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A refined protocol for calculating air flow rate of naturally-ventilated broiler barns based on CO_2 mass balance

Un protocolo refinado basado en balance de masa de CO_2 para el cálculo de la tasa de flujo de aire en instalaciones avicolas naturalmente ventiladas

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Abstract

This study was conducted to evaluate relatively simple protocols for monitoring ventilation rate (VR) in naturally-ventilated barns (NVB). The test protocols were first applied to a mechanically-ventilated broiler barn (MVB), where VR was estimated more accurately and then were used to calculate VR in the NVB. CO_2 concentrations were measured with two different sampling schemes: (S1) the average of indoor measurements along the length of the building at two heights of 0.5 m and 1.5 m from the litter floor; and (S2) same as previous but with concentration measurements taken only at 0.5 m from litter. The dynamic metabolic CO_2 production rate of the birds was predicted with two different algorithms: (A1) remaining constant throughout the dark and light periods, and (A2) varying with animal activity on an hourly basis. The results demonstrated that the combination of S2 with A1 or A2 yielded the best estimate of building VR in the NVB.

Keywords: building ventilation rate; aerial emissions from broiler barns; CO_2 mass balance; bland-altman chart.

Resumen

Este estudio se realizó para evaluar protocolos relativamente simples para el monitoreo de la tasa de ventilación (TV) en instalaciones pecuarias con ventilación natural (ENV). Los protocolos de ensayo se aplicaron primero a una instalación de pollos de engorde mecánicamente ventilada (EMV), donde TV se estimó con mayor precisión y luego se utilizaron para calcular la TV en la ENV. Las concentraciones de CO_2 se midieron con dos esquemas de muestreo diferentes: (S1) la media de las mediciones al interior y a lo largo de la longitud de la instalación a dos alturas de 0,5 m y 1,5 m del suelo; y (S2) igual que la anterior pero con las mediciones de concentración fueron realizadas únicamente a 0,5 m del suelo. La tasa de producción de CO_2 metabólico dinámico de las aves se predijo con dos algoritmos diferentes: (A1) el mantenimiento constante durante los periodos de luz y oscuridad, y (A2) que varía con la actividad de los animales sobre una base horaria. Los resultados demostraron que la combinación de S2 con A1 o A2 presentó la mejor estimación de TV en el ENV.

Palabras clave: tasa de ventilación en instalaciones, emisiones aéreas de instalaciones de pollos de engorde, balance de masa de CO_2, gráfico de bland-altman.

1. Introduction

A considerable amount of published literature on ammonia (NH_3) emissions from poultry production is devoted to the quantification of NH_3 emissions from mechanically-ventilated, environmentally-controlled poultry houses [1]. This kind of installation, however, is not typical in Brazil where poultry production systems feature open sidewalls without total control of the inside conditions. This practice is to take advantage of the tropical climate for natural ventilation to reduce production costs [2]. However, there are technical difficulties associated with measuring building ventilation rate (VR) and thus aerial emissions of such facilities [3].

Determination of the VR in mechanically-ventilated buildings (MVB) is relatively easy compared to naturally-ventilated buildings (NVB), because the VR in an MVB can be determined by directly measuring the airflow rates through all the openings or ventilation fans of the building and then totalized to obtain the overall building VR [4]. On the other hand, a NVB has large open contact areas with its outdoor environment, which is difficult to delimit. Various approaches exist to determine the VR of a NVB. One of the methods is based on the use of tracer gas, applicable to both mechanically and naturally ventilated buildings. The technique is based on mass balance of a tracer gas with a known release rate inside the building. Several gases can serve as tracers, with metabolically produced carbon dioxide (CO_2) being the most used because of advantages such as homogeneity in the air and reduced costs since it is readily available from the housed animals [5].

The challenge in using CO_2 as a tracer to determine the VR is the proper estimation of metabolic CO_2 production by the animals and other sources such as manure. There are two major methods of determining metabolic CO_2 production: one requires information of the respiratory quotient (RQ), and simplifies animal activity in dark and light periods [5]; (b) the other approach includes hourly variation of animal activities on the total metabolic CO_2 produced [4,6]. The question of how these two approaches compare to one another still needs to be answered. On the other hand, [7] mentioned that a crucial challenge for the determination of the VR in a NVB is choosing the locations for measuring the concentrations of CO_2. This reinforces the importance of the development of sampling schemes that lead to monitoring the representative average barn CO_2 concentrations.

