

Air temperature, carbon dioxide, and ammonia assessment inside a commercial cage layer barn with manure-drying tunnels

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ABSTRACT Understanding the air temperature distribution, ammonia (NH₃) and carbon dioxide (CO₂) levels in poultry housing systems are crucial to poultry health, welfare, and productivity. In this study, 4 Intelligent Portable Monitoring Units and 7 temperature sensors were installed inside and between the cages and above 2 minimum ventilation fans of a commercial stacked-deck cage laying hen house in the Midwest United States (425,000 laying hens) to continuously monitor the interior environment over a 6-month period. During cold conditions (March 12th–May 22nd), there was a variation noted, with barn center temperatures consistently being highest in the longitudinal and lateral direction ($P < 0.001$) and the top floor deck warmer than the bottom floor ($P < 0.05$). During hotter conditions (May 23rd–July 26th), the interior thermal environment was more uniform than during the winter, resulting in a difference only in the longitudinal direction. The daily CO₂ and NH₃ concentrations were 400 to 4,981 ppm and 0 to 42.3 ppm among the 4 sampling locations,

respectively. Both CO₂ and NH₃ decreased linearly with increasing outside temperatures. The mean NH₃ and CO₂ concentrations varied with sampling locations and with the outside temperatures ($P < 0.001$). For CO₂, the minimum ventilation sidewall had lower values than those measured in the barn's center ($P < 0.05$) during cold weather, while the barn center and the manure room sidewall consistently measured the highest concentrations during warmer weather ($P < 0.05$). For NH₃, the tunnel ventilation inlet end consistently had the lowest daily concentrations, whereas the in-cage and manure drying tunnel sidewall locations measured the highest concentrations ($P < 0.001$). Higher NH₃ and CO₂ concentrations were recorded within the cage than in the cage aisle ($P < 0.05$). The highest NH₃ concentration of 42 ppm was recorded above the minimum exhaust fan adjacent to the manure drying tunnel, which indicated that higher pressure (back pressure) in the manure drying tunnel allowed air leakage back into the production area through nonoperating sidewall fan shutters.

Key words: ammonia, carbon dioxide, air quality, hen level, laying hens

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INTRODUCTION

Controlling the living space environment, particularly the interior air temperature and air quality, for example, carbon dioxide (CO₂) and ammonia (NH₃) levels, is crucial to poultry's health, welfare, and productivity (Webster and Czarick, 2000; Dawkins et al., 2004;

Naseem and King, 2018). CO₂ and NH₃ are among the most common gases produced inside layer houses.

Common sources of CO₂ are bird respiration, byproducts of feces breakdown, floor litter buildup in some facilities, and use of unvented conventional propane/natural gas-fueled heaters (Jeppsson, 2000; Miles et al., 2006a; Cândido et al., 2018). Interior CO₂ levels are important factors for ventilation management in poultry houses and are commonly used to design appropriate minimum winter ventilation rates for maintaining indoor air quality and controlling moisture (Albright, 1990; Barber et al., 1993; Liang et al., 2005; Xin et al., 2009; Ni et al., 2017; Cândido et al., 2018; ASHRAE, 2019). The International Commission of Agricultural and Biosystems Engineering (CIGR, 1984) established the

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maximum CO₂ concentration inside a facility at 3,000 ppm for general production and 2,500 ppm for poultry production. For other industries, a CO₂ concentration of 5,000 ppm is suggested as the 8-h time-weighted exposure threshold limit value (ACGIH, 1998). Barber et al. (1993) evaluated the CO₂ concentrations in a number of 173 swine buildings and reported that the CO₂ concentrations were below 3,000 ppm for the majority of the swine buildings monitored when the ambient temperature was above 0°C; however, such concentration was a challenge to be maintained below for outside temperatures below 0°C (ASHRAE, 2019).

The magnitude of NH₃ concentration in poultry facilities varies by housing systems (cage, on litter, alternative systems, or aviaries), bird density (in cage or on unit floor area), feed composition, house management, and ventilation management (Kilic and Yaslioglu, 2014). High NH₃ concentrations in poultry houses can adversely affect the health and production performance of birds (Charles and Payne, 1966a; Miles et al., 2004, 2006b) and can cause respiratory diseases (e.g., coughing, upper respiratory tract bleeding, excessive secretions, and lung bleeding or inflammation). The literature is inconsistent regarding a specific NH₃ threshold concentration above which respiratory or physiological problems will occur for poultry. For human workers, recommended threshold NH₃ concentration is less than 25 ppm (Charles and Payne, 1966b; Al-Mashhadani and Beck, 1985; Kilic and Yaslioglu, 2014; Naseem and King, 2018). The US National Institute of Occupational Safety and Health and the US Occupational Safety and Health Administration have set human exposure limits to 25 and 50 ppm, respectively, for a time-weighted average (NIOSH, 2005). ASHRAE (2019) suggested that the NH₃ concentration should be maintained below 26 ppm or, ideally, 10 ppm for general HVAC environments.

Several studies on thermal environment and air quality have been conducted for laying hen facilities, of which were either survey-type investigations or short-duration studies (Green et al. 2009; Dobeic and Pintaric, 2011), with intermittent measurements (Wathes et al., 1997; Shepherd et al., 2015; Zhao et al., 2015). Wathes et al. (1997) surveyed the concentrations and emission rates of aerial NH₃, nitrous oxide (N₂O), methane (CH₄), and CO₂ in typical UK broiler, cage and perchery houses over a 24-h period during winter and summer and reported that the overall mean NH₃ concentration was 24.2 ppm, 13.5 ppm, and 12.3 ppm in the broiler, cage, and perchery houses, respectively. Kilic and Yaslioglu (2014) measured the NH₃ and CO₂ concentrations, air temperature, and relative humidity (RH) in a three-tier, neutral pressured laying hen house with 12,000 hens in Turkey. The average NH₃ concentration during the summer of 2013 was 8.1 ppm for exhaust and 5.4 ppm for inlet, while the average CO₂ concentration was 732 ppm for exhaust and 625 ppm for inlet throughout the summer. The temperature and RH sensors in the layer houses were installed in the middle of

the aisle. The overall minimum, average, and maximum values for indoor air temperature and RH were obtained as 16.8°C, 24.7°C, and 34.7°C and 33.6, 63.7, and 86.2%, respectively. These survey-type and intermittent studies usually used periodic measurements, which typically depict a small part of the actual picture and cannot adequately cover diurnal or seasonal variations (Ni et al. 2012). Ni et al. (2017) suggested that long-term (>6 months) and continuous (or high-frequency) monitoring were needed to reveal seasonal and diurnal variations and to obtain in-depth knowledge about thermal environment and air quality characteristics.

