ASSESSING VENTILATION RATE USING INDIRECT MEASUREMENT METHODS IN EXPERIMENTAL BENCH-SCALE HOUSES FOR LAYING HENS

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HIGHLIGHTS

- The carbon dioxide balance method provided better results for estimating ventilation rates in hen facilities compared to the heat balance method.
- Daily data aggregation enhances ventilation rate assessment reliability for carbon dioxide and heat balance methods.
- Integrating dynamic animal metabolism enhances model accuracy in poultry facility ventilation assessments.

ABSTRACT. *Ventilation rate (VR) is a key parameter for estimating emissions, but direct measurement is resource-intensive. The present study evaluates the accuracy of indirect methods, precisely the carbon dioxide (CO_2) and heat balances, in estimating VR from laying houses. Data from experiments with 720 laying hens over 8 weeks was analyzed to assess VR variations. The results showed that seasonal changes (temperature and relative humidity) affect VR. Models based on CO_2 and heat balances could estimate VR. However, they showed a weak correlation with direct measurement. The CO_2 balance method showed an R^2 of 0.28, while the heat balance method gave an R^2 of 0.07, with RMSE values of 1.46 m^3 h^{-1} hen^{-1} and 1.01 m^3 h^{-1} hen^{-1}, respectively. Hourly and daily averages improved the performance of indirect methods. In hourly grouped data, the R^2 for heat balance increased to 0.46, accompanied by decreased RMSE values (from 1.01 m^3 h^{-1} hen^{-1} to 0.14 m^3 h^{-1} hen^{-1}). The daily grouped data improved correlation numbers, with an R^2 of 0.85 for the CO_2 and 0.55 for the heat balance, respectively. At the same time, RMSE values dropped significantly (0.22 m^3 h^{-1} hen^{-1} for the CO_2 balance and 0.36 m^3 h^{-1} hen^{-1} for the heat balance). Multiple regression analysis showed that the CO_2 balance method could account for about 82% of VR variability, while the heat balance method explained only 13%. This study supports the CO_2 balance model for precise VR estimations in laying hen facilities. Improving the accuracy of VR estimation remains a priority. This study contributes to a better understanding of challenges and opportunities in assessing VR.*

Keywords. *Airflow rate, CO_2 balance, Egg production, Heat balance, Mechanical ventilation.*

Egg production is a fundamental part of the agricultural industry in the province of Québec, Canada. After Ontario, Québec is Canada's second-largest egg producer, supplying over 20% of the country's production (Government du Québec, 2023). Egg consumption will further increase as it has been estimated that there will be 9.7 billion people worldwide by 2050 (FAO, 2022), which will demand food (Alexandratos and Bruinsma, 2012). In addition, eggs represent one of the animal protein sources with the most accessible price for consumers, relative to beef, seafood, and pork (Statistics Canada, 2022). However, this demand will also be associated with an increase in the number of birds per housing area on the farms. This could generate a significant environmental challenge: gaseous emissions, particularly ammonia (NH_3) and carbon dioxide (CO_2) (Ranganathan et al., 2018), which can have a significant impact on air quality, reducing animal welfare and work quality conditions in the barn (Ni et al., 2017). Moreover, climate change conditions could produce heat stress episodes (Bist et al., 2023; David et al., 2015; Kang et al., 2016), which have put the ventilation systems of laying hen facilities into the spotlight. An adequate ventilation rate (VR) is essential for the welfare and productivity of laying hens and plays a critical role in regulating and managing gaseous emissions (Rosa et al., 2019).

Assessing emissions involves calculating the VR and measuring the difference in gas concentrations between the barn exhaust and inlet. Therefore, the accuracy in measuring VR is crucial to maintaining effective gas concentration

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monitoring (Chai et al., 2012; Rosa et al., 2019), quantifying the level of released gases, and estimating their impact on emissions. This knowledge enables producers and regulators to improve environmental quality by developing strategies for mitigating gaseous emissions, propelling the industry towards sustainable practice (Calvet et al., 2013; Gates et al., 2009).

Ventilation rate can be determined by direct and indirect methods (Liu et al., 2016; Wang et al., 2016; Barreto-Mendes et al., 2014; Xin et al., 2009). The direct method is one of the most common methods for determining VR. This approach uses equipment, such as anemometers, to measure the barn's air inlet and outlet speed. Then, VR is calculated by multiplying the airspeed by the cross-sectional area of the fans. This method provides accurate VR. Nevertheless, it presents considerable challenges (Ogink et al., 2013): calibration of anemometers (Park et al., 2018; Zhou et al., 2017), facility size, fan distribution, and obstacles across the building that can block the air and reduce its speed (Calvet et al., 2013; Gates et al., 2009), resources as time-consuming and labor-intensive required for data collection and analysis, making it challenging to measure continuously. The estimation of VR by indirect methods based on balance equations avoids these challenges by calculating from some specific parameters whose measurement is not as complicated and time-consuming as direct measurement.

Some indirect approaches have been widely studied, including tracer gas (Kiwan et al., 2013), moisture balance (Blanes and Pedersen, 2005), CO_2 balance (Rosa et al., 2019), and heat balance (Samer et al., 2011). The VR is determined using a tracer gas (sulfur hexafluoride; SF6) in partially enclosed livestock spaces. It is a standard method for measuring emissions from livestock buildings (Phillips et al., 2001). However, the use of SF6 must be approached cautiously due to the need for careful distribution to maintain uniform concentration comparable to the estimated gases, given its high density (Hassouna et al., 2015). Moisture balance is a low-cost and straightforward technique that reasonably estimates daily or half-day airflow. Nonetheless, this method does not give precise measurements over short time scales due to the high variability of key parameters, such as humidity and temperature (Hassouna et al., 2015). These factors can fluctuate rapidly in short periods, leading to less accurate estimations of ventilation.

The CO_2 and heat balance approaches offer complementary methods to estimate VR. For example, the CO_2 balance approach assumes that ventilation can explain the relationship between CO_2 production (primarily from the animal's metabolism and, if applicable, from the bedding and heating) and the CO_2 gradient between the inside and outside of the building (Li et al., 2004; Liu et al., 2016; Rosa et al., 2019). By measuring the indoor and outdoor CO_2 concentration and knowing the CO_2 production rate of animals, it is possible to calculate the VR required to maintain an acceptable CO_2 concentration. The heat balance approach explains the relationship between heat production (provided by the metabolism of livestock) and temperature gradient or enthalpy (Hassouna et al., 2015). However, each approach has its assumptions and limitations. Also, the accuracy in both methods decreases when the assessment is performed during short periods since both animal activity and CO_2 production change throughout the day. Nevertheless, these methods have advantages, such as being simple to achieve and low cost, and both can be implemented for assessing VR in various setting conditions.

Numerous research studies have explored the assessment of VR in laying hen facilities, employing both direct and indirect methods. Notably, Pedersen et al. (1998), Li et al. (2004), and Rosa et al. (2019) demonstrated a positive correlation for VR calculation between the direct and CO_2 balance methods. However, correlation analyses between CO_2 balance and direct methods have not consistently provided accurate VR estimations in egg production facilities. Liu et al. (2016) reported a weak correlation between exhaust and inlet CO_2 concentrations. Meanwhile, the heat balance method, widely used in various farm settings, has shown discrepancies in VR estimations for egg production facilities, as highlighted by studies such as those conducted by Pedersen et al. (1998) and Blanes and Pedersen (2005), indicating the need for corrections in precise calculations. It is important to highlight that the accuracy of indirect methods may depend on integration time (Chielo et al., 2016). Short integration times might lead to high variability and less accurate estimates due to transient fluctuations in environmental conditions. Conversely, longer integration times can smooth out these fluctuations, providing a more stable and accurate representation of VR. Despite valuable insights from these studies, a consensus on the best approach is currently lacking, and the literature does not offer clear indications of potential enhancements to data collection or equations for improved performance in assessing VR in diverse settings.

In this context, the present study had three primary objectives: (1) to test the accuracy of indirect methods involving CO_2 and heat balance for evaluating VR in a laying hen bench-scale experimental setup, (2) to evaluate how data aggregation can improve the accuracy of VR assessments, and (3) to identify the variables with the most significant influence on VR calculations.

Materials and Methods

Experimental Rooms and Animal Housing

The data used in the current study came from the experiments performed by Fournel et al. (2012). This research was carried out at the BABE ("Bilan agroenvironnemental des bâtiments d'élevage") experimental building belonging to the "Institut de recherche et de développement en agroenvironnement" (IRDA) located at the Centre de recherche en sciences animales de Deschambault (CRSAD; QC, Canada). The experimental building presents twelve individual rooms with the exact dimensions (1.2 m wide × 2.4 m long × 2.4 m high). Each room was airtight, with no air exchange between rooms, and they were equipped with ventilation, electric heating, and lighting instrumentation. The walls were lined with painted plywood covered with polyethylene on the lower half to protect against slurry. The floor was made of commercial-grade concrete slats, and each room had its manure management system: deep liquid manure pit (n = 4), manure belt (n = 4), and forced air drying (n = 4). For this study, data from all twelve rooms were used.

Three hundred sixty (360) white laying hens of the Lohmann LSL-Lite breed arrived at 19 weeks of age and were housed in the rooms (30 hens/room). Hens were reared in conventional cages (485.5 mm wide x 507 mm deep x 540 mm high) (Farmer Automatic, 2010) stacked in two columns, each of three cages for a total of six cages. Each cage included five hens (492 cm^2 hen^{-1}). The study was conducted in two consecutive eight-week trials: the first trial was performed from March to May 2010, and the second trial from June to August 2010, specifically during the egg-laying period between 19 and 27 weeks of age. These dates were chosen based on previous research findings by Fournel et al. (2011), which identified these eight weeks with the highest gas emissions rates. A two-week adaptation period was provided at the start of each experimental trial to ensure the hens' acclimatization and adaptation to their new environment.

