments on their emissions at two commercial pig finishing barns in northern Missouri during an 11-mo field study.

Materials and Methods

Barn Characteristics

The two mechanically ventilated pig finishing barns with shallow manure flushing systems, denoted as B1 and B2 (Fig. 1), were constructed in 1995. Each barn had dimensions of 61.0 × 13.2 × 2.4 m (L × W × H) and a capacity of 1100 pigs, with two rows of 24 pens and a center alley. New pigs were sent into the barns at about 25 kg and were marketed at about 123 kg. The growth cycles were 4 to 5 mo long. The pigs were fed identical diets between the two barns.

The barns had ceiling air inlets and 1.52-m high curtain air inlets on both north and south sidewalls. Fresh air typically entered the barn from ridge air intakes into the attic and through the ceiling air inlets. During warm weather, the sidewall curtains, about 7 m long near the east end wall, were open, allowing additional fresh air to enter the barns and exhaust from the west end wall fans. The barns were always under tunnel-ventilated conditions during normal operation. Each barn had three propane space heaters (Model C225, Automated Production Systems, Assumption, IL) to keep the barn warm when the indoor temperature was too low in cold weather.

There were five ventilation fans in the west end wall of each barn. One continuous 0.91-m direct-drive variable speed fan (Model MXB-4815, Airstream Ventilation Systems, Assumption, IL) was located in the center of the wall. The other four fans were 1.22-m diameter-belted exhaust fans (Model

GPMA-36, Airstream Ventilation Systems, Assumption, IL). The five fans were controlled in five stages based on barn temperature. The 0.91-m fans were always operating to provide minimum ventilation to the barns.

Manure was collected in four shallow gutters along the length of the barns under a fully slatted concrete floor. Lagoon effluent was flushed in the gutters from the east end and flowed out of the manure outlets at the west end of the barns. Each gutter was flushed for 2 min every 116 min. All four gutters were flushed one after another during the 116-min period with 29 min apart so that there were about 50 flushing events in each barn in a day.

Barn 2 was treated with soybean oil sprinkling from 31 Aug. 2002 to 28 Feb. 2003, misting of essential oils from 5 Mar. to 10 Apr. 2003, and misting of essential oils with water from 12 June to 16 July 2003 to evaluate their effects on air pollution reduction. The soybean oil was applied at a rate of 5 mL/m^2 per day for 1 min at 1400 h each day. The essential oil was heated to 60°C in a barrel drum heater and evaporated into the drum headspace. The vapors were continuously distributed with a blower from the headspace air into the barn near the middle of the barn. The water and essential oil dilution ratio was 150:1. The system operated continuously and the barn received about 0.87 L of oil and 132.49 L of water every day.

From 30 Apr. to 11 June 2003, the measurement system was used for a biocurtain study, and the gas concentration and emission data were not available for this paper.

Measurement, Data Acquisition, and Control

Valid data collection from the air quality study in the two barns started on 31 Aug. 2002 and ended on 16 July 2003. Continuous measurements were conducted for air pollutant concentrations, temperature, relative humidity (RH), static pressure, fan on/off status, fan exhaust air speed, and weather conditions. All measurements were at fixed locations except for the gas concentrations at three air sampling locations, where the intake of a set of gas analyzers was switched to one after another. All electronic signals from the analyzers, sensors, and control of relays were connected to data acquisition and control (DAC) hardware, which included a bank of FieldPoint modules and a PCI 6601 DIO card (National Instruments, Austin, TX).

A special DAC program was developed in our study using LabVIEW for Windows (National Instruments, Austin, TX) for communicating with the DAC hardware. Data acquired by the DAC system were sampled at a frequency of 1 Hz, averaged every 15 and 60 s, and saved every min into two data files, respectively. Time stamps and air sampling locations, which were controlled by the DAC program automatically, were also saved in the data files. However, the sampling locations could also be manually selected during the test.

Air Sampling and Analysis

Air was sampled at three locations: B1 exhaust, B2 exhaust, and ambient background (Fig. 1). The exhaust air sampling locations were inside the barns, 1 m from the center of the 0.91-m fan. The ambient sampling location was between the two barns at 4 m above the ground. The sampling locations were connected to a mobile lab through 10- to 35-m long, 6.4-mm ID Teflon tubing. A 47-mm-diameter in-line Teflon filter holder (Savillex Corp, Minnetonka, MN) with a 0.45-μm–pore size Teflon-laminated polypropylene membrane filter (Cole-Parmer, Vernon Hills, IL) was installed at the inlet of each tubing to prevent airborne particulate from entering the sampling system. The filters were replaced at least biweekly. Raceways of 10-cm-diameter PVC pipe were set up between the barns and the mobile lab to protect the tubing and sensor signal cables. A heating tape was wrapped around each tubing inside the raceway to prevent condensation.

A gas sampling system was controlled by the DAC system to facilitate automatic air sampling (Heber et al., 2006b). The system drew air samples sequentially and continuously from the three sampling locations to the mobile lab and provided sample air to the gas analyzers at 4 to 5 L/min. The sampling duration was 60 min for the two exhaust locations during the entire study. The ambient sampling duration was increased from 10 to 20 min on 23 Sept. 2002.

The CH_4 concentrations were measured with a Direct Methane and Non-Methane Hydrocarbon Analyzer (Model 55C, Thermo Electron, Franklin, MA), which was a back-flush gas chromatography system with a flame ionization detector, in accordance with the USEPA Reference Method 25. The analyzer automatically and repeatedly collected and analyzed small amounts of air sample, of which the minimum flow rate was 0.5 L/min. The analyzer's CH_4 measurement ranges were from 0 to 13.3 mg/m^3 (at standard conditions of 293 K and 101.3 kPa) or from 0 to 133 mg/m^3 with a precision of ± 2%, and its detection limit was 13.3 $\mu g/m^3$.