Xin et al. (2009) evaluated the ventilation rate in 2 broiler houses in Kentucky, USA, and reported a difference in CO₂ concentration range of 200 to 2,566 ppm between house air inlet and exhaust, which was equivalent to an interior CO₂ concentration of approximately 600 to 3,000 ppm (assuming a 400 ppm ambient CO₂ concentration). Their results agreed with an earlier study for manure belted layer houses in Iowa, USA (Li et al., 2005), which reported a range of 800 to 2,400 ppm CO₂ concentration at ventilation fans. Liang et al. (2005, 2006) estimated NH₃ emission rates for manure belted and high-rise layer houses. Their results showed that for manure belt houses, the NH₃ concentrations at exhaust fans were up to 15 ppm and 2–4 ppm in for Pennsylvania buildings in winter and summer, respectively; they reported concentrations of up to 8 ppm and 2–3 ppm for Iowa buildings in winter and summer, respectively. By contrast, high-rise houses in Iowa with a manure-pit showed a concentration range of 70–120 ppm during winter, and below 20 ppm during winter was noted at the manure pit. Those in Pennsylvania had NH₃ concentrations ranging from 40 to 100 ppm for winter and 10 to 40 ppm for summer. Ni et al. (2012) studied the characteristics of air pollutant concentrations of NH₃, H₂S, CO₂, and particulate matter (PM₁₀) in 2 high-rise houses having A-frame cages with 180,000 hens and 2 ten-tier cages houses with manure belts that housed 200,000 hens located in Indiana, USA, over a 2-year period. The results showed that variations in pollutant concentrations were affected by outdoor temperature, ventilation, hen condition, and farm management practices. When compared to the manure-belt houses, gas concentrations in the high-rise houses were higher for NH₃ and lower for CO₂. However, the scope of this study was limited to reporting pollutant concentrations only at the ventilation outlets of the fans. Zhao et al. (2015) compared the indoor NH₃ and CO₂ concentrations and thermal environment in three housing systems that included a conventional cage (200,000 hens), an aviary (50,000 hens), and an enriched colony (50,000 hens). Results showed that the average indoor temperatures were 24.6°C, 25.2°C, and 26.7°C, and the average RH were 57, 56, and 54%. The daily mean indoor NH₃ concentrations were 4.0 ppm, 6.7 ppm, and 2.8 ppm, and the daily mean indoor CO₂ concentrations were 2,083 ppm, 2,475 ppm, and 2,216 ppm for the conventional cage, aviary, and enriched colony house, respectively.

It is noted that large variations exist among results from different studies, which are associated with differences in housing types, management practices, local climatic conditions, and, to some extent, the associated measurement methods (Kaasik and Maasikmets, 2013). It was acknowledged that in previous studies, the sensors measuring the interior thermal environment (temperature, RH) or air quality (NH_3 , H_2S , CO_2 , PM_{10} , $\text{PM}_{2.5}$) in the manure-belt layer houses were generally installed in the middle of the aisle between cages (Green et al., 2009; Dobeic and Pintaric, 2011; Shepherd et al., 2015; Zhao et al., 2015). In other words, these measurements are more appropriate to demonstrate the thermal environment representing the building environment, rather than that experienced by the laying hens. The thermal environment and air quality at hen level can directly and negatively affect the health, welfare, and productivity of poultry. Large-scale (>250,000 hens per house) commercial laying hen housing with manure-drying tunnels has gained large interest in the past decades and is a common housing type in the global egg industry; thus, it is important to evaluate the interior thermal environment and air quality parameters for layer housing with manure-drying tunnels.

The Portable Monitoring Unit (PMU) was designed and developed for measuring air temperature, NH_3 , CO_2 concentrations, and building static pressure in livestock and poultry buildings (Gates et al., 2005) and had been widely used in air quality assessment in poultry houses (Li et al., 2005; Liang et al., 2005; Wheeler et al., 2006; Gates et al., 2008). The use of the first-generation PMUs entailed a substantial degree of manual setup and data processing, making field deployment of multiple PMUs simultaneously a logistical challenge. To improve the functionality and data processing of the PMUs, the PMU design was upgraded to the Intelligent Portable Monitoring Unit (iPMU) as reported in the study by Ji et al. (2016). The newer generation iPMUs are capable of measuring the NH_3 (uncertainty: ± 3 ppm) and CO_2 (accuracy: 1.5% of range and 2% of reading) concentrations and air temperature (accuracy: 0.75% of reading) simultaneously and providing real-time data processing and display and wireless data transfer.

The objectives of this article were 1) to assess the values and variability of interior air temperature and NH_3 and CO_2 concentrations monitored over 6 months inside a commercial laying hen barn with manure-drying tunnels and 2) to compare the NH_3 and CO_2 concentrations at the hen level (measured inside cages) and in the adjacent aisle (measured between cages in the hallway).

MATERIALS AND METHODS

Description of the Layer Barn

This study was conducted in a commercial laying hen house with enrichable cages and manure-drying tunnels, in the Midwest United States. The layer barn measured

27.8 m wide, 164.6 m long, and 10 m high, with a floor halfway between the ground and ceiling forming the top and bottom floors. The barn's interior contained 10 rows of enrichable cage stacks, with each stack consisting of 12 tiers (6 tiers on each floor) and with a manure belt under each cage. The building housed about 425,000 laying hens (White Leghorns W-36) at the time of this study. Two manure-drying tunnels with the same dimension (4.9 m wide \times 85 m long) were constructed at both sides of the building. Building layout and fan placements for the barn's ventilation system are illustrated in Figure 1. There were 31 fans with shutters and cones (1.32 m diameter; Officine Facco & C SpA, Via Venezia, Italy) on each sidewall, of which 10 were variable speed fans (Figure 1, minimum variable speed fans). In addition, a total of 130 constant-speed fans (1.32 m diameter; Officine Facco & C SpA, Via Venezia, Italy) were vertically placed in five rows at the building south end wall, and cooling pads were placed at the other end for hot weather operation. The designed values of minimum and maximum ventilation rate of the barn were approximately $0.6 \text{ m}^3 \text{ h}^{-1}$ per bird and $12.4 \text{ m}^3 \text{ h}^{-1}$ per bird, respectively, per the onsite manager. The barn ventilation operated in one of 2 modes: 1) during cold conditions, fresh air entered the barn through evenly distributed ceiling air inlets, and barn air exhausted through the fans placed along both sidewalls (mode 1); and 2) during hotter conditions, fresh air entered the barn through the evaporative pads placed at the building north end wall and barn air exhausted through tunnel fans at the south end wall and both sidewalls (mode 2). In both modes, stages of fans were sequentially activated as interior temperature rose above targeted room temperature.

A portion of each sidewall was connected to an extended room (4.9 m wide \times 85 m long) that functioned as a manure-drying room (Figure 2). The manure-drying room contains a 10-tier perforated belt (drying tunnel) that was designed to continuously dry feces produced in the barn by using the ventilation system and six exhaust fans and a curtain located on both exterior sidewalls of the manure-drying rooms. Barn air left the poultry house and entered the manure-drying tunnel, circulating upward through the feces on aerated manure belts to promote moisture removal and eventually exited the building. A proper balance of the static pressures between the hen occupied zone, the manure-drying tunnels, and the outside air is critical for proper operation of this system.

Interior Environmental Monitoring

Interior air temperature, NH_3 and CO_2 concentrations, and building static pressures were monitored from February to July 2016. The top and side views of the environmental measurement locations are shown in Figures 1 and 2.

Seven temperature dataloggers (HOBO U12-012, Onset Computer Corp., Bourne, MA) were used to measure the interior air temperatures from March 12th to