During the experiments, the hens were fed daily with 100 g hen^{-1} of commercial feed for laying hens (35.4 g kg^{-1} total nitrogen, 904 g kg^{-1} dry matter content, 22% proteins, 6.55% fat, 4.88% acid detergent fiber; 2005-000, Aliments Breton, St-Bernard-de-Beauce, QC, Canada). Fresh water was provided *ad libitum* by a solenoid valve connected to a data logger to ensure automatic control of the water supply. The lighting period was 13 h d^{-1}, 13.5 h d^{-1}, and 14 h d^{-1} in both trials for weeks 1–2, 3–4, and 4–8, respectively. The luminous intensity within the experimental rooms was maintained at 40 lux to standardize lighting conditions (Light Meter, Lux/FC, 840020C, Sper Scientific Ltd.). A more detailed description of the experimental setup is available in Fournel et al. (2012).

ENVIRONMENT AND CO_2 CONCENTRATIONS DATA COLLECTION

Ventilation, Temperature and Relative Humidity

Each room was equipped with a 0.3 m diameter variable-speed exhaust fan (Model VEN812448, Ziehl Fan Série Z, Les Industries et Équipements Laliberté Ltée, Québec, Canada). An electronic controller (model RM-2V2S r-matic, Les Industries et Équipements Laliberté Ltée, Québec, Canada) maintained the desired temperature and minimum airflow conditions. The fans operated continuously to ensure consistent ventilation. The refreshing air for each room was taken from a shared intake system that draws air from a centrally pre-conditioned duct (PCD). The PCD aims at (1) eliminating the impact of outside air conditions, thus reducing the seasonal effect on the tests, and (2) ensuring similar conditions at the entrance of the 12 rooms (before the secondary heating element). An air conditioner unit was placed at the central duct's entrance (fig. 1), activated during hot seasons to cool the inlet air. Similarly, a main heating system was located within the same central duct. In addition, each room was equipped with a secondary heating unit integrated into the ventilation duct to enable precise temperature regulation for each room (from commercial practices, the room temperature was set at 22.5°C). The temperature and relative humidity in each room were recorded at 15-minute intervals by a probe (model CS500, accuracy ± 0.3°C at 20°C; 15 ss of delayed response and ± 3% RH, Campbell Scientific Canada, Corp., Edmonton, AB, Canada).

CO_2 Concentrations

Air from each room was pumped to a mobile laboratory using Teflon™ tubing for air sampling. In the mobile laboratory, CO_2 levels were analyzed using a gas chromatograph (GC; model 3600, accuracy ±30 ppmv, Varian, Walnut Creek, CA, USA) equipped with an electron capture detector. Samples from the experimental rooms were drawn through the GC injection loop at 15-minute intervals, one room at a time. It took 3 hours to collect all CO_2 measurements from the twelve rooms. Gas concentrations were continuously monitored throughout the experiment and synchronized with the ventilation flow rate (1 room every 15 min). To calculate the hourly average, we thus grouped all CO^2 data for each hour, meaning the data collected between 0:00 and 0:59, then from 1:00 to 1:59, and so on. It is

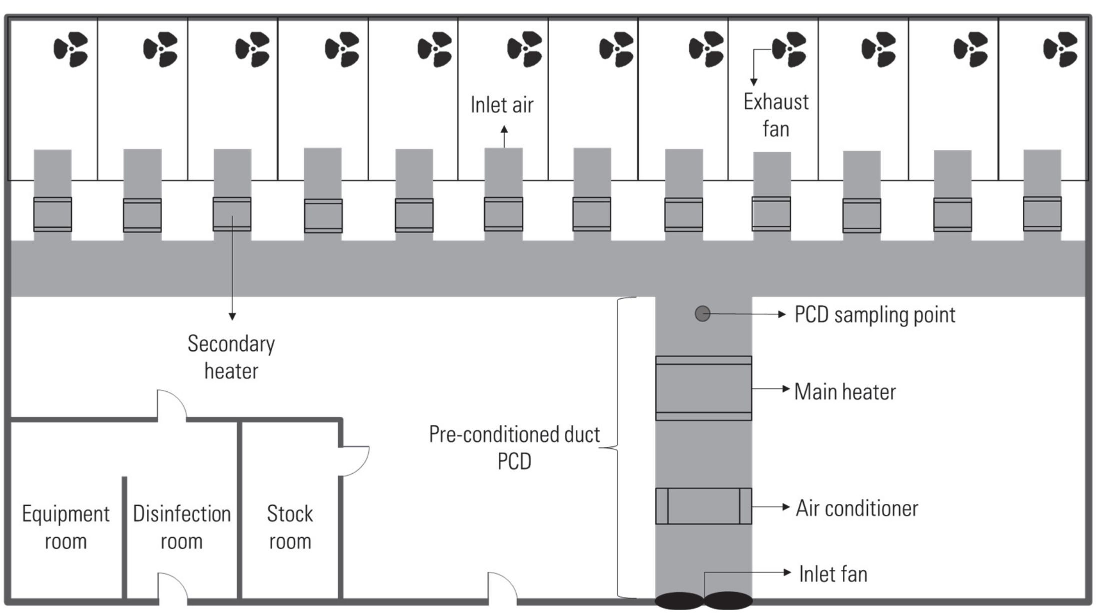

Figure 1. Schematic view of the BABE laboratory (adapted from Fournel et al., 2011).

important to note that the sampling did not occur at the same hour every day, so the sampling times could vary. Every three days between 12:00 PM and 1:00 PM, the concentration of three standard gases was analyzed to verify the measurements taken by the GC. Dust filters were placed at the Teflon™ collection tube entrances to prevent contamination and protect gas analyzer equipment.

METHODS ASSESSMENT

ORIFICE DAMPER

For this study, the orifice damper method was used as the standard reference to compare the accuracy of the CO_2 and heat balance methods. Ventilation rates were assessed using a 204-mm iris orifice damper (Model 200, with an accuracy of ± 5%, Continental Fan Manufacturing Inc., Buffalo, NY, USA) installed inside the exhaust duct of each room. Pressure differentials were recorded every 15 min, averaging all 10-s measurements. The VR was calculated using the following equation:

$$VR = k\sqrt{\Delta p} \times 1.698 \tag{1}$$

where

VR = the ventilation rate of the room ($m^3\ h^{-1}$)

k = constant that depends on the configuration of the iris damper (provided by the manufacturer)

Δp = the difference in static pressure (in H_2O)

1.698 = for units change.

CO_2 Balance Method

The VR is then dependent on the CO_2 balance from the livestock installations with an electric heating system, as indicated in the following equation 2:

$$VR_{CO_2} = \frac{PRCO_2\ \Psi}{\left([CO_2]_e - [CO_2]_i\right)} * 3600 \tag{2}$$

where

VR_{CO_2} = the ventilation rate of the room based on the CO_2 balance method ($m^3\ h^{-1}$)

$PRCO_2$ = the CO_2 production rate of the hens (mL CO_2 s^{-1})

Ψ = the animal activity (dimensionless) determined by equation 38 by Pederson and Sällvik (2002)

$[CO_2]_e$ = the exhaust CO_2 concentration (ppm)

$[CO_2]_i$ = the inlet CO_2 concentration (ppm)

3600 = units change.

The $PRCO_2$ can be described by the relationship between total heat production (THP) and respiration quotient (RQ), which was the volume of CO_2 released from the volume of oxygen utilized during the breathing activity of the hens (Brouwer, 1965):

$$PRCO_2 = \frac{\text{THP}}{\frac{16.18}{RQ} + 5.02} + CO_{2manure} \tag{3}$$

The RQ was assumed to be 0.92 (Ketelaars et al., 1985; Chepete and Xin, 2004; Rosa et al., 2019). The CO_2 produced by manure ($CO_{2manure}$) has been reported to be 1% during winter and 5% in summer (Hayes et al., 2013; Rosa et al., 2019). Consequently, the metabolic CO_2 during winter was estimated to be 99%, while it was set at 95% of the total CO_2 produced at the hen's barn during summer. The CO_2 produced by the heater was neglected because it was electric. The calculation of THP (W hen^{-1}) was performed according to equation 4 proposed by Pederson and Sällvik (2002) for laying hens housed in cages:

$$THP_{cages} = 6.28\ m^{0.75} + 25Y \tag{4}$$

where m is the mass of the hen (kg), Y is the egg production (kg d^{-1} hen^{-1}). This equation was developed at a temperature of 20°C, and as such a temperature correction was necessary (Pederson and Sällvik, 2002):

$$THP_{corr} = 1000 + 20(20 - T) \tag{5}$$

where THP_{corr} is the total heat production corrected for the temperature (W hen^{-1}), and T is the temperature (°C).

Heat Balance Method

The flow rate ($m^3\ h^{-1}$) from the heat balance was estimated following equation 6, which was adapted from Hassouna et al. (2015):

$$\text{VR}_{HBM} = \frac{Htot - GE}{\rho(Ea - Eb)} \tag{6}$$

$$Ea = E_{room} - E_{PCD} \tag{7a}$$

$$Eb = E_{PCD} - E_{out} \tag{7b}$$

where

VR_{HBM} = ventilation rate of the room based on the heat balance method ($m^3\ h^{-1}$)

E_{room} = enthalpy in each room (J kg^{-1} dry air) (ASHRAE, 2017)

E_{PCD} = enthalpy in the pre-conditioned duct (J kg^{-1} dry air) (ASHRAE, 2017)

E_{out} = enthalpy outdoor air (J kg^{-1} dry air) (ASHRAE, 2017)

$Htot$ = animal THP (J h^{-1})

GE = heat loss through the envelope (J h^{-1})

ρ = air mass volume in the building (kg m^{-3}), which considers the average between the inlet and exhaust density (ρ_{in} and ρ_{out}, coefficient of variation: 6%).