The CO_2 concentrations were measured with a photoacoustic infrared CO_2 Monitor (Model 3600, Mine Safety Appliances Company, Pittsburgh, PA), which utilized dual-frequency photoacoustic infrared absorption and corrected the CO_2 concentrations for water vapor content. The monitor had a sample flow rate of about 1.0 L/min and a measurement range from 0 to 18.3 g/m^3 with precision of ± 2% of full scale.

Barn Ventilation and Heating Measurement

Fan airflow rates were determined with four different measurements: (i) fan on/off control signal, (ii) barn differential static pressure, (iii) fan exhaust air speed, and (iv) field calibration using a portable fan tester (Gates et al., 2004). Data from these four methods helped obtain the best results possible for ventilation calculation (Heber et al., 2004; 2006a, 2006b; Tao, 2004).

The on/off status of each fan was monitored at the fan motor control relay and recorded with a digital input channel in the DAC system. Differential pressures between the inside and outside of the west end wall of each barn were measured with pressure transducers that had a measurement range of ± 100 Pa and an accuracy of ± 0.25% (Model 267, Setra, Boxborough, MA).

A 16-cm-diameter, bidirectional impeller anemometer (Model 27106R, R.M. Young Company, Traverse City, MI) was also mounted at the exhaust of each fan to measure air

Table 1. Summary of pig inventory, ventilation, temperature, and relative humidity in the two barns during full-barn days.

	Days†	ADM‡	Maximum	Minimum
Barn 1				
Pig number	222 d	1115 ± 6 head	1158 head	979 head
Mean pig mass	222 d	64.4 ± 3.0 kg	113.0 kg	24.7 kg
Ventilation rate	179 d	14.4 ± 1.6 m^3/s	38.5 m^3/s	1.7 m^3/s
Temperature	220 d	23.2 ± 0.5°C	30.6°C	14.9°C
Relative humidity	218 d	54 ± 1%	73%	40%
Barn 2				
Pig number	216 d	1116 ± 6 head	1244 head	881 head
Mean pig mass	216 d	63.6 ± 2.9 kg	106.0 kg	23.9 kg
Ventilation rate	173 d	14.6 ± 1.7 m^3/s	39.7 m^3/s	1.0 m^3/s
Temperature	193 d	22.7 ± 0.5°C	30.4°C	15.2°C
Relative humidity	202 d	57 ± 1%	74%	40%

† Days when the barns had > 80% pigs.

‡ Average daily mean ± 95% confidence interval.

velocity continuously. The output signal (0–1 VDC) of the anemometer was a function of the air speed. The anemometers had been calibrated at the Bioenvironmental and Structural Systems Laboratory at the University of Illinois at Urbana-Champaign to obtain relationships between fan airflow rates and the anemometers' voltage signal outputs. The fans used for calibration were identical to the fans installed in the barns. A unique pressure-based relationship was established for each anemometer before it was set up at the barns. These empirical equations were used to calculate real-time airflow rates during the study.

The portable fan tester was used to verify in-field airflow rates of three fans in B1 on 26 Nov. 2002 and three fans in B2 on 15 Apr. 2003. Obstacles in the barns prevented from testing the other four fans in the barns with the fan tester.

Fan curves that related the fan airflow rates to the barn differential pressures were developed based on the portable fan tester's and the anemometers' measurements. The curves were used to calculate barn ventilation rates based on the measured fan operation time and the differential pressure in the same way as used in a layer hen barn study (Lim et al., 2003).

The on/off status of each propane space heater was also monitored at the heater control relay and recorded as digital input signal in the DAC system.

Other Measurements

Relative humidity and temperature using RH/T transmitters (Model HMW61, Vaisala Inc., Woburn, MA) were used to monitor temperature and humidity at barn exhaust air sampling locations. Ambient RH and temperature were measured at an on-site weather tower.

Gas Release in Empty and Cleaned Barn

To study the gas releases from lagoon effluent, continuous measurement was conducted by manually setting the sampling location in B1 when the barn was empty and power-washed between two pig cycles in April 2003. Lagoon effluent was the only source of gas releases in B1 and the barn ventilation rate was kept constant at 4.31 m^3/s (standard deviation = 0.05 m^3/s) during the measurement.

Data Processing

Custom data processing software CAPECAB (Eisentraut et al., 2004) was used to process measurement data. Gas concentrations at each sampling location were divided into invalid data at the beginning of the sampling period and valid data at the end of the sampling period. The amount of invalid data depended on the equilibrium time of the sampling and measurement system, especially the gas analyzers. Its duration was 3 and 5 min for CO_2 and CH_4 air samples, respectively. Thus the valid concentration data consisted of 57 and 55 min for CO_2 and CH_4, respectively, from the 60-min sampling at the barns; and 17 and 15 min for CO_2 and CH_4, respectively, from the 20-min sampling at the ambient. The valid data were extracted and interpolated for emission calculations.

Barn gas emission rates were calculated by multiplying barn ventilation rate by the difference between barn exhaust and ambient gas concentrations. To avoid errors introduced into the daily averages due to unrepresentative data (e.g., only 5 h of nighttime gas concentration, which was usually high, to represent daily mean concentration) that could result in biased time weights, only complete-data-full-barn (CDFB) days were included in daily means for studying baseline emissions. The emission rates per animal unit (AU) were obtained by dividing the barn emission rate by the total pig mass and multiplying by 500. The live pig number and mass were provided by the farm inventory.

Results

Barn Inventory and Environmental Conditions

Barns 1 and 2 housed a maximum of 1158 and 1244 head of pigs during the 222 and 216 full barn days (with > 880 pigs in the barn), respectively (Table 1). Pig mass ranged from 24.7 to 113.0 kg for B1 and from 23.9 to 106.0 kg for B2. There were no significant statistical differences between the two barns for pig number ($P > 0.7$) and mean pig mass ($P > 0.6$) during the full barn days.