Hence, the objective of this study was to define and evaluate an effective protocol to determine the VR of a NVB from several alternative methods. The potential refinements (i.e., test methods) that were investigated included: (a) use of an algorithm that best represents the production and release of metabolic CO_2 in the barn, which includes either diurnal or constant animal activity, and (b) determination of a sampling scheme of CO_2 concentration that leads to the best average indoor concentration, amongst the tested schemes. Due to the non-existence of a reference method for the determination of the VR in NVBs that can be used to challenge the test methods, we applied these test methods to a MVB, where the comparison with a reference method (summation of airflow from all exhaust fans) was possible. The test method that yielded the best fit to the reference value was then used for the determination of the VR in the NVB.

2. Material and methods

2.1. Characteristics of the broiler barns and flock management

The study was conducted in two commercial broiler barns, one naturally ventilated and the other mechanically ventilated, both located on the same farm in the state of Minas Gerais, Brazil. The mechanically ventilated barn (MVB) measured 120.0m L × 14.0m W × 2.5m H, with a fiber-cement tile roof, and a polyurethane drop ceiling (the same material as used for the sidewall curtains). The sidewall curtains were closed most of the time, and the ventilation was provided with 8 newly installed exhaust fans (specified capacity of 39,329 $m^3 h^{-1}$ each of 1.5 HP and with a static pressure of 12.0 Pa) placed on the west end of the building. Fresh air was brought into the barn through air inlets located at the east end, and the inlet openings were adjusted manually, as needed. The ventilation program was based on indoor air temperature and consisted of 7 stages including minimum ventilation at the early age of the birds (< 3wk). The barn had an initial placement of 23,100 male Cobbs® chicks, and freshly dried coffee husks, serving as floor bedding, which had never been used to raise broilers before. Chicks were reared up to a marketing age of 45 d.

The naturally ventilated barn (NVB) that was used for the application of the best VR protocol measured 75m L x 12m W x 2.75m H. It had ceramic tiles and a polyurethane drop ceiling (the same material as used for sidewall curtains). Ventilation was provided through manual operation/opening of the sidewall curtains (fully open, half open, or nearly closed). The initial bird placement was 10,000 female Cobbs®, and had the same kind of non-used litter described for the MVB. This flock was also reared up to a marketing age of 45 d.

The lighting program was similar for both sexes and followed the management guidelines of [8], consisting of a 1-hour dark period between the ages 2 - 10 d; then the number of dark hours was increased to 9, and then decreased again to 8, 7 and 6 hours of dark at the ages of 22, 23 and 24 days, respectively. The light schedule then remained the same until the bird age was 39 d, when the number of dark hours was set to 5, decreasing one hour a night till pick up day. Because the birds were being reared during the summer period in Brazil, the dark hours were synchronized to sunrise, and thus the time of minimum animal activity (h_{min}) in eq. (4) usually occurred between 2:00AM and 5:00 AM.

2.2. Sampling scheme and data collection

Carbon dioxide (CO_2) concentrations were measured with a hand-held sensor (model AZ 77535 CO_2/Temp/RH Meter, AZ Instrument Corp., Taichung City, Taiwan) that had a measuring range of 0 ~ 9999 ppm, resolution of 1 ppm and accuracy of ± 30 ppm ± 5% of the reading (according to specifications, and calibrated at the factory). Data collection was done once every three hours, for a 48-hour period, performed weekly throughout the 7–week grow-out period.

Sampling scheme 1 (S1): Indoor CO_2 concentrations were measured at three different distances along the central axis of the building (at 20, 60 and 100 m from the exhaust fans), and at two different heights (0.5 and 1.5 m above the litter). Outdoor CO_2 concentrations were measured at three different points along the south side of the building, which was considered to be the air inlet, as during the experimental period the wind was consistently coming from the south.

Sampling scheme 2 (S2): Same as S1, except that the indoor concentrations were taken only at 0.5 m above the litter, i.e. closer to the CO_2 plume generated by the birds.