The latter is estimated by the following equation 8:

$$\rho = \frac{1}{287.06*(T + 273{,}15)} \times \left(p - 230{,}617*\ HR*exp\left[\frac{17{,}5043*T}{241{,}2 + T}\right]\right) \tag{8}$$

where

RH = the building's relative humidity (%)

T = the internal temperature (°C)

p = the internal pressure (Pa).

The GE was estimated by:

$$GE = \sum_i \frac{1}{R_{eff}} \cdot A(T_{in} - T_{out}) \tag{9}$$

where

R_{eff} ($m^2 \cdot K/W$) is the total effective thermal resistance of each room's component *i* (ceiling, wall, and floor)

$T_{in} - T_{out}$ (K) is the temperature difference between the interior and the exterior

A (m^2) is the surface area occupied by the assembly component.

The R_{eff} was calculated from the Isothermal Planes (Series-Parallel) method as described in the National Building Code of Canada and summarized by RNC (2016). The insulation values used were RSI_{roof}: 5.3 m^2 K W^{-1}, $RSI_{Fiberglass}$: 3.5 m^2 K W^{-1}, $RSI_{concrete}$: 1.2 m^2 K W^{-1}, $RSI_{plywood}$: 0.22 m^2 K W^{-1}. These values are consistent with those reported by ANSI (2017) and ASABE (2017).

Sensibility Analysis

Variogram Analysis of Response Surfaces

The Variogram Analysis of Response Surfaces (VARS; Razavi et al., 2019) toolbox was used to analyze the global sensitivity of both methods to estimate VR. The VARS approach is inspired by variogram analysis techniques, considering the response surface of a model as a spatially distributed dependent variable. Its distinctive feature is that it recognizes a continuous spatial covariance structure in the model response. The VARS was used to generate sensitivity indices for the different global analysis methods, enabling comparisons between the methods of Morris (1991), Sobol (1993), and VARS (Razavi and Gupta, 2016).

Two metrics were used: (1) the directional variogram plot represents the variability rate (i.e., sensitivity) across various scales in the factor space. As the perturbation scale increases, more distant pairs of points are considered, providing information on how the variability of the data changes at different spatial distances; and (2) the relative importance of the factors plot displays the importance or influence of different factors (independent variables) within a model. These metrics were used to understand which factors significantly impact the outcome or response variable.

The factors (independent variables) evaluated in the CO_2 balance method were inlet and outlet CO_2 concentration, hen weight, daily production rate, internal temperature, and time of day. The factors evaluated in the heat balance method were outdoor, indoor, and PCD temperature and relative humidity, hen weight, and daily production rate.

Sensitivity Analysis for Respiratory Quotient (RQ) and Total Heat Production (THP)

A sensitivity analysis was conducted to assess the impact of varying the total heat production (THP) and respiratory quotient (RQ) on the calculated ventilation rate using the CO_2 balance approach. Different RQ values ranging from 0.85 to 0.99 were selected based on literature reports for laying hens (Chepete et al., 2004). Similarly, THP values varied between 7.5 and 9.5 W/kg, reflecting common values observed in different hens' ages. The analysis involved calculating the root mean square error (RMSE) and coefficient of determination (R^2) for each combination of RQ and THP values. The RMSE indicates the model's accuracy, while R^2 represents the proportion of variability the model explains.

Model Evaluation and Error Determination

Two standard metrics were employed to assess the performance of the two evaluated methods: Root Mean Squared Error (RMSE) and R-squared (R^2) score. RMSE quantifies the average magnitude of errors between predicted and actual values, measuring the variability in the model's predictions. The R^2 expresses the percentage of variance in the dependent variable explained by the independent variable. Moore et al. (2013) proposed that an R^2 value less than 0.3 suggests none or a low effect, 0.3 to 0.5 implies a weak or low effect, 0.5 to 0.7 indicates a moderate effect, and values over 0.7 suggest a strong effect size. These metrics were calculated using the modules of Python (Pedregosa et al., 2011) mean_squared_error and r²_score functions from the sklearn. These metrics are widely used for these purposes (Kadiyala and Kumar, 2017; Srisa-An, 2021; Lin et al., 2023). Moreover, multiple regression was conducted to understand how the independent variables used in each model affect the VR determination.

The determination of the VR propagation of uncertainties by the orifice damper method, the CO_2 balance method, and the heat balance method is given by equation 9 (ASHRAE, 2005):

$$\frac{\partial VR}{VR} = \sqrt{\left(\frac{\partial VR}{\partial v_1}\ \varepsilon_1\right)^2 + \left(\frac{\partial VR}{\partial v_2}\ \varepsilon_2\right)^2 + \cdots + \left(\frac{\partial VR}{\partial v_n}\ \varepsilon_n\right)^2} \quad (10)$$

where v_n are the independent variables and ε_n are the uncertainties associated with each one.

The mean absolute error (MAE) and mean relative error (MRE) were estimated to determine the indirect models' accuracy in absolute and relative terms. The bias of indirect methods was also assessed to determine whether they systematically overestimated or underestimated the VR measurements compared to the orifice damper method.

Results

Laying Hens Performance

In both trials, hen weight varied from 1.4 ± 0.02 to 1.6 ± 0.03 kg hen^{-1}, and egg production ranged from 42.0 to 52.4 g d^{-1} hen^{-1}. There was no difference in water and feed intake between the two trials. Feed consumption was 97.5 and 96.8 g d^{-1} hen^{-1} in both experiments, respectively, while water intake remained at 0.2 L d^{-1} hen^{-1} for the entire experimental period. The fresh manure production was lower during the first trial (61.9 g d^{-1} hen^{-1}) than during the second experimental part (69.6 g d^{-1} hen^{-1}).

Environmental Parameters

The average outdoor temperature in the first trial (12.4°C) was noticeably lower, relative to the second trial (22.3°C) due to the seasonal transition (from March to May for trial one and June to August for trial two). The average room temperature remained relatively constant (22.2°C), indicating the proper functioning of the environmental control equipment. The change in seasonal temperatures only resulted in a slight difference in indoor temperature between trial one at 22.1°C and trial two at 22.4°C. The external relative humidity was similar in both experiments (58.5% and 57.6%, respectively). In the PCD, the average temperatures were 13.6°C and 18.8°C, respectively, and the relative humidities were 55.6% and 62.9%, respectively. Figure 2 indicates the temperature and relative humidity variations in both trials.

CO_2 CONCENTRATIONS

The CO_2 inlet concentrations in both trials (598.5 ± 43.5 ppm and 599.8 ± 79.9 ppm, respectively) were similar ($p > 0.05$). The CO_2 exhaust concentrations were notably higher in the first experiment (1118.5 ± 151.2 ppm; $p < 0.001$) than in the second experiment (1044.2 ± 137.1 ppm; $p < 0.001$). The difference between the exhaust and inlet CO_2 concentrations in both trials was higher than 200 ppm.

VENTILATION RATE CALCULATION

Orifice Damper Method

As expected, the seasonal shift impacted the average VR during trial two (4.1 $m^3\ h^{-1}\ hen^{-1}$) than in trial one (3.5 $m^3\ h^{-1}\ hen^{-1}$). In the first experiment, the ventilation flow rate ranged from 1.1 to 7.1 $m^3\ h^{-1}\ hen^{-1}$, while it varied from 2.0 to 7.8 $m^3\ h^{-1}\ hen^{-1}$ during the second experiment (fig. 3). Standard deviations of VR values were slightly higher in the second trial (0.88 $m^3\ h^{-1}\ hen^{-1}$) than in the first trial (0.82 $m^3\ h^{-1}\ hen^{-1}$). This was related to the temperature variation between day and night during trial two. The propagation of uncertainties ∂VR / VR for the orifice damper method was 0.5%.

Indirect Methods

The first trial displayed a slightly lower mean VR using both CO_2 balance (3.4 vs. 4.1 $m^3\ h^{-1}\ hen^{-1}$) and heat balance (3.5 vs. 3.8 $m^3\ h^{-1}\ hen^{-1}$) methods (table 1). These values were comparable to those calculated using the orifice damper method.

Compared to the orifice damper method, correlation analysis showed a weak correlation for the CO_2 and heat balances (R^2 = 0.28 and 0.07, respectively), with an RMSE equal to 1.46 $m^3\ h^{-1}\ hen^{-1}$ and 1.01 $m^3\ h^{-1}\ hen^{-1}$, respectively (fig. 4a). The residual plots indicate that the data do not exhibit a specific error pattern. In other words, there is no consistent trend of over- or underestimation across the evaluated methods (fig. 4b). The residuals are randomly distributed around zero, suggesting that the indirect methods perform relatively evenly compared to the orifice damper method. The propagation of uncertainties ∂VR / VR for the CO_2 and heat balance method was 3.1% and 12.3%, respectively. The MAE for the CO_2 balance method was 1.31 $m^3\ h^{-1}\ hen^{-1}$, and the MRE was 34.02%. For the heat balance method, the MAE was 0.87 $m^3\ h^{-1}\ hen^{-1}$, and the MRE was 22.57%. The CO_2 balance model tends to systematically underestimate the VR measurements by an average of 0.59 $m^3\ h^{-1}\ hen^{-1}$. In comparison, the heat balance model tends to systematically