Figure 2 presents the daily total pig mass in the barns, which included one complete and two partial pig cycles, and the daily mean ambient temperature during all monitoring days. The daily mean ambient temperature ranged from –18.1 to 30.1°C and the ADM temperature was 9.3 ± 1.3°C (mean ± 95% confidence interval) during these days, which showed typical seasonal variations at the farm.

Barn Ventilation, Temperature, Relative Humidity, and Heating

Barn 1 provided 179 and B2 provided 173 complete data (CD) days (>80% of valid measurement time per day) for ventilation rates, which corresponded to 0.018 m^3/s per m^2 floor surface for both barns (Table 1). The statistical difference of the ventilation rates between the two barns was not significant ($P > 0.8$). Figure 3 presents daily mean ventilation rates during all monitoring days, including the empty barn days in November 2002 when the ventilation fans were mostly turned

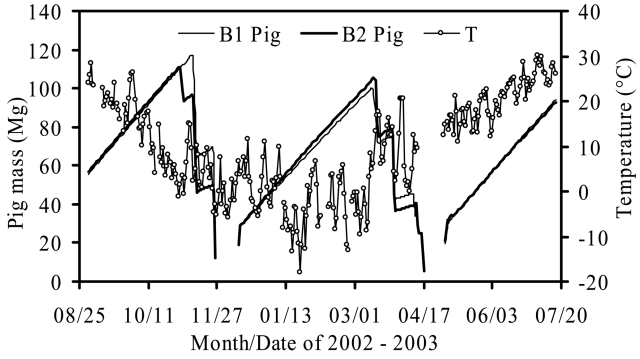

Fig. 2. Daily total pig mass in the two barns and daily mean outdoor temperature during all monitoring days.

off. Barn ventilation rates were strongly correlated to barn indoor temperatures. Correlation coefficients between these two variables were 0.94 and 0.92 for B1 and B2, respectively.

There was no significant statistical difference between the daily mean temperatures (Table 1) between the two barns ($P > 0.1$). Indoor temperatures were evidently affected by the ambient temperature. Correlation coefficients between indoor and ambient temperatures were 0.96 for B1 and 0.98 for B2.

However, there was significant statistical difference between the RH (Table 1) in the two barns ($P < 0.01$). Barn RH was correlated to ambient RH. The correlation coefficients were 0.60 and 0.65 for B1 and B2, respectively. No significant correlations were found between RH and other measurement variables.

The barn heating period was from 17 Nov. 2002 to 13 Apr. 2003, for a total of 147 d. The number of days with complete heating data were only 58 for B1 and 92 for B2 due to measurement errors. The minimum and maximum daily operating times of the space heaters were 0 and 16.5 h, respectively.

Methane Concentrations and Emissions

Table 2 summarizes the CH_4 concentrations and emission rates during the study. The CDFB days for the CH_4 emission calculation between the two barns (B1 = 134 and B2 = 131) were similar. Although the pig inventory, ventilation rate, and indoor temperature were statistically identical, there were significant differences for CH_4 concentrations ($P < 0.01$) and emission rates ($P < 0.01$) between the two barns. Barn 2 had

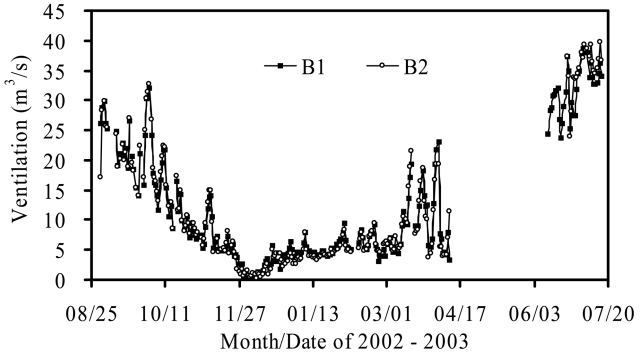

Fig. 3. Daily mean ventilation rate in the two barns during all monitoring days.

Table 2. Summary of the CH_4 study results.

	Days†	ADM‡	Maximum	Minimum
Ambient				
Concentration	182 d	1.3 ± 0.0 mg/m³	1.7 mg/m³	0.9 mg/m³
Barn 1				
Concentration	140 d	8.5 ± 0.6 mg/m³	17.8 mg/m³	2.3 mg/m³
Barn emission	134 d	5.4 ± 0.4 kg/d	11.2 kg/d	1.2 kg/d
Emission per AU	134 d	36.2 ± 2.0 g/d AU	87.0 g/d AU	13.1 g/d AU
Barn 2				
Concentration	136 d	7.3 ± 0.5 mg/m³	13.0 mg/m³	2.2 mg/m³
Barn emission	131 d	4.4 ± 0.4 kg/d	11.3 kg/d	0.5 kg/d
Emission per AU	131 d	28.8 ± 1.8 g/d AU	68.5 g/d AU	8.3 g/d AU

† Complete data days for ambient concentrations and complete-data-full-barn days for barn concentrations and emissions.

‡ Average daily mean ± 95% confidence interval.

lower ADM CH_4 concentration and emission rate than B1. Daily mean CH_4 concentrations (Fig. 4) and emission rates (Fig. 5) demonstrated seasonal variations for both barns. In the warm season, the concentrations were lower but the emission rates were higher than in the cold season.