2.3 Algorithms for calculating building ventilation rate (VR) and statistical analysis

2.3.1 Algorithms for calculating building ventilation rate (VR)

Building ventilation rate was estimated through eq. (1) [9].

$$VR=\frac{A\times(CO_2)_{metabolic}+(CO_2)_{litter}}{\Delta[CO_2]} \quad (1)$$

Where:

VR = the building ventilation flow $(m^3h^{-1}hpu^{-1})$;

A = the relative animal activity (non dimensional);

$(CO_2)_{metabolic}$ = metabolic CO_2 production by the animals $(m^3h^{-1}hpu^{-1})$;

$(CO_2)_{litter}$ = the CO_2 released by the litter $(m^3h^{-1}hpu^{-1})$;

$\Delta[CO_2]$ = $[CO_2]_{indoors}$ - $[CO_2]_{outdoors}$, the indoor and outdoor CO_2 concentrations, respectively (ppm).

CIGR [9] define 1 hpu (heat production unit) as 1000 W of total heat at 20°C. Two different algorithms were tested to estimate building VR, as follows.

<u>Varying metabolic CO_2 production (algorithm A1):</u> For this algorithm, A in eq. (1) was set constant and equal to 1, while the metabolic production of CO_2 was calculated using eq. (2) and (3), the same ones that were used by [5]. Here, animal activity was simplified to a dark and light period behavior, represented by two different respiratory quotients (RQ).

$$[CO_2]_{metabolic}=\frac{THP}{\frac{16.18}{RQ}+5.02} \quad (2)$$

$$THP=N\times 10.62\times m^{0.75} \quad (3)$$

Where:

THP = the total heat production of the animals under thermoneutral conditions (W);

RQ = respiratory quotient, non-dimensional;

N = number of animals in the barn;

m = animal body mass (kg).

The RQ value for broilers used in this algorithm was 0.9 [5], for all ages. According to [5], RQ values of tom turkeys remained constant and around 1.0 for ages of 1 – 35 days, and since broilers and young turkeys are similar in their bioenergetics, we used a constant RQ value for the tested bird age range. In this algorithm, dark *vs.* night activity was taken into consideration by reducing THP during the night period by 25%, as recommended by [5].

<u>Varying relative animal activity (algorithm A2):</u> For this algorithm, metabolic CO_2 production was set constant and equal to 0.180 m^3 h^{-1} hpu^{-1} for chicks with body weight < 0.5 kg and equal to 0.185 m^3 h^{-1} hpu^{-1} for body weight ≥ 0.5 kg [9], while the relative animal activity was calculated with the equations used by [10], namely the animal activity is represented by a sinusoidal model, of the following form.

$$A=1-a\times\sin\left[\left(\frac{2\pi}{24}\right)(h+6-h_{min})\right] \quad (4)$$

Where:

a = 0.08, a constant that expresses the amplitude with respect to the constant 1 [9];

h = time of the day (hour);

h_{min} = the time of the day with minimum activity after midnight (hour).

Total heat production data for both algorithms was adjusted for environmental temperature deviation from neutrality by using the eq. (5).

$$THP_{corr.T}=4\times 10^{-5}(20-T)^3 \quad (5)$$

Where:

$THP_{corr,T}$ = correction factor for temperature on total heat producton from the animals, based on the thermoneutral level of 20 °C, non-dimensional;

T = indoor air temperature, °C.

The contribution of CO_2 production from the litter was accounted for by multiplying the metabolic CO_2 production rate in both algorithms by a correction factor of 1.077, as suggested by [5]. In this study, the results obtained from the three sampling schemes were used as input to the two algorithms, resulting in four different test methods, which were compared to the reference method.

The labels attributed to the four test methods are: Test method 1- sampling scheme 1 and algorithm 1; Test method 2 - sampling scheme 1 and algorithm 2; Test method 3 - sampling scheme 2 and algorithm 1; Test Method 4 - Sampling scheme 2 and algorithm 2.

2.3.2 Reference method for the determination of building VR *and* statistical analysis

The reference procedure for calculating the VR of the MVB in this study consisted of the summation of the flow rate through all the running exhaust fans. The flow rate of the exhaust fans was calculated by measuring upstream air velocity via a hot wire anemometer (model 425, Testo ®, São Paulo, Brazil), with a specified measurement range of 0 ~ 2 m s^{-1}, resolution of 0.01 m s^{-1} and accuracy of ± (0.03 m s-1 + 5% of the reading), and was factory calibrated.