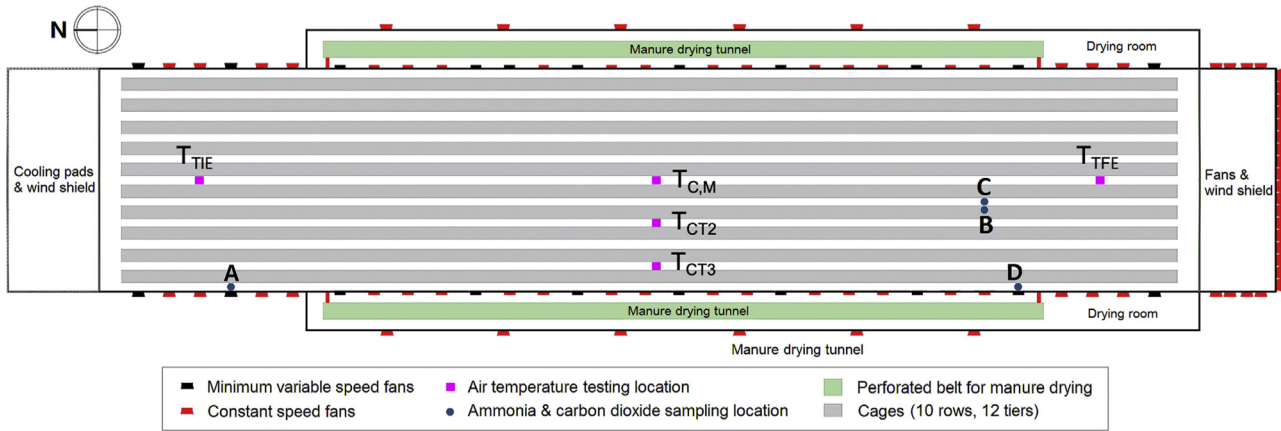


Figure 1. Barn layout, ventilation system, fan placements, sensor locations, and sampling points. The barn measured 27.8 m wide \times 164.6 m long and had 2 floors (12 tiers of cages) and housed about 425,000 laying hens (White Leghorns W-36). Two manure-drying rooms with the same dimension (4.9 m wide \times 85 m long), each contains a perforated manure-drying belt, were constructed at both sides of the building. Temperature measurements include at the tunnel ventilation inlet end (T_{TIE}), at the tunnel ventilation fans end (T_{TFE}), at the center of the barn in the middle across the width ($T_{C,M}$, T_{CT2} , and T_{CT3} , from the building center to the manure-drying tunnel side), and at the middle height of the first floor ($T_{C,B}$) and the second floor ($T_{C,T}$). A–D indicate the 4 locations where barn air was sampled for ammonia and carbon dioxide concentrations.

July 26th, 2016. The temperature dataloggers were installed in the following directions inside the barn to characterize a three-dimensional temperature profile of the barn: 1) longitudinal direction measurements included one at the tunnel ventilation inlet end (T_{TIE}) and one at the tunnel ventilation fans end (T_{TFE}); 2) lateral direction measurements included 3 in the center of the barn and in the middle across the width ($T_{C,M}$, T_{CT2} , and T_{CT3} , from the building center to the manure-drying tunnel side); and 3) vertical direction included 2 other temperature dataloggers located in the center lane and in the middle height of the first floor ($T_{C,B}$) and second floor ($T_{C,T}$). Another datalogger was set outside to record the ambient air temperature

(T_{OUT}) during the experiment period. All temperature data were recorded every 10 min.

Four iPMUs were used to simultaneously measure NH_3 and CO_2 concentrations in the center of the building (approximately the same height as the ceiling level of the sixth tier cage, 4.1 m above the floor). Barn air was sampled at 4 sampling points, including inside the cage to represent air conditions at the hen level (point B; Figures 2 and 3A); between cages to represent the adjacent aisle conditions (point C; Figures 2 and 3B); and above 2 continuously running minimum ventilation exhaust fans (points A and D; Figures 1 and 2). The iPMUs were programmed to collect data at a 10-s sampling interval for 5 min, following by a 55-min purging

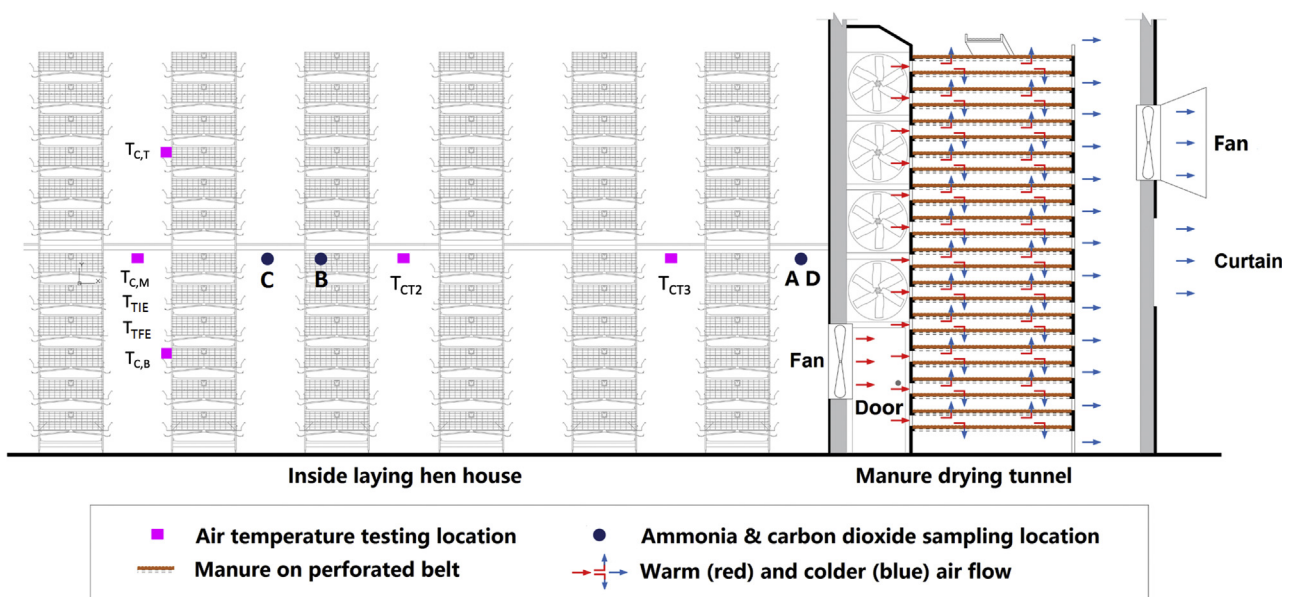


Figure 2. Partial (one-half) building cross-section view demonstrating the manure-drying system, sampling locations, manure-drying tunnel, exhaust fan, and curtain locations on the exterior wall. Temperature measurements include at the tunnel ventilation inlet end (T_{TIE}), at the tunnel ventilation fans end (T_{TFE}), at the center of the barn in the middle across the width ($T_{C,M}$, T_{CT2} , and T_{CT3} , from the building center to the manure-drying tunnel side), and at the middle height of the first floor ($T_{C,B}$) and the second floor ($T_{C,T}$). A–D indicate the 4 locations where barn air was sampled for ammonia and carbon dioxide concentrations.

cycle in which fresh air from outside was drawn into the sensors. The sampling cycle continued for 24 h, then was followed by a 48-h fresh air purge, after which the process repeated. Building static differential pressure between bird production area, manure-drying tunnel (bird area to perforated belts), manure-drying room (perforated belts to drying room exterior wall), and outside was regularly measured using a handheld differential pressure meter (Testo, 512, 0–20 hPa, Testo SMI Sdn Bhd, Malaysia). The static pressure in each location was collected along with other environmental data.

All environmental measurement sensors deployed in this study were checked and calibrated. The air temperature sensors were calibrated using a National Institute of Standards and Technology-certified Heating and Cooling Temperature Calibrator (CL134-1; OMEGA Engineering, Inc., Norwalk, CT) before and about every 4 wk during the experiment. The NH₃ and CO₂ sensors in the iPMUs were calibrated using calibration-grade reference gases before farm installation.

Data and Statistical Analysis

The following statistical analyses were performed using SAS (version 9.4; SAS Institute Inc., Cary, NC) and RStudio (version 1.2.5001; RStudio Inc., Boston, MA). The air temperature distribution inside the barn was represented as follows: 1) longitudinally by comparing T_{TIE}, T_{C,M}, and T_{TFE}; 2) laterally by comparing T_{C,M}, T_{CT2}, and T_{CT3}; and 3) vertically by comparing T_{C,B}, T_{C,M}, and T_{C,T}. The daily means (\pm SD) of the interior temperatures and the outside temperature were analyzed and plotted over the 2 monitoring periods associated with ventilation mode 1 (March 12th–May 22nd) and mode 2 (May 23rd–July 26th). The means and the SD of these temperature measurements during the 2 monitoring periods were tabulated. T_{OUT} was included in the temporal distribution

plot for reference. A Tukey mean separation was performed by PROC ANOVA in SAS for the daily mean air temperatures to explore if temperature variation presented in the directions listed previously with significant effects acknowledged at $P < 0.05$.