Carbon Dioxide Concentrations and Emissions

Table 3 summarizes the CO_2 concentrations and emission rates during the study. Significant differences were found between the two barns for CO_2 concentrations ($P < 0.05$) and emission rates ($P < 0.01$). Barn 2 had higher ADM CO_2 concentration and emission rate than B1. The daily mean CO_2 concentrations demonstrated a clear seasonal variation with the highest in cold weather and lowest in warm weather (Fig. 6). They were inversely correlated to ambient temperature (correlation coefficients were –0.91 for B1 and –0.94 for B2). The daily mean CO_2 emission rates were also inversely correlated to ambient temperature (Fig. 7) and the correlation coefficients were –0.43 for B1 and –0.49 for B2.

The relationship between the propane heaters' operation time and the CO_2 emission per AU in B2 is presented in Fig. 8. The day with the highest CO_2 emission per AU during the entire study in B2 was on 21 Dec. 2002 (Fig. 7) and was the day when the three heaters operated for the longest time (69% or 16.5 h of the day). A 1-h data graph showing the CO_2 emission under the influence of propane heaters is presented in Fig. 9, in which the mean CO_2 emissions from

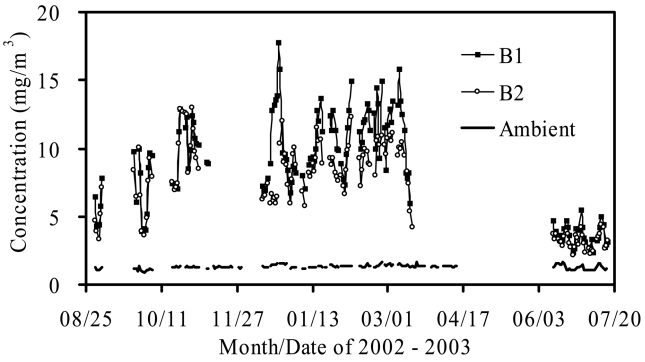

Fig. 4. Daily mean CH_4 concentrations in the two barns during complete-data-full-barn (CDFB) days and in ambient air during all monitoring days.

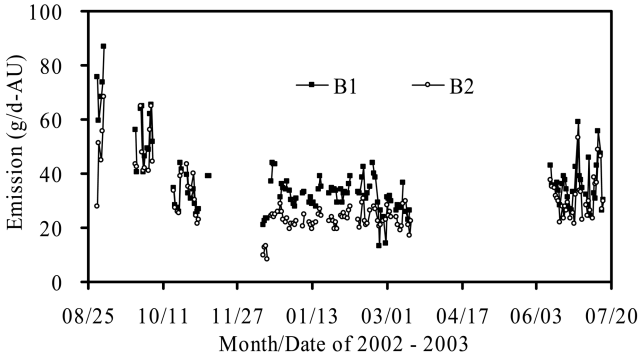

Fig. 5. Daily mean CH_4 emission rates from the two barns during complete-data-full-barn (CDFB) days.

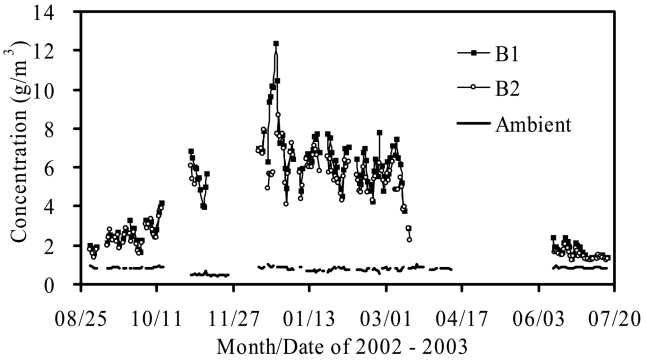

Fig. 6. Daily mean CO_2 concentrations in the two barns during complete-data-full-barn (CDFB) days and in ambient air during all monitoring days.

B2 without and with the heater operation were 12.6 and 17.3 g/s, respectively. The net CO_2 produced by three heaters in B2 was 4.7 g/s on the test day shown in Fig. 9.

Methane and Carbon Dioxide Emissions during Different Study Periods

Table 4 presents the CDFB-day CH_4 and CO_2 emissions during different study periods. Results demonstrated that B2 had statistically significant reduction for both CH_4 and CO_2 emissions compared with B1 during all three comparison studies: oil sprinkling, misting essential oils, and misting essential oils with water. However, during the four CDFB days without any treatment between the oil sprinkling and the misting essential oils, the CH_4 and CO_2 emissions were also significantly lower in B2 than in B1.

Gases from Lagoon Effluent

Figure 10 provides an example that illustrates the gas concentration patterns relative to the barn flushing when B1 was empty and power-washed. Regular higher concentrations of CH_4 and CO_2 were clearly seen following the flushes. As a comparison, the H_2S concentration pattern was very similar to the CH_4 pattern while the NH_3 concentration fluctuations were independent of the flushes. The minimum and maximum concentrations between the flushes were 1.9 and 4.2 mg/m^3 for CH_4 and 1045 and 1115 mg/m^3 for CO_2, respectively. Assuming ambient concentrations of 1.3 mg/m^3 for CH_4 and 804 mg/m^3 for CO_2 as measured before the empty barn study, the B1 emission rates during the 24-h empty barn study on 24 Apr. 2003 were 6.1 mg/s (0.53 kg/d) for CH_4 and 1.17 g/s (101 kg/d) for CO_2. They were equivalent to 9.8% CH_4 and 4.1% CO_2 of the full barn emissions from B1 during the entire study (Tables 2 and 3).

Table 3. Summary of the CO_2 study results.