Measurements were taken at 16 traverse points evenly distributed across the fan's entrance area. Mean air velocity was then multiplied by the fan area to obtain the fan VR. Because the flow rate through the exhaust fans can vary with barn static pressure, which was not monitored, every time a new stage of fans was activated, a new measurement of their flow rate was taken.

In order to assess how the reference measurement method for the VR is related to each of the test methods, an analysis was performed with the software SAS 9.2®, that delineates agreement between each of the test methods and the reference method. Specifically, the agreement was assessed by regressing the difference between the reference and test methods ($\Delta_{VR} = VR_{reference} - VR_{test}$) and the mean VR obtained by both methods ($\overline{VR_i} = [VR_{reference} + VR_{test}]/2$), where if the null hypothesis H_o of $\Delta VR = 0$ cannot be rejected, there would be no difference between the two methods. This method was proposed by [11] and improved by [12], in which ΔVR is regressed on $\overline{VR_i}$ (eq. 6).

$$\Delta VR = \beta_0 + \beta_1 \times \overline{VR}_i + \varepsilon_i \qquad (6)$$

Where:

$\Delta VR = (VR_{reference} - VR_{alternative})$, $m^3\ h^{-1}\ bird^{-1}$;

β_o = Y-intercept, a measure of systematic positive or negative bias ($m^3\ h^{-1}\ bird^{-1}$);

β_1 = Slope, a measure of nonsystematic heterogeneous bias, non-dimensional;

$\overline{VR_i}$= is the average of VR measured with reference and alternative method ($m^3\ h^{-1}\ bird^{-1}$);

ε_i = independent normally distributed homogeneous random error ($m^3\ h^{-1}\ bird^{-1}$).

In Equation 6, the intercept (β_0) and the slope (β_1) represent homogeneous and heterogeneous systematic bias, respectively. A test of significance for each coefficient was carried on with PROC REG in SAS to assess if the systematic bias is statistically different from zero.

After the measurement of estimated bias, attention was also given to the nature of the random error in the measurements provided by each test method. The magnitude of the error was calculated as the standard error (SE) and the data set tested for non-uniform error distribution [13] with the Heteroscedasticity Test (HCT) in SAS. When the existence of non-uniformity was detected, the calculation of the adjusted SE (also called “white” error) for β_0 and β_1 was done through the option ACOV in the MODEL statement of PROC REG in SAS.

3. Results and discussion

3.1 Assessment of Agreement between Reference and Test Methods in the MVB

The regression lines for the comparison between reference and the four different test methods for measurement of VR are presented in Fig. 1. The plots show heterogeneous patterns in the spread of the data points along the measurement range for all four test methods, the points tended to spread further apart in the mid-range of the tested values. Evidence at the level of 95% confidence for the existence of heterogeneous spread of the random error can be seen in Table 1. The results confirm the existence of heterogeneous error distribution for most of the test methods. As a reaction to that, the significance test for the coefficients in the regression represented by eq. (6) was done with the corrected SEs ($SE_{\beta 0}$ and $SE_{\beta 1}$, Table 1) [12].

Regression results for the model in eq. (6) for all four test methods can also be seen in Table 1. The significance test for β_0 in eq. (6) revealed that for all test methods, a systematic positive homogeneous error was present. A systematic underestimation of CO_2 production leads to an