The daily means of the interior CO₂ and NH₃ concentrations were evaluated for seasonal and spatial effects, based on daily average ambient temperatures recorded. The daily average T_{OUT} (noon to noon) was categorized into 4 thermal ranges, that is, <0, 0–10, 10–20, and >20°C. Analyses of the interior CO₂ and NH₃ concentrations were sorted into the T_{OUT} categories, and the number of monitoring days experiencing the T_{OUT} categories was tabulated. The daily means of the NH₃ and CO₂ concentrations at each sampling point were averaged and tabulated for each T_{OUT} category. The mean values (\pm SD) of the indoor air temperatures, CO₂, and NH₃ were analyzed by analysis of variance (ANOVA) for effects of T_{OUT} category, sampling point, and T_{OUT} category \times sampling point interaction. The analyses were carried out by two-way ANOVA in RStudio. Normality of the dependent variable for each T_{OUT} category was verified and accepted at $P > 0.01$. The Tukey-Kramer test for differences of least square means was used to determine significant differences between variable means ($P < 0.05$) due to unequal sample sizes between T_{OUT} categories. A box-whisker plot was created for the daily means of the interior CO₂ and NH₃ concentrations measured at the 4 sampling points and the T_{OUT} categories. The CO₂ and NH₃ concentrations were further explored for sampling points B (hen level) and C (cage aisle) by plotting the concentrations against date of the experiment and the T_{OUT} to depict the characteristics of their temporal and thermal profiles at the hen level and at cage aisle. A linear regression was fitted for the average concentrations between points B and C, for T_{OUT} < 20°C (ventilation mode 1), and for T_{OUT} > 20°C (mode 2), respectively. The results of

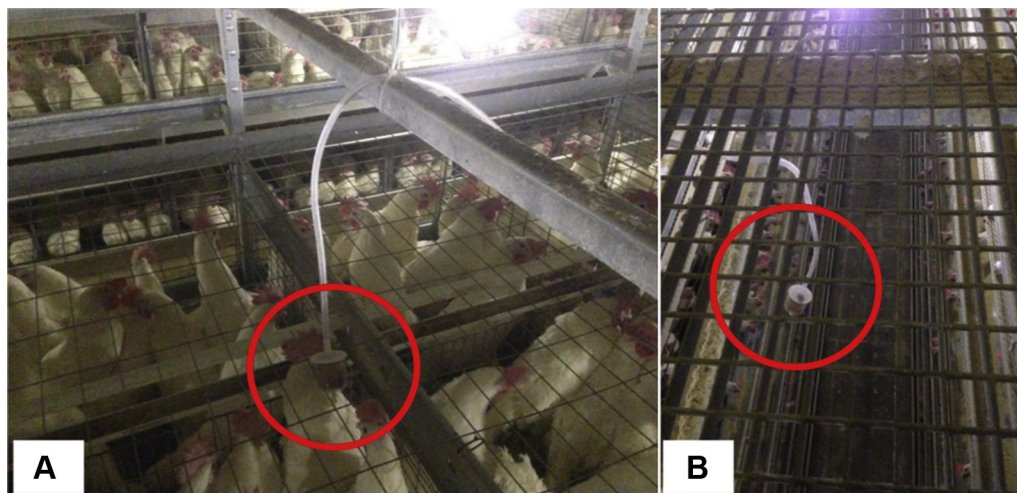


Figure 3. Sampling locations of barn air: (A) inside hen cages to represent air conditions at the hen level (sampling point B) and (B) between cages to represent the adjacent aisle (hallway) air conditions (sampling point C). Sampling points B and C with dust cup filters installed were at the same heights and locations of the two dust cup filters are shown in the red circles.

the slope, the intercept, and the coefficient of determination (R^2) of the linear model were included. The average building static pressure in each location was used as supplemental information to understand the barn ventilation management.

RESULTS AND DISCUSSION

Temperature Distribution

Daily average air temperatures computed from measurements at different locations inside the barn and the ambient temperatures during the monitoring period are shown in Figure 4. Table 1 provides a summary of descriptive statistics (mean \pm SD) and the results of the mean separation analysis for the interior air temperatures measured at different sampling locations during the 2 monitoring periods that were associated with ventilation mode 1 and mode 2, respectively.

During monitoring, the daily average T_{OUT} ranged from 3.7°C to 22.4°C and 17.2°C to 30.3°C for testing periods March 12th–May 22nd and May 23rd–July 26th,

respectively. All interior temperature measurements (longitudinal and lateral) paralleled the ambient temperature. During the first testing period, there was a spatial variation in temperature distribution for all 3 directions, indicating the thermal environment was not uniform in the barn. In the longitudinal direction, temperatures measured at the barn center ($T_{C,M}$), the tunnel ventilation inlet end (T_{TIE}), and the tunnel ventilation exhaust fans end (T_{TFE}) were all different ($P < 0.05$), with $T_{C,M}$ consistently being the highest and T_{TFE} being the lowest. When tunnel ventilation fans were not running, the tunnel fans end was 0.8°C colder than the tunnel inlet end, and both ends were colder than the middle by 3.4°C–4.2°C. In the lateral direction, the warmest temperatures were measured at $T_{C,M}$ ($P < 0.05$), while no difference was observed between T_{CT2} and T_{CT3} located in the middle across the width toward the manure-drying tunnel wall. Vertically, the mean temperature at the center lane on the top floor ($T_{C,T}$) was 1.6°C and 1.8°C greater ($P < 0.05$) than that at the middle or at the bottom floor ($T_{C,M}$ and $T_{C,B}$), respectively, indicating a vertical temperature