	Days†	ADM‡	Maximum	Minimum
Ambient				
Concentration	184 d	0.77 ± 0.02 g/m^3	1.05 g/m^3	0.41 g/m^3
Barn 1				
Concentration	156 d	4.53 ± 0.38 g/m^3	12.38 g/m^3	1.26 g/m^3
Barn emission	146 d	2445 ± 90 kg/d	4210 kg/d	1230 kg/d
Emission per AU	146 d	17.5 ± 0.8 kg/d AU	33.5 kg/d AU	7.9 kg/d AU
Barn 2				
Concentration	144 d	4.00 ± 0.34 g/m^3	8.69 g/m^3	1.21 g/m^3
Barn emission	137 d	2011 ± 87 kg/d	3690 kg/d	603 kg/d
Emission per AU	137 d	14.2 ± 0.6 kg/d AU	26.0 kg/d AU	7.9 kg/d AU

† Complete data days for ambient concentrations and complete-data-full-barn days for barn concentrations and emissions.

‡ Average daily mean ± 95% confidence interval.

Discussion

Methane and Carbon Dioxide Emissions at Pig Farms

The two greenhouse gases, CH_4 and CO_2, are major components in biogas that can be obtained by a technology of controlled anaerobic fermentation, or biomethanation. Animal manure (a mixture of dung, urea, water, feed, and bedding materials) is an excellent substrate for biomethanation (Ni and Nyns, 1993). Although it was not under controlled anaerobic fermentation, the manure accumulated in the two barns and the lagoon in our study was partially under anaerobic conditions. Naturally, CH_4 and CO_2 were produced from manure in the barns and lagoon.

Among eight independent studies shown in Table 5, including our study, the quantities of CH_4 emission ranged from 10.5 to 43.9 g/d AU. The lowest reported emission of 10.5 g/d AU by Su et al. (2003) was obtained from anaerobic wastewater treatment for pig farms. All other seven studies were from different countries or with different pig housing systems. Their data demonstrated a range from 13.7 to 43.9 g/d AU. Emission rates obtained in our study were in the upper middle of the range.

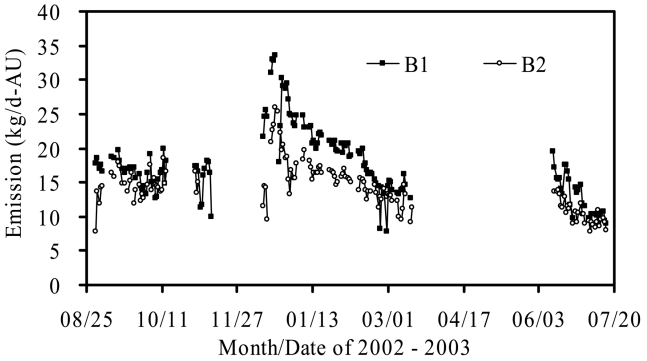

Fig. 7. Daily mean CO_2 emission rates from the two barns during complete-data-full-barn (CDFB) days.

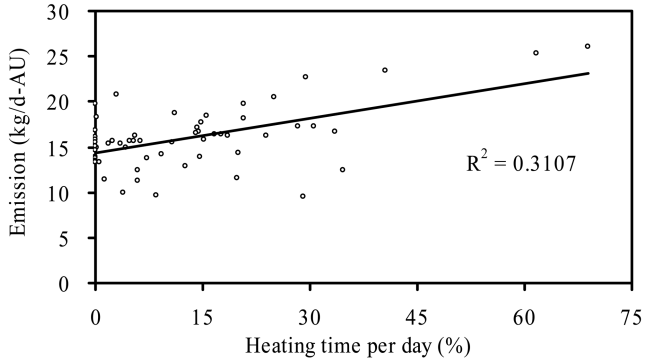

Fig. 8. Relationship between barn heating and CO_2 emission at B2.

Table 6 compares the CO_2 emissions from B1 and B2 with ten other published studies. The data showed great variations that ranged from 0.01 to 28.2 kg/d AU. However, unlike CH_4, CO_2 in the pig industry can have three sources: CO_2 exhaled from pigs (Ni et al., 1999a), released from manure (Ni et al., 1999b), and produced from combustion heaters. Only six publications (Osada et al., 1998; Lim et al., 1999; Delcourt et al., 2001; Nicks et al., 2003, 2004; Dong et al., 2007) in Table 6 had data that included at least the sources of pig exhalation and manure release and were comparable with our study. These CO_2 emission rates range from 6.5 to 28.2 kg/d AU, which demonstrated a larger variation than the CH_4 emissions. Data obtained in our study are in the upper range, lower than those from two deep pig finishing buildings reported by Lim et al. (1999) and similar to that obtained by Dong et al. (2007).

Seasonal temperature and ventilation variations appeared to have contrary effects on CH_4 and CO_2 emissions per AU in our study. While the CH_4 emissions were lower in winter compared with summer (Fig. 5), the CO_2 emissions were higher in winter (Fig. 7). The reason for this was the additional CO_2 generated by the propane space heaters.

The operation of propane heaters was found to have a notable effect on CO_2 concentrations in pig finishing barns in our previous study (Ni et al., 2000). Proportional correlations between CO_2 emission per AU and daily heating time was also established in this study in B2 (Fig. 8). Within 4 to 5 min after the space heaters were turned on, increased CO_2 concentrations were detected. The delay of the CO_2 emission compared with the heating in Fig. 9 was due to the transportation of CO_2 in the barn and the response time of the gas concentration measurement system. The heating also increased the indoor temperature, which induced a slight increase in ventilation rate (Fig. 9). Data shown in Fig. 9 were obtained at midnight when the pigs were in a tranquil condition with minimal activity and the CO_2 exhalation rate was the most stable (Ni et al., 1999a). The tranquil time test enabled the calculation of the heaters' actual CO_2 production which was 282 g/min. This capacity was equivalent to 37.3% of the CO_2 exhaled by the pigs at tranquil conditions and released from manure on the test day (Fig. 9). However, the heaters only operated for an average of 3.2 h/d in B2 during 147 d in winter and early spring. Moreover, CO_2 from heating largely depends on the geographical location of the farm and the weather conditions.