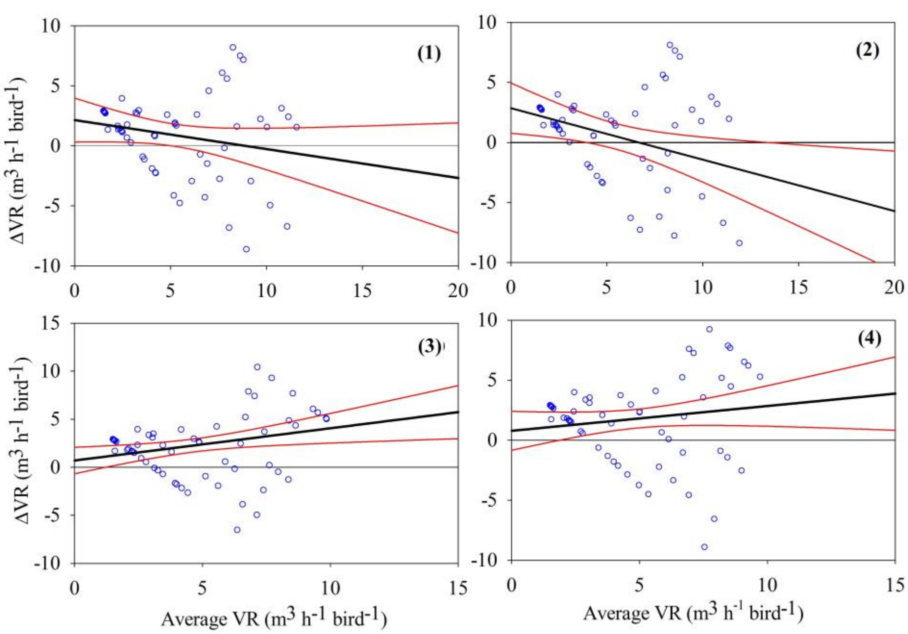

Figure 1. Plots for the difference between each of the alternative CO_2 balance methods for measuring ventilation flow rate (ΔVR) and the standard method against the average of the two methods ($\overline{VR}$) being compared. The four test methods are the combination of: (1) sampling scheme 1 and algorithm 1; (2) scheme 1 and algorithm 2; (3) sampling scheme 2 and algorithm 1; (4) Sampling scheme 2 and algorithm 2.

Table 1.
Summary of statistics for the evaluation of agreement between reference and 4 test methods, by regressing data to the model $\Delta VR=\beta_0+\beta_1\overline{VR}$

Test Method	1	2	3	4
$\widehat{\beta_0} \pm SE_{\beta_0}$, ($m^3 h^{-1} bird^{-1}$)	2.2* ± 0.5	2.9* ± 0.6	1.1* ± 0.8	1.4* ± 0.9
$\widehat{\beta_1} \pm SE_{\beta_1}$ (non-dimensional)	-0.2 ± 0.1	-0.4 ± 0.2	0.2 ± 0.2	0.1 ± 0.2
Adj. R^2	0.02	0.08	0.02	0.0099
p-value for regression	0.1270	0.0128	0.1405	0.5389
N	64	64	64	64

* Estimated coefficient is significantly different than zero at the level of 95% probability;

underestimation of ventilation rate (eq.1) and explains why the bias represented by β_0 had a positive nature, the lowest regressed intercept values were (1.1 ± 0.8) $m3h^{-1}bird^{-1}$ for test method 3 and (1.4 ± 0.9) $m3h^{-1}bird^{-1}$ for test method 4 (Table 1). Potential reasons for the existence of systematic bias could be the models used to estimate the metabolic CO_2 production in the barn, which were based on empirical coefficients (either RQ for algorithm 1 or the constant rate of production of CO_2 in algorithm 2) for broiler breeds tested during the 90s or earlier, while the modern broilers have growth rates that are increasing over the years, consequently increasing animal metabolic rate, and thus producing more CO_2 [5].

Calvet et al. [14] suggested that the model for determination of VR from CO_2 balance for broiler litters should be adjusted with updated coefficients that account for both environmental temperature and modern strains of broilers that have been obtained by advances in genetics and improved feed composition. Havenstein et al. [15] stated that broiler growth rate in terms of body weight (BW) increased by approximately 73 g yr^{-1} from 1976 to 1991, while increased BW means increase in metabolic rate, improved feed conversion rate and consequently more release of CO_2 per animal, with time. Hence, it is necessary that new experiments be designed and performed on the quantification of the bioenergetics of the modern breeds of broilers in order to update and improve the metabolic CO_2 production estimates.

The significance test for β_1 indicated that the majority of test methods presented systematic heterogeneous bias that did not statistically differ from 0, presenting values that ranged from (-0.4 ± 0.2) to (0.2 ± 0.2). This outcome indicates that systematic heterogeneous bias was nearly inexistent for any of the test methods.

Results of the non-linear regression analysis performed to adjust VR *vs.* $\Delta[CO_2]$ data from all test methods to the model in $VR = a\times\Delta[CO_2]^b$ can be seen in Table 2. Empirical values obtained for the coefficient b for test methods 3 and 4 were (-0.9 ± 0.1), being significantly equal to -1 ($p < 0.0001$), indicating that these test methods present the best fit to the model. Hence, because tests methods 3 and 4 presented the lowest systematic bias while yielding the best fit with the theoretical model, they were regarded as the most appropriate for application to the NVB.