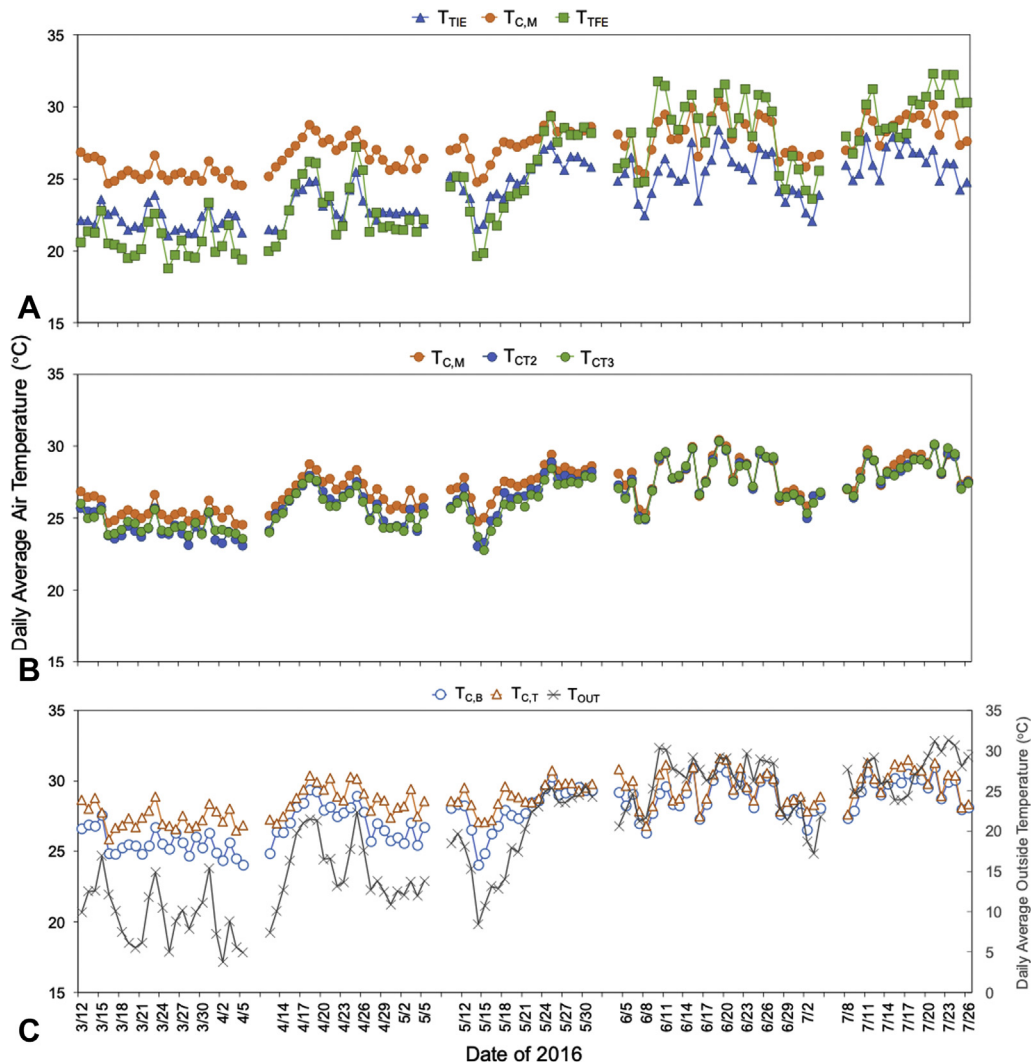


Figure 4. Daily average air temperature at different sampling locations (as indicated in Figure 2) over the experiment period: (A) longitudinal temperature distribution including T_{TIE} , $T_{C,M}$, and T_{TFE} ; (B) lateral temperature distribution including $T_{C,M}$, T_{CT2} , and T_{CT3} ; and (C) vertical temperature distribution including $T_{C,B}$ and $T_{C,T}$. The ambient air temperature measured outside of the barn (T_{OUT}) is included.

Table 1. Summary of descriptive statistics (mean \pm SD) and the results of the mean separation analysis for the interior air temperatures measured at different sampling locations during the 2 monitoring periods that were predominantly associated with ventilation mode 1 and mode 2.

Testing period	T _{OUT} (°C)	Daily average air temperature ¹ (°C, mean \pm SD)						
		T _{TIE}	T _{C, M}	T _{TFE}	T _{CT2}	T _{CT3}	T _{C, B}	T _{C, T}
3/12-5/22	13.0 \pm 4.8	22.9 \pm 1.3 ^D	26.3 \pm 1.1 ^B	22.1 \pm 2.1 ^E	25.2 \pm 1.3 ^C	25.1 \pm 1.1 ^C	26.5 \pm 1.4 ^B	28.1 \pm 1.1 ^A
5/24-7/26	26.0 \pm 3.1	25.7 \pm 1.4 ^D	28.2 \pm 1.2 ^C	28.6 \pm 2.2 ^{B,C}	27.9 \pm 1.3 ^C	27.9 \pm 1.3 ^C	29.1 \pm 1.1 ^{A,B}	29.6 \pm 1.2 ^A

Different superscript uppercase letters within the same row indicate that means under the same testing period differ significantly ($P < 0.05$) using the Tukey test for difference of the means.

¹Temperature measurements include at the tunnel ventilation inlet end (T_{TIE}), at the tunnel ventilation fans end (T_{TFE}), at the center of the barn in the middle across the width (T_{C,M}, T_{CT2}, and T_{CT3}, from the building center towards the manure-drying room), and at the middle height of the first floor (T_{C,B}) and the second floor (T_{C,T}).

difference, and although this was reduced in the second testing period, it was not eliminated. During the second testing period, a temperature difference in the longitudinal direction was noticed ($P < 0.05$), with the tunnel ventilation inlet end temperatures (T_{TIE}) consistently lower than the barn center (T_{C,M}) or the tunnel ventilation exhaust fans end (T_{TFE}) as evaporative cooling operated, and a mean temperature rise of 2.6°C between T_{TFE} and outside air (T_{OUT}). No difference was noted for temperature measurements in other directions. It should be noted that air temperatures were measured at only 7 locations in this study. When appropriate, both air temperature and RH should be measured at more testing locations for comprehensive assessment of spatial distribution inside modern size commercial layer barns.

As T_{OUT} gradually increased during the year, the barn ventilation transitioned to mode 2, from May 22nd to June 11th and June 28th to July 7th, and was conducted completely in mode 2 from June 12th to June 28th and July 8th to July 26th. Our results showed that the tunnel ventilation inlet side consistently recorded the lowest air temperatures of these testing periods. Wang et al. (2019) noted a similar pattern of temperature distribution along the building length direction in a poultry house operated with tunnel ventilation system. Their results showed that the air temperature greatly increased along the building length direction in the poultry house with tunnel ventilation system, that is, cooler near the inlets and warmer near the fans, and the temperature at the three different sampling locations increased along the length of the barn because of the addition of sensible heat produced from the laying hens (Wang et al., 2018, 2019). Regardless of the longitudinal gradient observed, there was no difference found laterally (among T_{C,M}, T_{CT2}, and T_{CT3}) or vertically (between T_{C,B} and T_{C,T}), indicating uniform air temperature distribution along these directions and suggesting that tunnel ventilation effectively encouraged more fresh air distribution inside the barn and created a more uniform thermal environment than during the winter. A similar pattern of uniform temperature distribution along the width and the height of a poultry barn with tunnel ventilation in the summer was also reported by Webster and Czarick (2000). This is due to the air flow coming from the evaporative cooling pads (tunnel

ventilation inlet end), which were installed on the gable wall or/and both sidewalls in one end of the building, while fans were installed on the other end. Thus, continuous airflow from the evaporative cooling pads to the exhaust end was noted and provided air with uniform temperature along the width distribution of a poultry house (Hui et al., 2016; Freitas et al., 2018, 2019), with a linear increase from bird heat production (Gates et al., 1992).

Carbon Dioxide Concentrations

The daily mean CO₂ concentrations measured at sampling points A, B, C, and D are provided in Table 2, along with a summary of descriptive statistics (mean \pm SD) and the results of the mean separation analysis for the daily CO₂ concentrations at different sampling points under different ambient thermal categories. Any difference in CO₂ concentrations between the hen level and the adjacent aisle was useful to assess the gas environment experienced by laying hens and was further explored by plotting the temporal profile of daily CO₂ concentrations (Figures 5A, 5B) and its relationship with ambient temperatures (Figure 6). The daily CO₂ concentrations were regressed for the ventilation mode 1 (T_{OUT} < 20°C) and mode 2 (T_{OUT} > 20°C).

The daily average CO₂ concentrations ranged from 400 to 4,981 ppm among the 4 sampling locations. Results indicate that CO₂ concentrations were significantly different for both the T_{OUT} category and sampling location ($P < 0.001$), as well as the interaction of T_{OUT} category \times sampling location ($P < 0.001$). The daily mean CO₂ concentrations at all sampling points decreased with increasing T_{OUT}. When operated under ventilation mode 1, relatively high indoor CO₂ concentrations (means of 2,924 ppm, 3,352 ppm, 3,214 ppm, and 3,046 ppm for points A to D, respectively) were found in cold weather due to the low ventilation rate to maintain room temperature, with a strong linear decrease with outside temperature (Figure 6, mode 1). When the barn ventilation switched to mode 2, low CO₂ concentrations at ambient levels (approximately 400 ppm) were observed during warm temperatures (Figure 6, mode 2). The results were similar to those from the study by Ni et al. (2012), who reported high daily mean CO₂ concentrations between January and

Table 2. Descriptive statistics (mean \pm SD) of CO₂ and NH₃ concentrations at 4 different testing sampling locations (A, B, C, and D).