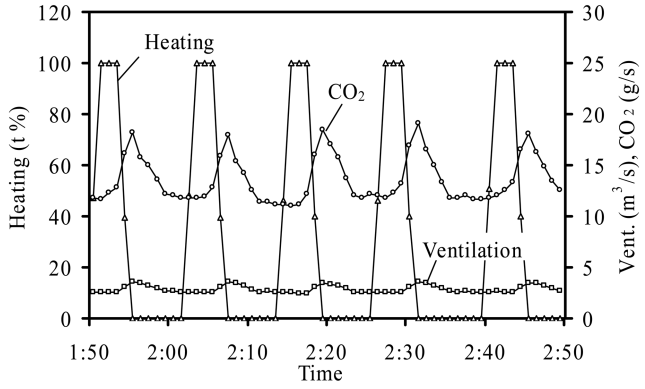

Fig. 9. Effect of periodic 4-min heating on barn ventilation rate and CO_2 emission with 1146 pigs at 39 kg each in B2 on 31 Dec. 2002.

Table 4. Methane and CO_2 emissions during different study periods.

	CDFB days	Emission per day per AU	*P*
	d		
Oil sprinkling			
B1 CH_4, g	90	37.2	< 0.01
B2 CH_4, g	86	28.7	
B1 CO_2, kg	104	19.2	< 0.01
B2 CO_2, kg	94	15.7	
Between oil sprinkling and misting essential oils (no treatment)			
B1 CH_4, g	4	30.8	< 0.01
B2 CH_4, g	4	25.6	
B1 CO_2, kg	4	14.7	< 0.01
B2 CO_2, kg	4	12.9	
Misting essential oils			
B1 CH_4, g	8	27.7	< 0.05
B2 CH_4, g	9	22.6	
B1 CO_2, kg	7	14.0	< 0.01
B2 CO_2, kg	8	11.4	
Misting essential oils with water			
B1 CH_4, g	32	36.1	< 0.05
B2 CH_4, g	32	31.1	
B1 CO_2, kg	31	12.9	< 0.01
B2 CO_2, kg	31	10.5	

To increase the data completeness in future research, we suggest the heaters be monitored in a simple and reliable way by measuring the temperatures at the heaters' air exhausts.

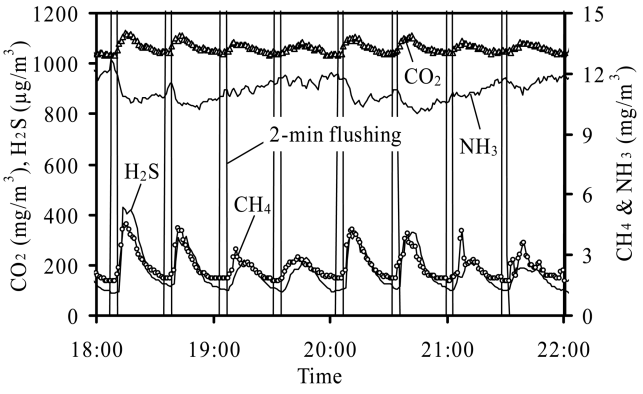

Fig. 10. Gas concentrations and periodic 2-min lagoon effluent flushing under constant ventilation in B1 when it was empty and power-washed on 24 Apr. 2003.

Table 5. Comparisons of CH_4 emission rates in the literature.

Measurement condition	Reported quantities	Conversion to g/d AU	Ref.§
Finishing pigs on deep litter (Belgium)	4.8 g/pig	24.0 †	1
Finishing pigs in control unit, 8 wks (Denmark)	302 g/pig per 8 wks	27.0 †	2
Finishing pigs in test unit, 8 wks (Denmark)	268 g/pig per 8 wks	23.9 †	2
Weaned pigs on sawdust-based litter (Belgium)	0.77 g/d pig	21.4 ‡	3
Weaned pigs on straw-based litter (Belgium)	1.58 g/d pig	43.9 ‡	3
Pig farm anaerobic wastewater treatment (Taiwan)	0.76 kg/yr pig	10.5 †	4
Finishing pigs on sawdust-based litter (Belgium)	4.96 g/d pig	24.8 †	5
Finishing pigs on straw-based litter (Belgium)	7.39 g/d pig	36.9 †	5
Growing-finishing pig, naturally ventilated barns (China)		32.1	6
Finishing pig without daily manure removal (Austria)	1.3 g/h AU	31.2	7
Finishing pig with daily manure removal (Austria)	0.57 g/h AU	13.7	7
Finishing pig in B1 (our study, USA)		36.2 ± 2.0	
Finishing pig in B2 (our study, USA)		28.8 ± 1.8	

† Assuming 100 kg/pig.

‡ Assuming 18 kg/pig.

§ References: 1. Delcourt et al. (2001); 2. Osada et al. (1998); 3. Nicks et al. (2003); 4. Su et al. (2003); 5. Nicks et al.(2004); 6. Dong et al. (2007); 7. Amon et al. (2007).

However, if only monthly or annual data are needed, the monthly or annual propane consumption can be used to calculate the CO_2 production by the heaters.

Effect of Oil Treatment on Methane and Carbon Dioxide Emissions

Although our study was conducted in two statistically identical barns, the treated B2 reduced 14.1% of the CH_4 concentration, 11.7% of the CO_2 concentration, 20.4% of the CH_4 emission per AU, and 18.9% of the CO_2 emission per AU compared with B1 during all CDFB days (Tables 2 and 3). Soybean oil sprinkling, misting essential oils, and misting essential oils with water in B2 were the only known barn conditions that differed from B1.