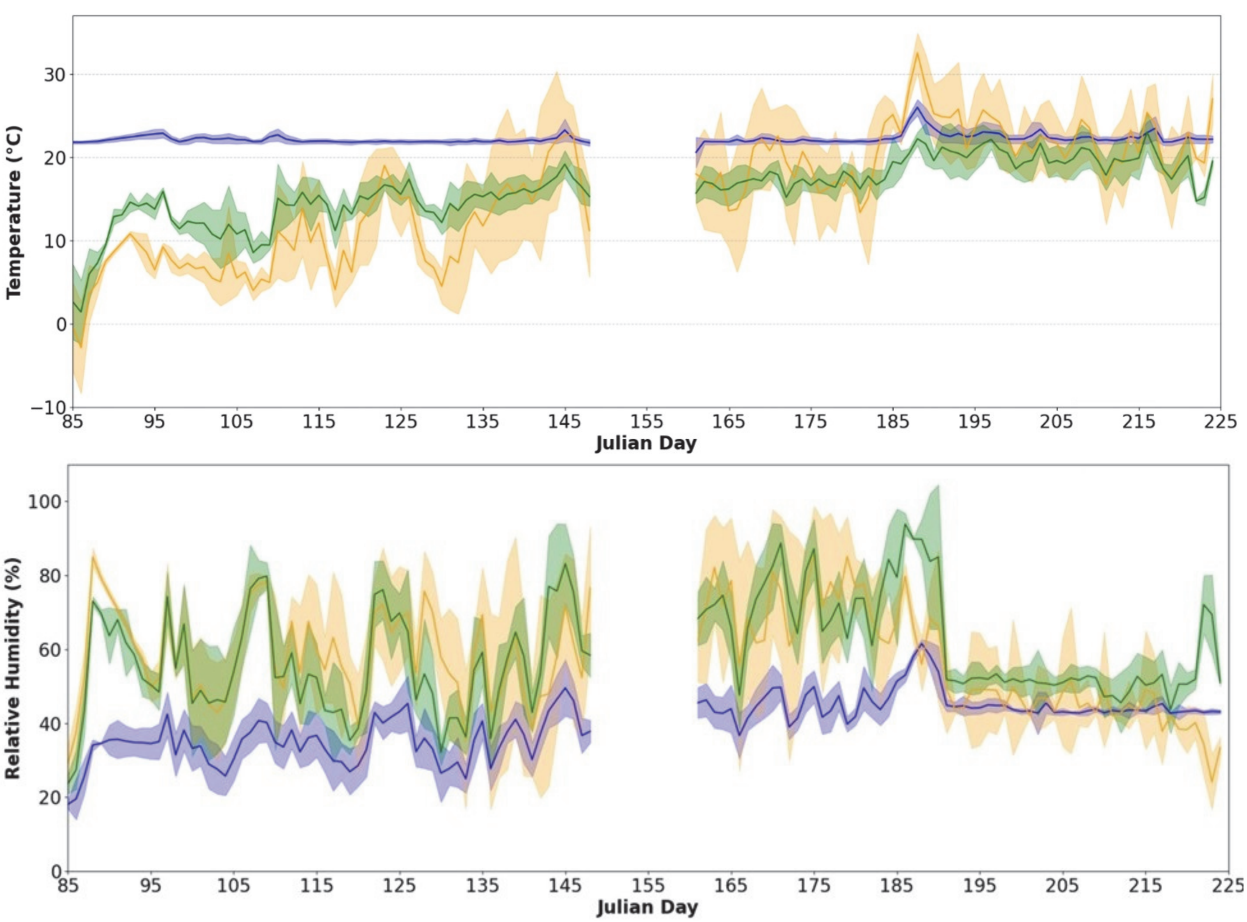

Figure 2. Evolution of rooms (blue), PCD (green), and outdoor (yellow) daily mean temperature (upper) and relative humidity (lower) with standard deviations (shadowed) during trial one (85–148 Julian days) and trial two (160–224 Julian days).

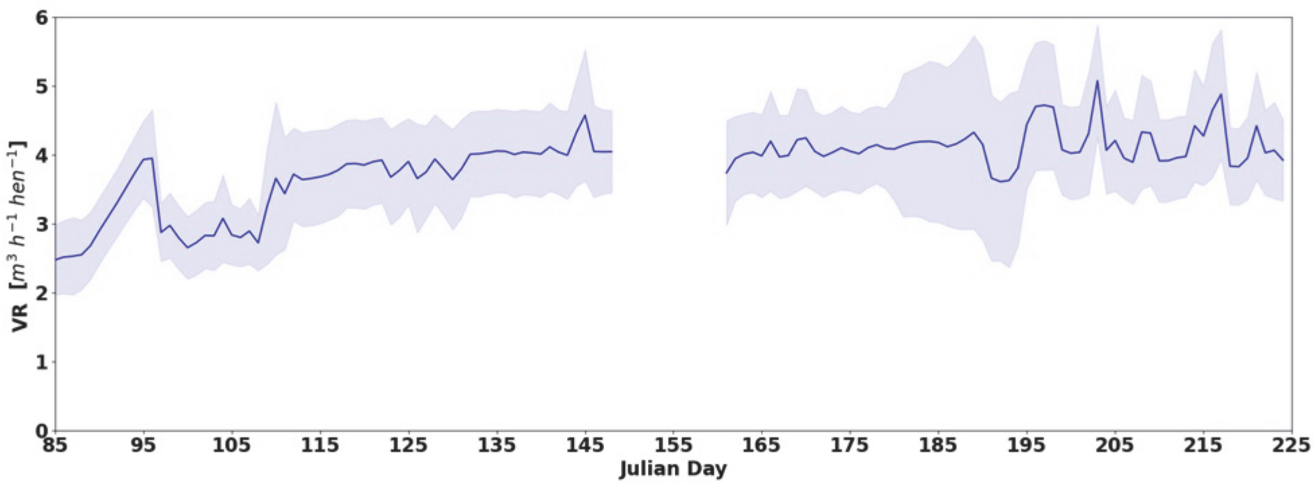

Figure 3. Ventilation rate determined by the orifice damper method with standard deviations from all rooms (shadowed) during trial one (85–148 Julian days) and trial two (160–224 Julian days).

Table 1. Ventilation rate tendency for two trials using CO_2 and heat balance methods.

Trial	Method	Mean ($m^3\ h^{-1}\ hen^{-1}$)	Min ($m^3\ h^{-1}\ hen^{-1}$)	Max ($m^3\ h^{-1}\ hen^{-1}$)
1	CO_2 balance	3.4 ± 1.0	1.1	7.7
	Heat balance	3.5 ± 1.1	0.1	8.3
2	CO_2 balance	4.1 ± 1.1	2.1	8.6
	Heat balance	3.8 ± 1.0	0.0	9.2

underestimate the VR measurements by an average of 0.17 $m^3\ h^{-1}\ hen^{-1}$.

Data was grouped on an hourly and daily basis. In the hourly grouped data, the CO_2 balance R^2 remained at 0.28, but for heat balance, R^2 increased to 0.46. However, the RMSE decreased for both indirect method approaches (0.17 $m^3\ h^{-1}\ hen^{-1}$ and 0.14 $m^3\ h^{-1}\ hen^{-1}$, respectively; fig. 5). The MAE and the MRE also had a decrease in CO_2 balance (MAE = 0.52 $m^3\ h^{-1}\ hen^{-1}$, and MRE = 13.64%) and heat balance (MAE = 0.18 $m^3\ h^{-1}\ hen^{-1}$, and MRE = 4.75%). Daily groups substantially increased the R^2 for both methods (0.85 and 0.55, respectively), showing a strong correlation with the orifice damper method (fig. 5). Furthermore, the RMSE dropped, concerning the unaveraged data, to 0.22 $m^3\ h^{-1}\ hen^{-1}$ for CO_2 and 0.36 $m^3\ h^{-1}\ hen^{-1}$ for heat balance, significantly enhancing prediction accuracy when considering daily averages. The MAE and the MRE also had a decrease in CO_2 balance (MAE = 0.53 $m^3\ h^{-1}\ hen^{-1}$, and MRE = 13.75%) and heat balance (MAE = 0.34 $m^3\ h^{-1}\ hen^{-1}$, and MRE = 8.87%) to ungrouped data. The bias remained similar for both methods (-0.52 $m^3\ h^{-1}\ hen^{-1}$ for CO_2 balance and -0.17 for heat balance) in hourly and daily basis grouped data.

According to the multiple regression analysis, the independent variables integrated into the model can account for approximately 82% of the variability in VR from the CO_2 balance method. In contrast, the heat balance method demonstrates a more constrained ability to elucidate the fluctuations in VR, with an R^2 of 0.13. This lower R^2 value implies that only 13% of the variance in VR can be explained by the variables included in the heat balance model.

Sensibility Analysis

Figure 6 shows global sensitivity analysis results for the CO_2 balance method. The directional variogram indicated that, in the CO_2 model, the inlet CO_2 concentration was the most sensitive variable. According to the three evaluation methods, this variable has the most relative importance.

Figure 7 shows global sensitivity analysis results for the heat balance method. The directional variogram showed that for the heat model, the variable with the most significant sensitivity as the range of perturbation increases was the PCD temperature. According to the three evaluation methods, this variable has the most relative importance.

The sensitivity analysis results for RQ are summarized in table 2a, while the results for THP are shown in table 2b.

DISCUSSION

The present study is a bench-scale level approach in which data were collected during two trials for VR determination. The results of the orifice damper method and indirect methods revealed that the VR varied between the two experimental trials, reflecting the impact of seasonal changes. During the second trial, the hens required more ventilation due to the warmer weather, which led to higher VR values. Accordingly, the values align with the recommended flow rates in Québec, which are 0.2 L s^{-1} hen^{-1} (0.7 $m^3\ h^{-1}\ hen^{-1}$) in winter and 3.3 L s^{-1} hen^{-1} (11.9 $m^3\ h^{-1}\ hen^{-1}$) in summer (Fournel et al., 2012).