Gases	Daily average ambient temperature range (°C) (days encountered this range)	Daily mean concentration (mean \pm SD, ppm)				T _{OUT} \times location interaction
		Sampling point A	Sampling point B	Sampling point C	Sampling point D	
CO ₂	<0 (4 D)	2,924 \pm 416 ^{b,A}	3,352 \pm 487 ^{a,A}	3,214 \pm 421 ^{a,A}	3,046 \pm 466 ^{b,A}	1
	0 to 10 (8 D)	1,896 \pm 358 ^{c,B}	2,389 \pm 395 ^{a,B}	2,239 \pm 375 ^{b,B}	2,350 \pm 448 ^{a,B}	
	10 to 20 (16 D)	1,501 \pm 357 ^{c,C}	1,786 \pm 465 ^{a,C}	1,689 \pm 410 ^{b,C}	1,789 \pm 418 ^{a,C}	
	>20 (20 D)	707 \pm 307 ^{c,D}	1,030 \pm 284 ^{a,D}	917 \pm 281 ^{b,D}	995 \pm 363 ^{a,D}	
NH ₃	<0 (4 D)	7.8 \pm 2.8 ^{d,A}	22.0 \pm 5.2 ^{b,A}	20.4 \pm 4.5 ^{c,A}	28.1 \pm 4.7 ^{a,A}	1
	0 to 10 (8 D)	2.4 \pm 2.2 ^{d,B}	14.6 \pm 5.2 ^{a,B}	11.1 \pm 4.1 ^{c,B}	12.8 \pm 3.7 ^{b,B}	
	10 to 20 (16 D)	1.4 \pm 2.3 ^{c,B}	11.7 \pm 6.0 ^{a,C}	9.5 \pm 4.6 ^{b,C}	10.1 \pm 5.1 ^{b,C}	
	>20 (20 D)	0.0 \pm 0.0 ^{d,C}	2.0 \pm 2.6 ^{a,D}	0.8 \pm 1.9 ^{c,D}	1.2 \pm 2.2 ^{b,D}	

Results of the two-way ANOVA for effects of sampling location and T_{OUT} categories and sampling location \times T_{OUT} on CO₂ and NH₃ concentrations are included.

Different superscript lowercase letters within the same row indicate that means under the same thermal category differ significantly ($P < 0.05$) using the Tukey test for difference of the means.

Different superscript uppercase letters within the same column indicate that means under the same sampling location differ significantly ($P < 0.05$) using the Tukey test for difference of the means.

¹There is a significant interaction effect of the outside temperature categories and the sampling locations ($P < 0.001$).

March (winter) and low values during July and August (summer). When the ambient temperature exceeded 25°C, the barn was operated with tunnel ventilation (mode 2), and the CO₂ concentrations remained at reasonably low levels (<1,000 ppm). Ni et al. (2012) and Zhao et al. (2013) also observed low CO₂ levels with increased air temperature, presumably from the increased house ventilation rates with increased interior temperatures during summer conditions.

Within each T_{OUT} thermal category, differences in CO₂ measured concentrations at different sampling points were observed ($P < 0.05$). For T_{OUT} below 0°C, CO₂ concentrations measured at the minimum ventilation sidewall fans (sampling points A and D) were lower ($P < 0.05$) than those measured in the barn's center (points B and C). As ambient temperature increased, the CO₂ concentrations measured at different sampling points followed a similar pattern, with sampling point A having the lowest CO₂ concentrations and sampling points B and D the highest concentrations ($P < 0.001$). Among all the sampling locations inside the barn, sampling point A consistently had the lowest CO₂ concentration for all T_{OUT} categories ($P < 0.001$). One explanation for this was that the sampling location was located on the tunnel ventilation inlet end, where fresh air was drawn into the barn during warmer weather (mode 2). For cold weather (mode 1), CO₂ levels at sampling point A were lower than those at sampling point D. This could be explained by that the pressure difference for fans at sampling point A that exhaust directly to the exterior was lower (16 \pm 9 Pa) than that at sampling point D that exhaust to the manure-drying tunnel (29 \pm 10 Pa). Compared with the CO₂ concentration at point C, higher concentration was detected at point D for T_{OUT} greater than 0°C ($P < 0.05$). The mean CO₂ concentrations measured in the cage (point B) were slightly greater ($P < 0.001$) than those in the adjacent aisle (point C) (1,898 \pm 787 ppm and 1,781 \pm 758 ppm, respectively).

Ammonia Concentrations

Mean (\pm SD) daily NH₃ concentrations at sampling points A, B, C, and D and the results of the two-way ANOVA with mean separation analysis for the daily NH₃ concentrations at different sampling points under different ambient thermal categories are provided in Table 2. Figures 7A, 7B illustrate the distribution of the daily mean NH₃ concentrations of each sampling point for each T_{OUT} category. Difference comparisons of NH₃ concentrations between the hen level and the adjacent aisle is useful to assess the gas environment experienced by laying hens and was further explored by plotting the temporal profile of daily NH₃ concentrations (Figure 7B) and its relationship with ambient temperatures (Figure 8). The daily mean NH₃ concentrations were regressed for the ventilation mode 1 (T_{OUT} < 20°C) and mode 2 (T_{OUT} > 20°C).

Figure 7A shows that the NH₃ in the layer hen house exhibited a wide range of daily mean concentrations over the course of this study. The daily NH₃ concentrations recorded within the barn ranged from 0 to 28.1 ppm on average, with extreme values above 40 ppm observed during colder outside temperatures. The patterns of the seasonal distribution and variation of NH₃ concentrations shown in Figures 7A, 7B resemble those of the CO₂ concentrations (Figure 5). Daily mean NH₃ concentrations were significant for T_{OUT} category and sampling location effects ($P < 0.001$) and the interaction of T_{OUT} category \times sampling location ($P < 0.001$). NH₃ concentrations in other layer barns are also affected by ventilation rate, which is largely influenced by outside air temperature (Lin et al. 2017). At the same sampling location, T_{OUT} categories greatly impacted the indoor air NH₃ concentrations (Figure 8), where lower NH₃ concentrations always corresponded to higher T_{OUT}, and higher NH₃ concentrations associated with lower T_{OUT}, during which the barn ventilation rates were reduced to a minimum value (0.6 m³ h⁻¹ per bird) to