Vegetable oil sprinkling has been studied by other researchers to reduce air pollutants, mainly dust and airborne bacteria, in pig buildings (Zhang et al., 1996; Kim et al., 2006). The effectiveness of oil on gas emission reduction is controversial. One study that tested layers of rapeseed oil on slurry under slats reported NH_3 and odor reduction. However, the study found increased CH_4 emissions from stored pig slurry of about 60% because the oil was biodegradable (Pahl et al., 2002). Nonnenmann et al. (2004) found that vegetable oil sprinkling did not make significant differences on NH_3 and CO_2 in pig barns. Rule et al. (2005) also found that treatment with an acid-oil-alcohol aerosol had no effect on NH_3 reduction although it significantly reduced dust concentrations. The positive results of our study, which showed that B2 reduced 22.8% of CH_4 and 18.2% of CO_2 emissions with oil sprinkling (Table 4), were not in agreement with previous work by other researchers.

Essential oil had been used to control odor in laboratory and field conditions (Varel and Miller, 2001; Varel et al., 2004, 2006). Varel and Miller (2001) concluded that carvacrol inhibited the production of all volatile fatty acids in pig waste. However, no studies of essential oil to reduce gas emissions from pig barns were found in the literature. Both of our essential

Table 6. Comparison of CO_2 emission, release, and exhalation data in the literature.

Measurement conditions	Reported quantities	Conversion to kg/d AU	Ref.¶
Finishing pigs (average mass 59.5 kg) in control unit (Denmark)	5540 g/pig per week	6.6	1
Finishing pigs (average mass 59.0 kg) in test unit, 8 wks (Denmark)	5440 g/pig per week	6.6	1
Release from manure pit of emptied pig barn (Belgium)	18.4 and 25.8 g/h m^2	N/A	2
Release from manure pit in occupied barn (Belgium)	42.1 g/h m^2 pit	2.8§	2
Exhalation of 32 to 105 kg finishing pigs in tranquil conditions (Belgium)	41.5 to 73.9 g/h pig	10.1	3
866 pigs/barn with 72.4 kg mean pig mass (USA)	147.6 kg/h barn	28.2	4
Finishing pigs on deep litter (Belgium)	1.3 kg/d per pig	6.5†	5
Growing-finishing pig, naturally ventilated barn (Sweden)	81 and 120 g/h pig	9.7, 14.4†	6
Weaned pigs on sawdust-based litter (Belgium)	481 g/d pig	13.4‡	7
Weaned pigs on straw-based litter (Belgium)	463 g/d pig	12.9‡	7
Pig farm anaerobic wastewater treatment (Taiwan)	0.714 kg/yr pig	0.01†	8
Finishing pigs on sawdust-based litter (Belgium)	1.32 kg/d pig	6.6†	9
Finishing pigs on straw-based litter (Belgium)	1.30 kg/d pig	6.5†	9
Growing-finishing pig, naturally ventilated barns (China)		16.7	10
Finishing pig in B1 (our study, USA)		17.5 ± 0.8	
Finishing pig in B2 (our study, USA)		14.2 ± 0.6	

† Assuming 100 kg/pig.

‡ Assuming 18 kg/pig.

§ Pit surface area 26.7 m^2, total pig mass 4900 kg.

¶ References: 1. Osada et al. (1998); 2. Ni et al. (1999b); 3. Ni et al. (1999a); 4. Lim et al. (1999); 5. Delcourt et al. (2001); 6. Jeppsson (2002); 7. Nicks et al. (2003); 8. Su et al. (2003); 9. Nicks et al.(2004); 10. Dong et al. (2007).

oils provided positive reductions for CH_4 and CO_2 emissions although the misting essential oils only had less than 10 CDFB days. These were the first of such data ever reported.

However, it is interesting to note that during the four CDFB days when there was no oil treatment between the oil sprinkling and misting essential oils studies, there were still significant CH_4 and CO_2 emission reductions in B2 (Table 4). Nevertheless, it was unclear whether this was due to the residue effect of the oil sprinkling in B2 or some other unknown factors between the two barns. Future studies can be improved by testing the oil treatment in both barns but alternating the treatment and control roles of the barns. In this way, the effect of treatment can be better identified. In addition, the mechanism of reducing gas emissions from animal barns by oil treatments needs further study.

Methane and Carbon Dioxide from Lagoon Effluent

The flushing systems in B1 and B2 pumped lagoon effluent through the barns for about 6.8% of the time (98–100 min) daily and each flushing covered 25% of the shallow gutter surface area. Although this only accounted for about 1.7% of the time-area in the barns, CH_4 and CO_2 from the effluent was carried and released in the barns. It was difficult to distinguish this portion of gases in the measurement data when the barns were filled with pigs because of the multiple gas sources in the barns, e.g., the manure on the floor and in the pit and the CO_2 exhaled by the pigs. However, this portion of gases was clearly detected when the lagoon effluent was the only source of gas release in the empty and cleaned barn (Fig. 10).

Taking into account the 1100-pig full barn capacity of B1, the 0.53 kg/d CH_4 from lagoon effluent in the empty and cleaned B1 was equivalent to 0.48 g/d per pig, or about 23% of the 2.10 g/d per pig CH_4 release from the pig farm anaerobic wastewater reported by Su et al. (2003). This supported the fact that the flushing effluent in our study only represented part of the lagoon water. The 101 kg/d CO_2 from flushing effluent in the empty and cleaned B1 was equivalent to 0.09 kg/d per pig. In full barns with manure covering the floor and filling in the pit or in barns with a deep manure pit, more CO_2 is expected to be released from the manure.