3.2. Calculations of VR for the NVB with the Best Selected Test Methods

Calculated mean VR values by age for the NVB, obtained with test methods 3 and 4 are presented in Table 3 along with those obtained by [16], who recommended minimum, maximum VR values related to bird body weight. The VR data obtained with test methods 3 and 4 in this study compare well with those from [16], especially for the maximum recommended values.

Table 2.
Non-linear regression results for the fit of experimental and calculated data from the mechanically ventilated building (MVB) to the model $VR = a\times\Delta[CO_2]^b$

Test method	Mean $\Delta[CO_2]$, ppm	a ± SE	b ± SE	Adj. R^2	Regression P-value
1	977	6273 ± 4383	-0.6 ± 0.1	0.33	< 0.0001
2	977	7828 ± 5948	-0.6 ± 0.1	0.31	< 0.0001
3	1015	1109 ± 718	-0.9* ± 0.1	0.51	< 0.0001
4	1015	1297 ± 899	-0.9* ± 0.1	0.48	< 0.0001

*the parameter estimate is not significantly different than the theoretical value of -1 at a confidence level of 95%.

Table 3.
Data of bird body weight and ventilation rates (VR, m^3 h^{-1} $bird^{-1}$) for broiler chickens as a function of bird age (d) presented by [16] and calculated in this study for the naturally ventilated barn (NVB) with test methods 3 and 4.

Bird age (wk)	Lacambra, 1997	This study	
		Test method 3	Test method 4
1	0.3	0.8 ± 0.2	0.8 ± 0.2
2	0.8	2.0 ± 0.5	2.0 ± 0.4
3	2.1	1.6 ± 0.2	1.6 ± 0.2
4	4.3	2.1 ± 0.3	2.1 ± 0.3
5	7.5	4.1 ± 0.6	4.6 ± 0.7
6	11.5	8.1 ± 0.7	8.9 ± 0.8

The range of variability in VR by age for the NVB calculated with test methods 3 and 4 are also presented in Table 3 in terms of standard error of the mean (SE), going from 0.2 m^3 h^{-1} $bird^{-1}$ to 0.7 m^3 h^{-1} $bird^{-1}$ for ages 1 and 6 wk, respectively for test method 3 and from 0.2 m^3 h^{-1} $bird^{-1}$ to 0.8 m^3 h^{-1} $bird^{-1}$ for ages 1 and 6 wk, respectively for test method 4.

The uncertainty associated with the use of the CO_2 mass balance for NVBs in livestock has been evaluated by [10] for pig barns and by [17] for dairy cow barns. One of the reasons for the relative variability appointed in most of these studies is the dependence on wind forces that cause both the concentrations to vary by a large extent and most importantly, causing the difference of CO_2 concentration between the inside and outside of the barn (ΔCO_2) to be small, which is when the CO_2 balance method should be used with care in naturally ventilated barns; Ouwerkerk and Pedersen [18] suggested that ΔCO_2 values should not be lower than 200 ppm in order for the method to yield reliable results. In this study, more than 90% of the values for ΔCO_2 used in tests methods 3 or 4 for the NVB met the > 200 ppm criteria of [18], ranging from 105 to 1596 ppm with mean and SE of (577 ± 34) ppm for both test methods.

4. Conclusions

Four combinations of two sampling schemes and two sets of calculations were tested to measure the ventilation rate of a mechanically ventilated negative pressure broiler barn based on the metabolic CO_2 mass balance method. The best test methods were selected in terms of presence of smallest systematic and heterogeneous bias, and were applied to calculate ventilation rate across a naturally ventilated broiler house. The following conclusions can be drawn:

- Including either variable animal activity throughout the day or averaged dark and light periods in calculations of metabolic CO_2 production combined with sampling CO_2 concentrations measured at the influence zone of the birds yielded the best estimates of VR for the negative pressure barn as compared to the reference method;
- Estimates of air flow rate for the naturally ventilated barn were calculated by considering variable animal activity throughout the day and with measurements of CO_2 concentrations at the bird influence zone, with values ranging from (0.44 ± 0.04) m^3 h^{-1} $bird^{-1}$ and (10 ± 1) m^3 h^{-1} $bird^{-1}$ at the ages of 1 and 7 weeks.

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