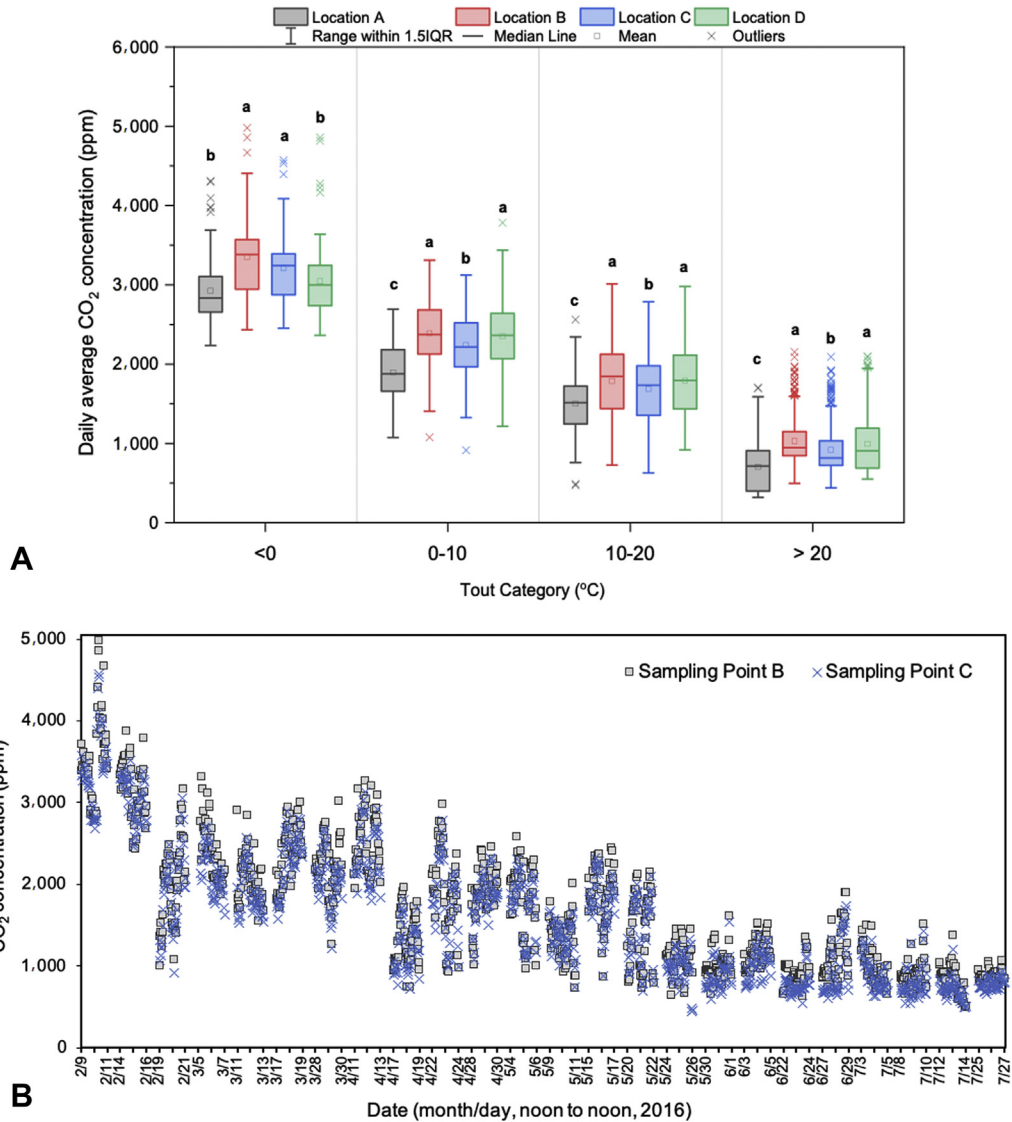


Figure 5. (A) Distribution of daily average CO₂ concentrations measured at sampling points A–D under 4 different T_{OUT} thermal categories that were monitored from February 9th–July 27th, 2016. Different letters “a–d” within the image indicate that different sampling locations had significantly different means (*P* < 0.05) using the Tukey test for difference of the means. (B) Daily average CO₂ concentrations at sampling points B (hen level) and C (adjacent aisle) measured by the iPMUs from February 9th–July 27th, 2016.

conserve energy while maintaining adequate indoor air quality. A few studies were previously conducted to assess NH₃ concentrations inside layer facilities, with different layer farms showing unique characterization of their interior NH₃ conditions. Wathes et al. (1997) monitored a NH₃ concentration range of 12–24 ppm in a layer barn, and Cheng et al. (2011) measured NH₃ concentrations in layer houses with cage systems, of which the NH₃ concentration ranged from 0.5 to 12.5 ppm. NH₃ concentrations were positively correlated to the moisture contents of the air (Ni et al. 2017), and higher in-house NH₃ concentrations in winter were caused by lower ventilation rates and wetter litter conditions due to insufficient drying.

Regardless of the T_{OUT} categories, NH₃ concentrations also varied among different sampling locations. From Table 2, sampling point A consistently had the

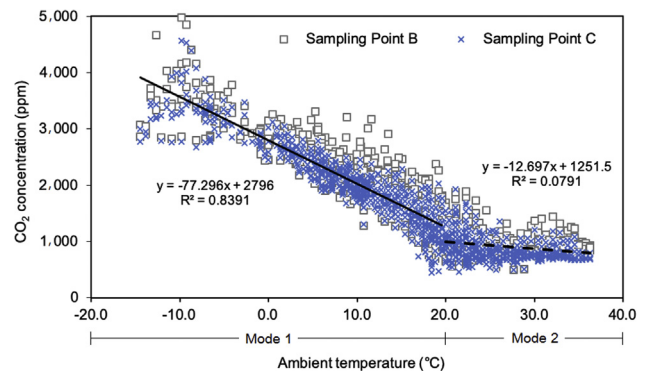


Figure 6. Relationship between daily average CO₂ concentrations measured at hen level (sampling point B), at adjacent aisle (sampling point C), and the corresponding ambient temperatures (T_{OUT}). The CO₂ concentrations were regressed for the ventilation mode 1 (T_{OUT} < 20°C) and mode 2 (T_{OUT} > 20°C).

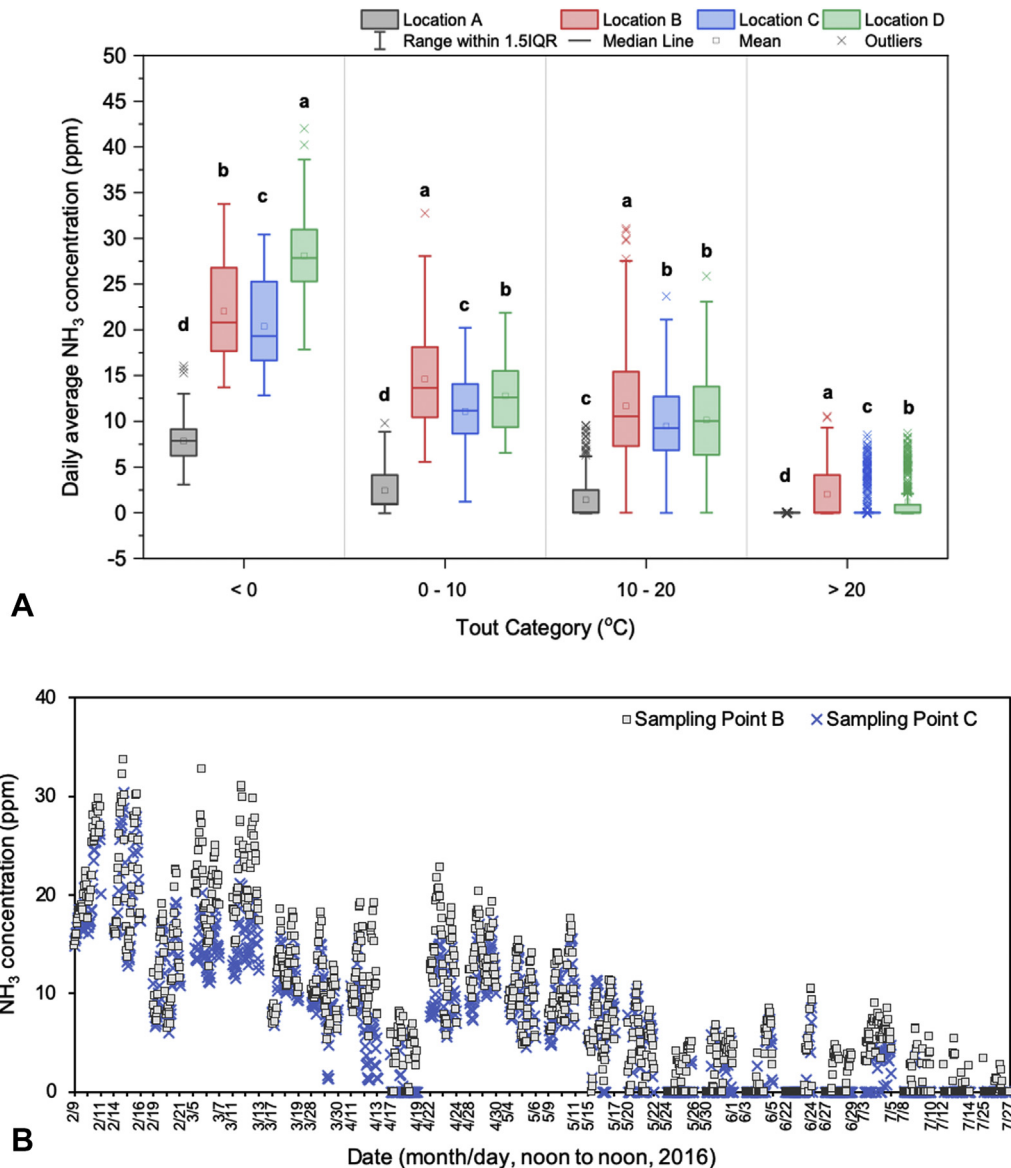


Figure 7. (A) Distribution of daily average NH₃ concentrations measured at sampling points A–D under 4 different T_{OUT} thermal categories that were monitored from February 9th–July 27th, 2016. Different letters “a–d” within the image indicate that different sampling locations had significantly different means ($P < 0.05$) using the Tukey test for difference of the means. (B) Daily average NH₃ concentrations at sampling points B (in cage) and C (adjacent aisle) measured by the iPMUs from February 9th–July 27th, 2016.