The VR values recorded in this experiment exhibit similarities with those reported in studies involving laying hens. For instance, Lin et al. (2018) reported a daily VR ranging from 1.9 to 8.7 $m^3\ h^{-1}\ hen^{-1}$ on a commercial hen farm, which is similar to the findings of this study. Similarly, Chai et al. (2012) reported VR values ranging from 0.6 to 5.0 $m^3\ h^{-1}\ hen^{-1}$ for commercial layer houses. These findings across studies emphasize the consistency in the impact of temperature on VR in laying hen facilities. It is evident that variations in temperature, especially between the seasons, influence the VR requirements of laying hens (Chielo et al., 2016).

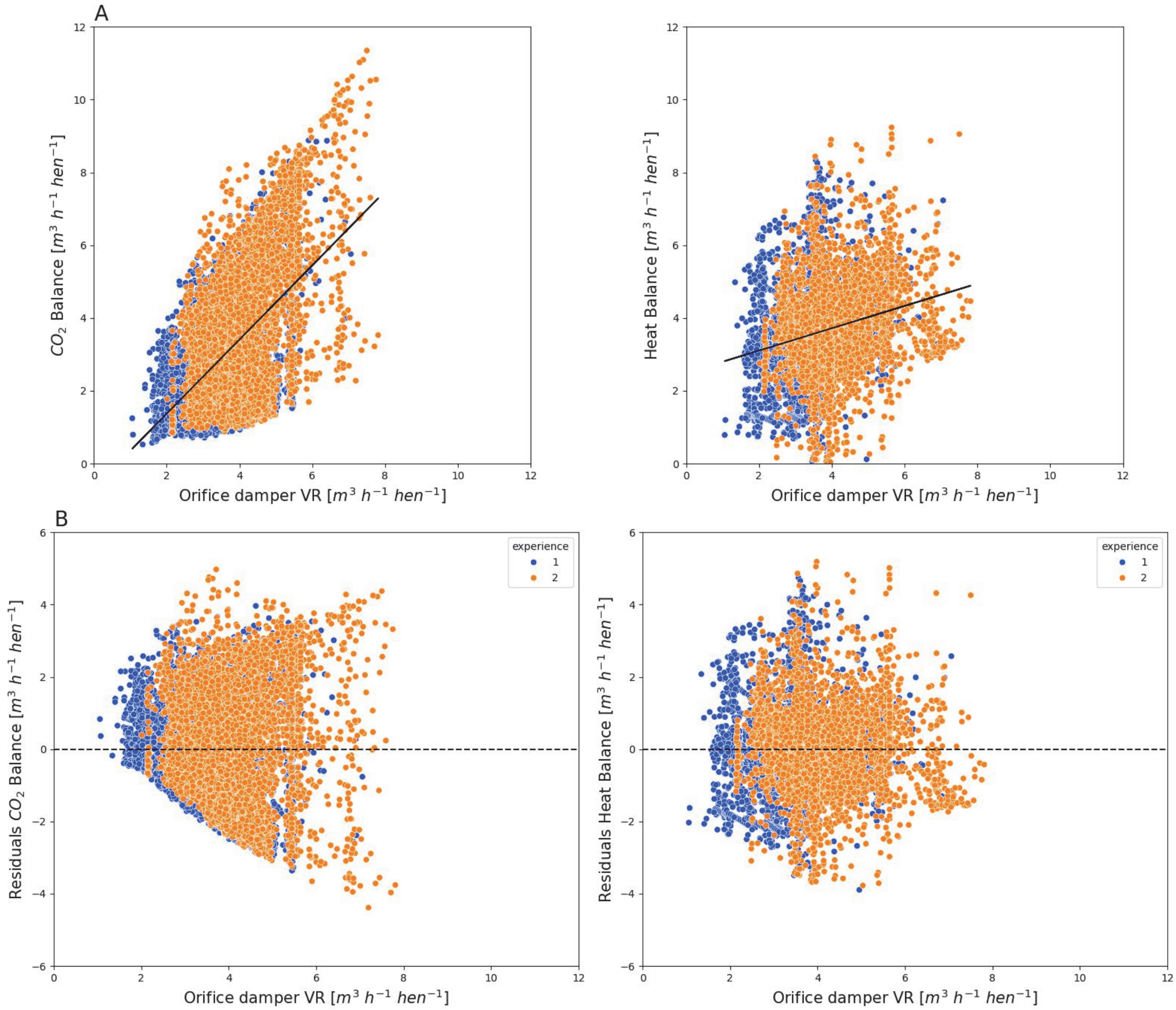

Figure 4. (A) Comparison between the orifice damper method and indirect methods (CO_2 balance on the left and heat balance on the right) for trial one (●) and trial two (x). (B) Residuals plots for indirect methods (CO_2 balance on the left and heat balance on the right) for trial one (●) and trial two (x).

ESTIMATED VENTILATION RATE BY INDIRECT METHODS

Correlation analysis between CO_2 balance and the orifice damper method did not accurately estimate VR in egg production facilities on a short-term basis. Several studies have assessed VR for laying hens by the CO_2 balance method (Li et al., 2004; Liu et al., 2016; Pedersen et al., 1998; Rosa et al., 2019). Liu et al. (2016) found a VR prediction with an R^2 of 0.13 in laying hens when the differences between exhaust and inlet CO_2 concentrations were higher than 200 ppm. Our research found a similar variability in CO_2 concentration indoors and outdoors, which aligns with these findings. These same authors also found a high variability of VR due to the RQ, which, according to van Ouwerkerk and Pedersen (1994), may be due to metabolic rate and feed intake.

In alignment with our study, other researchers have noted improved performance of the CO_2 balance method when daily data averaging is employed. Pedersen et al. (1998) assessed VR in livestock buildings for laying hens. The CO_2 balance method gave good results on a 24-hour basis, with an R^2 equal to 0.90, which is the same as the other methods for assessing heat and moisture balances. Li et al. (2004) compared the VR obtained by direct measurement and CO_2 balance in a commercial laying hen house. The comparisons of VR between the direct and CO_2 balance were made at semi-hourly, hourly, bi-hourly (every two hours), and daily average time intervals. These averages presented good correlations (R^2 of 0.90, 0.92, 0.93, and 0.96). Rosa et al. (2019) evaluated the accuracy of the CO_2 balance indirect method to assess VR in a mechanically ventilated laying hen facility by integrating CO_2 concentration data at two-hour intervals. The indirect method was compared with the direct hot wire anemometer (HWA) and fan rotational speed [laser tachometers (LT)] methods. They observed an association between the HWA with an R = 0.86 and the LT with an R = 0.85. According to the aforementioned studies, it has been consistently observed that utilizing time interval integration has a positive impact on reducing the noise and the variability in the data. Our results also support this finding. Implementing time interval integration improves the accuracy of VR calculations.

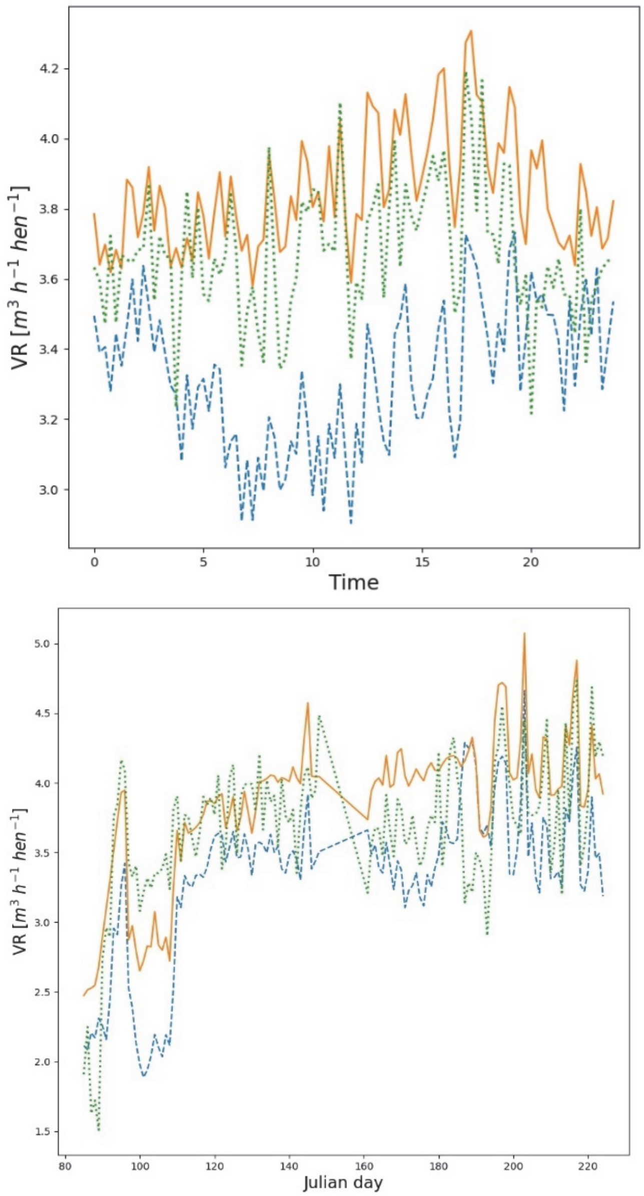

Figure 5. Average VR for the three methods: orifice damper (-), CO_2 balance (- -), and heat balance (···) over Julian day (above) and time within a day (in hours; below).

Other farm species have also evidenced the good performance of the CO_2 balance when grouping by specific intervals. Blanes and Pedersen (2005) measured VR in a pig house for 41 days and compared it to estimates calculated by CO_2 balance on a diurnal and hourly basis. A good correlation between measured and calculated VR was obtained on a 24-hour basis (R^2 = 0.97) and on an hourly basis (R^2 = 0.92). The latter study indicates that the correlation between measured and estimated VR hourly can be improved by considering the diurnal variation in CO_2 production. This shows that daily variations in animal activity (heat, humidity, and metabolic CO_2 production) influence the accuracy of VR prediction using the CO_2 method. Therefore, further research is necessary to determine these parameters accurately.