The empty and cleaned barn study also provided an opportunity to investigate gas release behavior. Compared with NH_3, whose concentration pattern could not be related to the flushing, evident and regular peaks of H_2S, CH_4, and CO_2 concentrations occurred following the flushing events (Fig. 10). The delay of the gas peaks compared with the flushing time was also due to gas transportation and instrument response in the measurement system. Peak emissions of H_2S right after lagoon water flush has been reported in other studies (Lim et al., 2004). The similarity of CH_4 and CO_2 with H_2S release peaks after the flushing suggested that their releases from liquid manure might fall under the same mechanism of "bubble release" as H_2S (Ni et al., 2001). At agitation of liquid manure during flushing, micro-bubbles dissolved in the liquid were forced to collide with each other and form larger bubbles to release as biogas. However, compared with H_2S and CH_4, the CO_2 concentration peaks after the flushing were less visible and would be impossible to identify in occupied barns.

Variation of Reported Methane and Carbon Dioxide Emissions

Variations of emission rates reported in the literature shown in Tables 4 and 5 may have been caused by different factors. The design of animal barns and the management of the stored manure have an apparent effect on the CH_4 and CO_2 emissions. Long-term manure storage in deep-pit pig barns may result in greater gas emissions from the building because of the larger quantity of manure in the barns. Nicks et al. (2003, 2004) also reported that pig houses with sawdust-based litter emitted 33% less CH_4 than straw-based litter but without reducing CO_2 emissions. Results of our study provided CH_4 and CO_2 emissions from pig barns with shallow manure flushing systems and propane space heaters that was previously unavailable.

Temperature is an important factor for CH_4 and CO_2 emissions. Methanogenesis in solid manure increases with increasing temperatures. The CH_4 emissions from solid pig manure peaked at 35 to 45°C (Husted, 1994). Jeppsson (2002) reported a close correlation between temperature and CO_2 production (R^2 = 0.42–0.83) in a growing/finishing pig building. Moller et al. (2004) found that the effect of temperature on CH_4 and CO_2 production from animal manure also depended on storage duration. Amon et al. (2007) reported data showing higher CH_4 emissions in a warm period than in a cold period. Indoor temperature was the only factor that affected barn ventilations and heater operations in our study. High temperature induced high ventilation not only during the diel cycle, but also seasonally. A high ventilation rate in summer greatly diluted CH_4 and CO_2 concentrations but was correlated to high CH_4 emissions (Fig. 4–6). However, low temperature in cold weather added emissions of CO_2 originating from fossil fuel combustion in the propane heaters.

Short-term measurement and poorly distributed samples produce biased results due to unaccounted diel and seasonal variations. Osada et al. (1998) found that gas emissions at the peak hours in the afternoon were twice as high as those observed in the early morning, even though the room temperature was kept at around 17°C. Husted (1994) observed large spatial and seasonal variations of gas emissions from manure in dynamic chambers in a year-long study. Our 11 mo long measurement clearly demonstrated seasonal variations of gas concentrations and emissions (Fig. 4–7). However, due to the bio-curtain test from 30 Apr. to 11 June 2003, the empty barns between the groups of pigs, and other reasons including sensor and gas analyzer failures, the CDFB emission days were only about 40% of our entire study days and these CDFB days were not evenly distributed in the four seasons.

Finally, characteristics of the measurement instruments and their maintenance may also cause differences in measured data. Osada et al. (1998) employed an infrared photoacoustic detection instrument to measure gas emissions in pig units but admitted that this instrument tended to overestimate the

CH_4 values in the samples. The gas analyzers and measurement methodology used in our project have not been reported by other researchers in similar studies. Future comparison of different methodologies and technologies will help to increase the accuracy and comparability of measurement data in this field.

Conclusions

1. The baseline CH_4 emissions were 36.2 ± 2.0 g/d AU from B1 and 28.8 ± 1.8 g/d AU from B2. They were in the upper middle of the range of six other published CH_4 emission rates from pig housing that ranged from 13.7 to 43.9 g/d AU.
2. The baseline CO_2 emissions from pig exhalation, manure release, and combustion heaters were 17.5 ± 0.8 kg/d AU from B1 and 14.2 ± 0.6 kg/d AU from B2. They were in the upper range of the 6.5 to 28.2 kg/d AU CO_2 emissions from pig barns in eight other independent studies.
3. The CO_2 production by three heaters in B2 was 282 g/min. The heaters operated for an average of 3.2 h a day in B2 during 147 d in winter and early spring. The CO_2 production from heaters in pig barns depends on geographical location of the farm and weather conditions and may vary from year to year.
4. Barn 2 significantly reduced CH_4 (by 20.4%) and CO_2 (by 18.9%) emissions per AU compared with B1 as a result of the treatment of oil sprinkling, misting essential oils, and misting essential oils with water. The mechanism of the gas emission reduction by oil treatment deserves more investigation and future experiment design can be improved.
5. There were significant quantities of CH_4 and CO_2 off gassing from recycled lagoon effluent, equivalent to 9.8 and 4.1% of the CDFB CH_4 and CO_2 emissions, respectively. The actual greenhouse gas emissions per AU from the pig farm were expected to be greater than the baseline barn data obtained in our study if the emissions from outdoor lagoons were included.
6. Evident and regular CH_4 and CO_2 release peaks immediately following the flushing in the empty and cleaned barn suggested that CH_4 and CO_2 had similar release mechanism as H_2S but were different from NH_3.
7. Diel and seasonal fluctuations of ambient temperature induced changes in barn ventilation rates and indoor temperature, and influenced barn CH_4 and CO_2 concentrations and emission rates.
8. The long-term measurement and the CDFB approach in data analysis reduced baseline emission errors because they minimized the bias that could be easily introduced by seasonal and diel emission variations.
9. No effect of RH inside the barns was observed in the CH_4 and CO_2 concentrations and emission rates.
10. Improvements in future studies are suggested to practice more efficient quality assurance and quality control for enhanced data completeness and to design an experiment for better comparison of abatement technologies.

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