lowest daily NH₃ concentrations compared with the other three sampling locations ($P < 0.001$). The overall mean NH₃ concentrations measured in the cage (point B) and near the cage (point C) were 12.5 ± 4.75 ppm and 10.4 ± 3.80 ppm ($P < 0.001$), respectively. During all T_{OUT} conditions, sampling points B and D consistently had the highest NH₃ concentrations ($P < 0.001$), with the highest mean NH₃ concentration of 42.3 ppm during the entire course of the monitoring recorded at sampling point D (above the minimum exhaust fan adjacent to the manure-drying tunnel) for T_{OUT} < 0°C.

Ventilation Management

As reported by the producer, the ventilation was mainly conducted in mode 1 from March 12th to May

22nd in 2016 (solely in mode 1 from March 12th to May 5th, and predominantly in mode 1 from May 5th to May 22nd). During cold weather (ventilation mode 1), we observed lower temperature toward the tunnel fans end and a higher ammonia concentration measured at sampling point D near the manure-drying tunnel. Ventilation design and management can potentially explain this. Based on our observation, during ventilation mode 1, fresh air was drawn into the barn through ceiling inlets and distributed to the barn interior. Air then exited through the continuously running side-wall fans and into the manure-drying tunnels, which were pressurized above atmospheric conditions. Referring to Figure 9, the static pressures at the manure-drying tunnel (P_3) and manure-drying room (P_2) were above atmospheric pressure (P_0). This back pressure allows higher concentration ammonia air to leak into the bird area

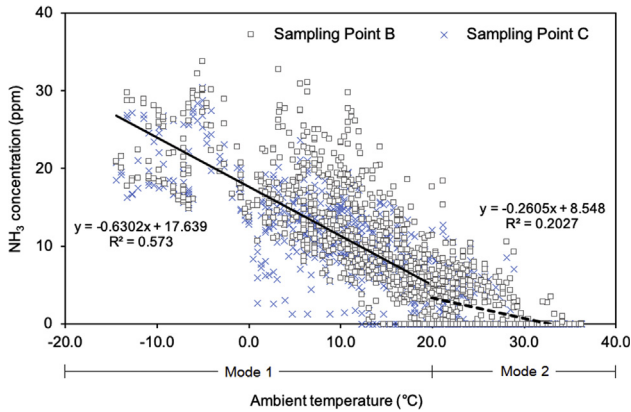


Figure 8. Relationship between daily NH_3 means for the hen level (point B) and cage adjacent aisle (point C) and the corresponding ambient temperatures (T_{OUT}). The NH_3 concentrations were regressed for the ventilation mode 1 ($T_{\text{OUT}} < 20^\circ\text{C}$) and mode 2 ($T_{\text{OUT}} > 20^\circ\text{C}$).

(sampling location D) through fan louvers and other cracks. Ideally, to alleviate this situation, the fans on the exterior walls of the manure-drying room should pull a greater suction (P_{0-2}) than the sidewall fans that blow into the manure-drying room (P_{3-1} and P_{2-1}). In fact, the average measured value of P_{0-2} was only 1 ± 4 Pa during both ventilation modes, whereas P_{3-1} and P_{2-1} were 29 ± 10 and 17 ± 10 Pa, respectively, during mode 1 from March 12th to May 22nd. However, the pressure difference for fans such as those at sampling point A that exhaust directly to the exterior (P_{0-1}) was lower (16 ± 9 Pa). Consequently, the amount of airflow from these fans was reduced, resulting in higher air temperatures recorded in the barn center than in both ends of the barn (T_{TIE} and T_{TFE}). Warmer temperatures observed on the top floor indicated that there was insufficient fresh air circulation at higher elevations in the barn as compared to the bottom floor. Leakage of air caused by back pressure between the manure-drying tunnel and the bird area could also explain the relatively high NH_3 concentrations at sampling point D. Management practices to adjust operational static

pressure differences, which fans to operate during coldest conditions, and methods to reduce back pressure induced leakage were suggested to the producer.

CONCLUSIONS

The following conclusions were drawn from the assessment of interior air temperature, NH_3 , and CO_2 concentrations in a commercial caged layer barn with manure-drying tunnels and comparison of the NH_3 and CO_2 concentrations between inside cages (hen level) and the adjacent aisle:

1. During ventilation for cold conditions (March 12th–May 22nd), there was a variation in temperature distribution longitudinally, laterally, and vertically. Temperatures at the barn center were consistently the highest ($26.3^\circ\text{C} \pm 1.1^\circ\text{C}$), whereas the tunnel inlet end and tunnel ventilation fan end were lower ($22.9^\circ\text{C} \pm 1.3^\circ\text{C}$ and $22.1^\circ\text{C} \pm 2.1^\circ\text{C}$, respectively). Vertically, temperatures measured at the barn center on the top floor were significantly greater ($P < 0.05$) than those measured on the bottom floor. During ventilation for warmer outside temperatures (May 23rd–July 26th), only a variation in the longitudinal direction was noted ($P < 0.05$).
2. The CO_2 and NH_3 concentrations varied significantly with the sampling location inside the building and with outside temperature. Both CO_2 and NH_3 decreased linearly with increasing T_{OUT} (approximately 77 ppm CO_2 and 0.6 ppm NH_3 per $^\circ\text{C}$ rise for $T_{\text{OUT}} < 20^\circ\text{C}$).
3. The CO_2 and NH_3 concentrations measured inside the cages were higher than those in adjacent aisle ($P < 0.001$), except for when average daily $T_{\text{OUT}} < 0^\circ\text{C}$.
4. Air leakage through the nonoperating fans shutters from the manure-drying tunnel to the barn, probably from excess back pressure between the drying tunnel and the barn, caused higher NH_3 concentration near the sidewalls in bird production area.

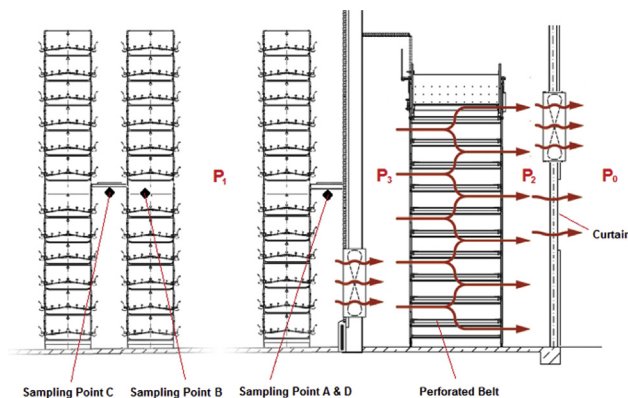


Figure 9. Schematic of static pressures in the layer barn (partial elevation shown) interior, manure-drying tunnel, and the ambient environment during cold weather conditions. Normally, $P_0 > P_2 \geq P_3 > P_1$. Higher pressures at P_3 and P_2 created a back pressure that can induce air flows through nonoperating fan louvers and back into the bird area.

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