The heat balance method has been found to provide inaccurate VR estimations in egg production facilities. This is due to inaccuracies in calculating various factors such as heat transfer coefficient, temperature differences, and diurnal variations in total heat produced by animals in response to changes in ambient conditions. Although few studies have reported the use of this method for VR determination, it has been used in laying hen facilities (Pedersen et al., 1998), pig houses (Blanes and Pedersen, 2005), and dairy barns (Samer et al., 2011). Pedersen et al. (1998) evaluated the calculation of VR over 24 hours through the heat method compared to two other indirect methods (CO_2 and moisture balance). For periods under 24 h, diurnal changes in animal heat production required correction for precise calculation of VR. Blanes and Pedersen (2005) compared VR measured in a pig house with heat balance estimation on diurnal and hourly bases. The study demonstrates a strong correlation between the measured and calculated daily and hourly VR (R^2 = 0.92 and 0.83, respectively). As seen in the two aforementioned studies, there was a good correlation when averaging the data, which can be corroborated with our studies. However, our correlation for this method is lower than in the studies, potentially influenced by various factors. First, the configuration of the laboratory room, including factors such as the PCD, could introduce facility-specific variability in heat transfer dynamics, affecting method accuracy. The PCD's positioning and material influence conduction losses, while internal components generate additional heat. External ambient conditions can also influence heat loss. Sudden temperature changes or extreme weather conditions can lead to disturbances in the thermal dynamics of PCD. Additionally, discrepancies in measurement methods for parameters like heat transfer coefficients, temperature differences, and the total heat produced by animals may contribute to inaccurate prediction.

Data aggregation significantly enhances VR assessment reliability using the CO_2 and heat balance methods. Nevertheless, according to the findings, the CO_2 balance model could be a promising approach for precise VR estimations in laying hen facilities. The performance of this method, mainly when data are aggregated daily, is supported by correlations observed in various studies across different barn animals (Xin et al., 2009; Estelles et al., 2011; Edouard et al., 2016; Liu et al., 2016). Aggregation allows you to summarize this detailed data without losing the ability to analyze daily trends and fluctuations. Also, data aggregation offers a way to manage and analyze large datasets effectively while preserving the necessary resolution to understand daily fluctuations. However, it is important to recognize the limitations of daily data aggregation. Averaging the data smooths out short-term fluctuations in VR, potentially masking significant dynamic changes. Additionally, this method reduces sensitivity to transient events, such as sudden changes in temperature or humidity, which may lead to an oversimplification of the complex interactions between environmental factors and VR. In contrast, the heat balance method has shown limitations in accurately estimating VR due to the inherent processes in the poultry facility, such as environmental conditions (Hassouna et al., 2015) and heat production (Chepete et al., 2004; Hayes et al., 2013). These insights emphasize the need for method-specific considerations and highlight the significance of refining VR estimation techniques for optimal laying hen welfare and environmental impact assessments.

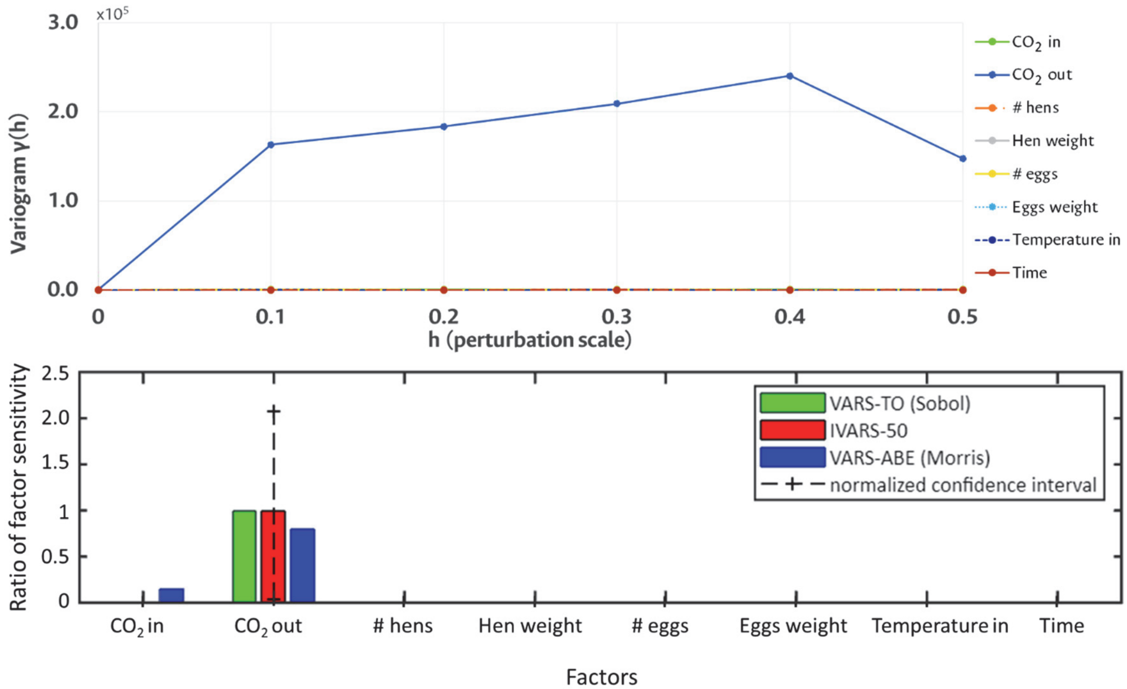

Figure 6. Global sensitivity analysis results for CO_2 balance method. Directional variogram that manifests sensitivity across the range of perturbation scales (fluctuations in data values as they move away from the reference point) (above) and the relative importance of the factors (independent variables) according to the three approaches (below). The ratio of factor sensitivity is the value of each metric divided by the summed values of that metric over all the factors. Abbr.: CO_2 in: CO_2 exhaust concentration, CO_2 out: CO_2 inlet concentration, # hens: total number of hens, # eggs: total number of eggs per day.

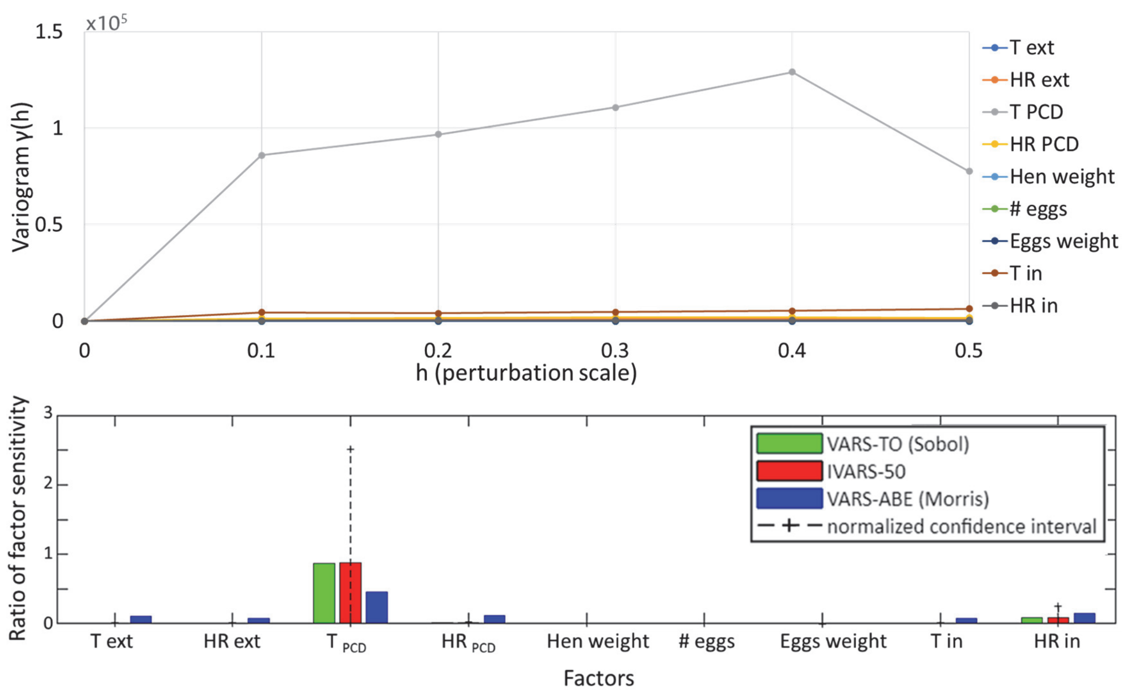

Figure 7. Global sensitivity analysis results for heat balance method. Directional variogram that manifests sensitivity across the range of perturbation scales (fluctuations in data values as they move away from the reference point) (above) and the relative importance of the factors (independent variables) according to the three approaches (below). The ratio of factor sensitivity is the value of each metric divided by the summed values of that metric over all the factors. Abbr.: T ext: outdoor temperature, HR ext: outdoor relative humidity, T PCD: pre-conditioned duct temperature; HR PCD: pre-conditioned duct relative humidity; T in: indoor temperature, HR in: indoor relative humidity.

Although both balance methods have challenges, such as inaccuracies in calculating the VR on a short-term basis, grouping data daily improves VR calculations and makes those methods variables. Implementing these indirect methods offers a practical innovation, reducing the resource-intensive demands of direct measurement methods and providing a more feasible approach for continuous VR monitoring in poultry facilities. Additionally, this method can

Table 2a. Sensitivity analysis results for total heat production (THP).

THP	R^2	RMSE
7.5	0.27	1.853
8.0	0.27	2.013
8.5	0.27	2.203
9.0	0.27	2.414
9.5	0.27	2.643

Table 2b. Sensitivity analysis results for respiratory quotient (RQ).

RQ	R^2	RMSE
0.85	0.052	1.726
0.86	0.052	1.719
0.88	0.052	1.707
0.92	0.052	1.688
0.95	0.052	1.678
0.99	0.052	1.672

enhance real-time air quality monitoring, early detection of ventilation failures, and integration with farm management software for improved environmental control and animal welfare decision-making.

Multiple Regression and Sensitivity Analysis

The CO_2 balance method has good explanatory capacity due to the significant contribution of independent variables such as inlet/exhaust CO_2 concentration, hen weight, daily production rate, internal temperature, and time of day to the overall understanding of VR dynamics. This aligns with the variables that Xin et al. (2009) and Samer et al. (2011) claimed to affect the CO_2 balance to assess VR. The sensibility analysis highlights the inlet CO_2 concentration as the most sensitive variable in VR calculation by the CO_2 balance method. Pedersen et al. (1998) conducted a sensitivity analysis of pig houses during winter and summer. They discovered that an increase of 50 ppm in external CO_2 concentration can lead to uncertainty in VR in both seasons. The sensitivity analysis for THP and RQ demonstrates that these variables significantly influence VR estimation through the CO_2 balance method. While Ketelaars et al. (1985) reported an average RQ of 0.92 for laying hens aged from 19 to 27 weeks, van Ouwerkerk and Pedersen (1994) highlighted that RQ depends on metabolic rate, feed intake, and the individual status of the animal, noting that it increases with feed intake. Similarly, as outlined in previous discussions, THP is influenced by environmental factors such as temperature and humidity (Chepete et al., 2004). Therefore, variations in THP directly impact VR calculations, given that higher heat production necessitates increased ventilation to dissipate excess heat.

In contrast, the heat balance method demonstrates a limited capacity to elucidate VR variations, as indicated by the lower R^2 value. This suggests that the heat balance model might not wholly capture the VR dynamics, leaving room for factors that could influence the fitting of the model, such as unaccounted H_2O from manure, sampling point locations, and limitations in models, particularly those incapable of accommodating diurnal variations (Wang et al., 2016). For this approach, the sensibility analysis identifies the PCD temperature as the most sensitive variable as the range of perturbation increases. While the objectives of the PCD system aim to stabilize and standardize the testing environment, the model's sensitivity to variations in PCD temperature underscores the critical role that temperature control plays in achieving those objectives. Sudden changes in outside temperature can cause a delayed response in the air temperature of the PCD. This is due to the thermal inertia of the system, which can take time to stabilize after significant changes in external conditions. Additionally, it could lead to differences in the temperature of air supplied to each room, potentially introducing variability in the testing conditions and compromising the comparability of results across the rooms. However, commercial farms generally do not have a PCD for inlet air. In Québec and Ontario provinces, mechanically ventilated layer houses generally have controlled air intake systems strategically placed to allow fresh air to enter and distribute it evenly (Ontario Ministry of Agriculture, 2010).

To improve the model's accuracy, it could be necessary to consider animal metabolism dynamics such as animal activity, CO_2 production, and RQ. Exploring adjustments or corrections to behavioral variables can further refine predictions. A full recovery test, such as releasing a known amount of CO_2 and measuring ventilation rate and CO_2 concentrations, or using an electrical heater to assess heat loss, would be useful for validating the environmental room setup. This approach needs to be considered in future research. Likewise, it is important to investigate different variables that are in line with the practicalities of commercial farming. Models must evolve to capture diurnal variations in animal behavior and environmental conditions. Adapting models to encompass animal behavior and practical variables and implementing robust validation processes could enhance the accuracy of VR models in commercial laying hen facilities.

Conclusions

This study assesses the accuracy of indirect techniques, precisely the CO_2 and heat balance, compared to the orifice damper method in estimating VR in an experimental bench-scale context for laying hens. The temporal resolution of data plays a crucial role in their performance. The CO_2 balance model demonstrates its ability to explain VR dynamics effectively, while the heat balance model exhibits constraints. The sensitivity analysis highlights the significance of exhaust CO_2 concentration and PCD temperature, underscoring the need for nuanced and adaptable VR estimation approaches.

The results showed that among the evaluated methods (CO_2 and heat balance), the CO_2 balance method demonstrated higher accuracy. Although both methods rely on assumptions, the CO_2 balance method provided a better fit for estimating VR, especially when daily data aggregation was applied, significantly enhancing its accuracy compared to the heat balance method. Additionally, the CO_2 balance method requires fewer input variables to determine VR, thereby reducing the potential for errors. Furthermore, the research highlights that sensitivity analysis emphasizes the significance of specific variables in influencing the model and could offer insights for potential adaptations or corrections. Further research is essential to evaluate how the animal's daytime behavior impacts its metabolism and, subsequently, the production of heat and CO_2.

Future studies and practical applications should focus on enhancing data collection methods for comprehensive VR analysis and implementing adaptable systems to address seasonal variations, ensuring year-round welfare for laying hens.

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References

Alexandratos, N., & Bruinsma, J. (2012). World Agriculture towards 2030/2050: The 2012 revision. ESA Working Paper No. 12-03. Rome, Italy: United Nations FAO. Retrieved from https://www.fao.org/4/ap106e/ap106e.pdf

ASABE Standards. (2017). ANSI/ASAE S401.2 Guidelines for use of thermal insulation in agricultural buildings. St. Joseph, MI: ASABE.

ASHRAE. (2005). Engineering analysis of experimental data. Atlanta, GA: ASHRAE. Retrieved from https://webstore.ansi.org/preview-pages/ASHRAE/preview_ASHRAE+Guideline+2-2005.pdf

ASHRAE. (2017). Psychrometrics. In *2017 ASHRAE Handbook - Fundamentals.*

Barreto-Mendes, L., Ferreira-Tinoco, I. d., Ogink, N., Osorio-Hernandez, R., & Osorio-Saraz, J. A. (2014). A refined protocol for calculating air flow rate of naturally-ventilated broiler barns based on co2 mass balance. *DYNA, 81*(185), 189-195. https://doi.org/10.15446/dyna.v81n185.38069

Bist, R. B., Subedi, S., Chai, L., & Yang, X. (2023). Ammonia emissions, impacts, and mitigation strategies for poultry production: A critical review. *J. Environ. Manag., 328*, 116919. https://doi.org/10.1016/j.jenvman.2022.116919

Blanes, V., & Pedersen, S. (2005). Ventilation flow in pig houses measured and calculated by carbon dioxide, moisture and heat balance equations. *Biosyst. Eng., 92*(4), 483-493. https://doi.org/10.1016/j.biosystemseng.2005.09.002

Brouwer, E. (1965). Report of sub-committee on constants and factors. In *Proceedings of the 3rd Symposium on Energy Metabolism* (pp. 441-443). Academic Press.

Calvet, S., Gates, R. S., Zhang, G., Estellés, F., Ogink, N. W., Pedersen, S., & Berckmans, D. (2013). Measuring gas emissions from livestock buildings: A review on uncertainty analysis and error sources. *Biosyst. Eng., 116*(3), 221-231. https://doi.org/10.1016/j.biosystemseng.2012.11.004

Chai, L., Ni, J. Q., Diehl, C. A., Kilic, I., Heber, A. J., Chen, Y.,... Chen, L. (2012). Ventilation rates in large commercial layer hen houses with two-year continuous monitoring. *Br. Poult. Sci., 53*(1), 19-31. https://doi.org/10.1080/00071668.2011.643766

Chepete, H. J., & Xin, H. (2004). Ventilation rates of a laying hen house based on new vs. old heat and moisture production data. *Appl. Eng. Agric., 20*(6), 835-842. https://doi.org/10.13031/2013.17722

Chepete, J., Xin, H., Puma, M., & Gates, R. (2004). Heat and moisture production of poultry and their housing systems: Pullets and layers. *ASHRAE Trans., 110*(2), 286-299.

Chielo, L. I., Pike, T., & Cooper, J. (2016). Ranging behaviour of commercial free-range laying hens. *Animals, 6*(5), 28. https://doi.org/10.3390/ani6050028

David, B., Mejdell, C., Michel, V., Lund, V., & Moe, R. O. (2015). Air quality in alternative housing systems may have an impact on laying hen welfare. Part II — Ammonia. *Animals, 5*(3), 886-896. https://doi.org/10.3390/ani5030389

Edouard, N., Mosquera, J., van Dooren, H. J., Mendes, L. B., & Ogink, N. W. (2016). Comparison of CO2- and SF6- based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn. *Biosyst. Eng., 149*, 11-23. https://doi.org/10.1016/j.biosystemseng.2016.06.001

Estelles, F., Fernandez, N., Torres, A. G., & Calvet, S. (1970). Use of CO2 balances to determine ventilation rates in a fattening rabbit house. *Span. J. Agric. Res., 9*(3), 713-720. https://doi.org/10.5424/sjar/20110903-368-10

FAO. (2022). World Population Prospects 2022, Summary of Results. *UN DESA/POP/2021/TR/NO. 3*. New York: United Nations FAO, Department of Economic and Social Affairs.

Farmer Automatic. (2010). Multi-Deck system layer cage. [Online] https://farmerautomatic.com/brochure/MultiDeckSystem.pdf (page visited on May 16, 2023)

Fournel, S. (2011). Étude comparative des émissions de gaz et d'odeurs issues de différents systèmes de gestion des déjections en production d'oeufs de consommation. MS thesis. Quebec: Québec : Université Laval.

Fournel, S., Pelletier, F., Godbout, S., Lagacé, R., & Feddes, J. (2012). Greenhouse gas emissions from three cage layer housing systems. *Animals, 2*(1), 1-15. https://doi.org/10.3390/ani2010001

Gates, R. S., Casey, K. D., Xin, H., & Burns, R. T. (2009). Building emissions uncertainty estimates. *Trans. ASABE, 52*(4), 1345-1351. https://doi.org/10.13031/2013.27784

Gouvernement du Québec. (2023). Production d'œufs. Retrieved from https://www.quebec.ca/agriculture-environnement-et-ressources-naturelles/agriculture/industrie-agricole-au-quebec/productions-agricoles/production-oeufs

Hassouna, M., Eglin, T., Cellier, P., Colomb, V., Cohan, J.-P., Decuq, C.,... Rochette, Y. (2016). Measuring emissions from livestock farming: Greenhouse gases, ammonia and nitrogen oxides. INRA-ADEME.

Hayes, M. D., Xin, H., Li, H., Shepherd, T. A., Zhao, Y., & Stinn, J. P. (2013). Heat and moisture production of hy-line brown hens in aviary houses in the midwestern U.S. *Trans. ASABE, 56*(2), 753-761. https://doi.org/10.13031/2013.42663

Kadiyala, A., & Kumar, A. (2017). Applications of Python to evaluate environmental data science problems. *Environ. Prog. Sustainable Energy, 36*(6), 1580-1586. https://doi.org/10.1002/ep.12786

Kang, H. K., Park, S. B., Kim, S. H., & Kim, C. H. (2016). Effects of stock density on the laying performance, blood parameter, corticosterone, litter quality, gas emission and bone mineral density of laying hens in floor pens. *Poultr. Sci., 95*(12), 2764-2770. https://doi.org/10.3382/ps/pew264

Ketelaars, E. H., Arets, A., Van Der Hel, W., Wilbrink, A. J., & Verstegen, M. W. (1985). Effect of housing systems on the energy balance of laying hens. *Neth. J. Agric. Sci., 33*, 35-43. https://doi.org/10.18174/njas.v33i1.16869

Kiwan, A., Berg, W., Fiedler, M., Ammon, C., Gläser, M., Müller, H.-J., & Brunsch, R. (2013). Air exchange rate measurements in naturally ventilated dairy buildings using the tracer gas decay method with 85Kr, compared to CO2 mass balance and discharge coefficient methods. *Biosyst. Eng., 116*(3), 286-296. https://doi.org/10.1016/j.biosystemseng.2012.11.011

Li, H., Xin, H., & Liang, Y. (2004). Comparison of direct vs. indirect ventilation rate determination for manure belt laying hen houses. Paper No. 044177. *Proc. 2004 ASAE/CSAE Annual Int. Meeting.* St. Joseph, MI: ASABE. https://doi.org/10.13031/2013.16892

Lin, X., Zhang, R., Jiang, S., El-Mashad, H. M., & Xin, H. (2018). Fan and ventilation rate monitoring of cage-free layer houses in California. *Trans. ASABE, 61*(6), 1939-1950. https://doi.org/10.13031/trans.12831

Lin, Z., Huang, X., & Chen, J. (2023). Prediction model of sailing ship price based on random forest regression. *Highlights Bus. Econ. Manag., 16*, 29-33. https://doi.org/10.54097/hbem.v16i.10530

Liu, Z., Powers, W., & Harmon, J. (2016). Estimating ventilation rates of animal houses through CO2 balance. *Trans. ASABE, 59*(1), 321-328. https://doi.org/10.13031/trans.59.10235

Moore, D. S., Notz, W., & Fligner, M. A. (2013). *The basic practice of statistics* (6th ed.). W.H. Freeman and Company.

Morris, M. D. (1991). Factorial sampling plans for preliminary computational experiments. *Technometrics, 33*(2), 161-174. https://doi.org/10.1080/00401706.1991.10484804

Ni, J.-Q., Liu, S., Diehl, C. A., Lim, T.-T., Bogan, B. W., Chen, L.,... Heber, A. J. (2017). Emission factors and characteristics of ammonia, hydrogen sulfide, carbon dioxide, and particulate matter at two high-rise layer hen houses. *Atmos. Environ., 154*, 260-273. https://doi.org/10.1016/j.atmosenv.2017.01.050

Ogink, N. W., Mosquera, J., Calvet, S., & Zhang, G. (2013). Methods for measuring gas emissions from naturally ventilated livestock buildings: Developments over the last decade and perspectives for improvement. *Biosyst. Eng., 116*(3), 297-308. https://doi.org/10.1016/j.biosystemseng.2012.10.005

Ontario Ministry of Agriculture, Food and Rural Affairs. (2010). Ventilation for livestock and poultry barns. *Publication 833*. Toronto, ON: Queen's Printer for Ontario.

Ouwerkerk, E. N., & Pedersen, S. (1994). Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. *Proc. XII CIGR World Congress on Agricultural Engineering.*

Park, G., Lee, I.-b., Yeo, U.-h., Ha, T., Kim, R.-w., & Lee, S.-y. (2018). Ventilation rate formula for mechanically ventilated broiler houses considering aerodynamics and ventilation operating conditions. *Biosyst. Eng., 175*, 82-95. https://doi.org/10.1016/j.biosystemseng.2018.09.002

Pedersen, S., Takai, H., Johnsen, J. O., Metz, J. H., Groot Koerkamp, P. W., Uenk, G. H.,... Wathes, C. M. (1998). A comparison of three balance methods for calculating ventilation rates in livestock buildings. *J. Agric. Eng. Res., 70*(1), 25-37. https://doi.org/10.1006/jaer.1997.0276

Pederson, S., & Sällvik, K. (2002). 4th Report of working group on climatization of animal houses : Heat and moisture production at animal and house levels. CIGR, EurAgEng, Research Centre Bygholm, Danish Institute of Agricultural Sciences. Retrieved from https://www.cigr.org/sites/default/files/documets/CIGR_4TH_WORK_GR.pdf

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., … Duchesnay, E. (2011). Scikit-learn: Machine Learning in Python. Journal of Machine Learning Research, 12, 2825–2830.

Phillips, V. R., Lee, D. S., Scholtens, R., Garland, J. A., & Sneath, R. W. (2001). SE — Structures and environment: A review of methods for measuring emission rates of ammonia from livestock buildings and slurry or manure stores, Part 2: Monitoring flux rates, concentrations and airflow rates. *J. Agric. Eng. Res., 78*(1), 1-14. https://doi.org/10.1006/jaer.2000.0618

Ranganathan, J., Waite, R., Searchinger, T., & Hanson, C. (2018). How to sustainably feed 10 billion people by 2050, in 21 charts. World Resources Institute. Retrieved from https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts

Razavi, S., & Gupta, H. V. (2016). A new framework for comprehensive, robust, and efficient global sensitivity analysis: 2. Application. *Water Resour. Res., 52*(1), 440-455. https://doi.org/10.1002/2015WR017559

Razavi, S., Sheikholeslami, R., Gupta, H. V., & Haghnegahdar, A. (2019). VARS-TOOL: A toolbox for comprehensive, efficient, and robust sensitivity and uncertainty analysis. *Environ. Model. Softw., 112*, 95-107. https://doi.org/10.1016/j.envsoft.2018.10.005

RNC. (2016). Tables for calculating effective thermal resistance of opaque assemblies. Retrieved from https://natural-resources.canada.ca/energy/efficiency/housing/new-homes/energy-starr-new-homes-standard/tables-for-calculating-effective-thermal-resistance-opaque-assemblies/14176

Rosa, E., Arriaga, H., Calvet, S., & Merino, P. (2019). Assessing ventilation rate measurements in a mechanically ventilated laying hen facility. *Poultr. Sci., 98*(3), 1211-1221. https://doi.org/10.3382/ps/pey524

Samer, M., Loebsin, C., Fiedler, M., Ammon, C., Berg, W., Sanftleben, P., & Brunsch, R. (2011). Heat balance and tracer gas technique for airflow rates measurement and gaseous emissions quantification in naturally ventilated livestock buildings. *Energy Build., 43*(12), 3718-3728. https://doi.org/10.1016/j.enbuild.2011.10.008

Sobol, I. M. (1993). Sensitivity estimates for nonlinear mathematical models. *Math. Model. Comput. Exp., 1*(4), 407-414. Retrieved from https://www.andreasaltelli.eu/file/repository/sobol1993.pdf

Srisa-An, C. (2021). Guideline of collinearity - Avoidable regression models on time-series analysis. *Proc. 2021 2nd Int. Conf. on Big Data Analytics and Practices (IBDAP)* (pp. 28-32). IEEE. https://doi.org/10.1109/IBDAP52511.2021.9552165

Statistics Canada. (2022). Table 18-10-0002-01: Monthly average retail prices for food and other selected products. https://doi.org/10.25318/1810000201-eng

Wang, X., Ndegwa, P. M., Joo, H., Neerackal, G. M., Stöckle, C. O., Liu, H., & Harrison, J. H. (2016). Indirect method versus direct method for measuring ventilation rates in naturally ventilated dairy houses. *Biosyst. Eng., 144*, 13-25. https://doi.org/10.1016/j.biosystemseng.2016.01.010

Xin, H., Li, H., Burns, R. T., Gates, R. S., Overhults, D. G., & Earnest, J. W. (2009). Use of CO2 concentration difference or CO2 balance to assess ventilation rate of broiler houses. *Trans. ASABE, 52*(4), 1353-1361. https://doi.org/10.13031/2013.27787

Zhou, Z., Qin, Z., Li, H., Sun, Q., Xia, L., & Yu, G. (2017). Balance model to calculate the ventilation rate of a mechanically ventilated finishing pig house in east China. *Proc. 2017 Int. Conf. Material Science, Energy and Environmental Engineering (MSEEE 2017)*, pp. 200-206. Atlantis Press. https://doi.org/10.2991/mseee-17.2017.37

NOMENCLATURE

VR = Ventilation rate ($m^3\ h^{-1}$)

$PRCO_2$ = CO_2 production rate (mL CO_2 s^{-1})

THP = Total heat production (J h^{-1})

RQ = Respiration quotient

PCD = Pre-conditioned duct

VARS = Variogram Analysis of Response Surfaces