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Keywords

Dust emissions, Livestock, Ventilation, Air pollution, Chickens

Disciplines

Bioresource and Agricultural Engineering

Comments

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ABSTRACT

Particulate matter (PM) was measured in the ventilation exhaust air of a caged layer house using three tapered element oscillating microbalances (TEOMs). Diurnal patterns of PM concentration and emission were observed during 6 days in June 2002. The average daily mean (±95% c.i.) concentrations and emissions were 39±8.0, 518±74, and 1887±563 $\mu g/m^3$ and 1.1±0.3, 16±3.4, and 63±15 g/d-AU for $PM_{2.5}$, PM_{10}, and total suspended particulates (TSP), respectively. Daytime (lights on) $PM_{2.5}$, PM_{10}, and TSP concentrations were 151, 108, and 136% higher ($P<0.05$) than at night. Emissions peaked during the day when birds were most active and ventilation rates were the highest. Wide diurnal variations in PM concentration and ventilation were observed. PM emission was correlated to ventilation, ambient and exhaust temperatures, and relative humidity ($P<0.05$).

KEYWORDS. Dust emissions, Livestock, Ventilation, Air pollution, Chickens.

INTRODUCTION AND OBJECTIVES

Emissions of particulate matter (PM) from industrial sources are regulated by the Clean Air Act (CAA) (Cooper and Alley, 1994). Large livestock production facilities may emit quantities of PM that approach the limits by the CAA for industrial sources. Confined animal buildings are important for reducing the cost of production, but are usually the most significant source of PM emissions at intensive livestock production facilities. Regulators have taken an interest in the quantity of PM emitted by these facilities because of their large inventories of hens, which have increased dramatically in the last two decades. Factors affecting building PM emissions include building design and management, animal activity, the feed type, condition and handling, ventilation, and the manure collection system. Bird activity is a major cause of PM emitted by modern high-rise laying houses with stacked cages (Heber et al., 2002).

A total of 329 livestock buildings including pigs, cattle and poultry were surveyed in Europe with a 24 h data set from each building (Wathes et al., 1998). Measurements of PM were made at seven locations in an internal vertical cross-section using gravimetric methods (Takai et al., 1998). Poultry houses had poor air quality because of high ammonia, inhalable and respirable dust, and endotoxin concentrations. Percheries and caged laying houses had higher inhalable PM concentrations during the day than at night (Takai et al., 1998). Wathes et al. (1998) concluded that the calculation of ventilation introduced the greatest uncertainty into emission rate determinations.

Hinz and Linke (1998ab) pioneered the first use of the tapered element oscillating microbalance (TEOM) to obtain real-time PM measurements in livestock buildings. The PM measurements in one swine finishing house and one broiler house were coupled with continuous measurements of ventilation using impeller anemometers or the CO_2 balance method (Feddes et al., 1984) to assess emission characteristics. In the finishing house, definite peaks of PM concentrations at feeding times, and a 2:1 day/night ratio were observed with both the gravimetric method and the TEOM.

Although several studies of total suspended particulates (TSP or inhalable dust) and respirable dust (PM_5) concentrations have been conducted (Hinz and Linke, 1998b; Wathes et al., 1998), simultaneous continuous monitoring of emissions of TSP, PM_{10} (aerodynamic diameter < 10 μm), and $PM_{2.5}$ (aerodynamic diameter < 2.5 μm) from livestock buildings has not been reported. As compared with integrated gravimetric sampling techniques used in prior studies, the measurement of real-time PM mass concentrations using the microweighing technology practiced in the TEOM presents new opportunities for studying livestock PM emissions. When coupled with real-time measurements of ventilation, diurnal variations of PM emissions can be determined. Therefore, the objectives of this study were to evaluate and characterize $PM_{2.5}$, PM_{10}, and TSP concentrations and emissions at a caged-layer house.

MATERIALS AND METHODS

Experimental Barns

The caged-hen layer house was a 250,000-hen, one-year-old, two-story building located at the NW corner of a 14-barn facility in north-central Indiana. It had a 3.7-m high flat ceiling on the hen-occupied second story, and was 36.6 m wide and 182.9 m long. Automatic adjustments of ceiling air inlets over each row of cages were based on temperature. Manure drying on the first floor was enhanced with 91.5-cm dia. auxiliary circulation fans (Model 40404-36, Choretime-Brock, Milford, IN). Seventy-three, 1.23-m dia. belted exhaust fans (Model 38233-4, Choretime-Brock) were distributed along the sidewalls of the first floor, and were grouped into eight fan stages for temperature-based control. Second floor lights were automatically shut off from 20:00 to 04:00.

Data was collected from June 3 to June 8, 2002. Measurements of PM, building pressure, ventilation fan operation, temperatures (T), relative humidity (RH), and gas concentrations at building exhausts and inlets were automatic (Heber et al., 2002). The continuous emission monitoring equipment was housed in an instrument trailer or shelter that was parked approximately midway along the south side of the building near the 17^{th} fan from the east end. This fan was one of the five continuous minimum winter ventilation fans in fan stage 1, and was considered to be the primary representative exhaust fan (PREF).

Temperature and Relative Humidity Measurement and Data Collection

A T and RH sensor (Model HO8-032-08, Hobo, MicroDAQ, Warner, NH) with precisions of ±0.2 °C and ±3%, respectively, was positioned near the PREF's inlet. A solar-shielded (Model RS1, MicroDAQ) T/RH probe was use to monitor outdoor conditions.

The attic air T and RH were measured continuously with precisions of ±0.6 °C and ± 3%, respectively (Model 50Y, Vaisala, Woburn, MA). Static pressure differences (±0.5 Pa) across the sidewalls were monitored with differential pressure sensors (Model 267, Setra, Boxborough, MA).

Data were recorded on a PC, except for T and RH that were downloaded biweekly from battery-operated sensors. Blocks of data collected at 1 Hz were averaged and stored every 60 s. All PM data were recorded and averaged by the PC on 60-s intervals and internally on 10-min intervals.

Ventilation Airflow Measurement

The operating status of each fan stage was monitored via auxiliary contacts of fan motor control relays. Vane anemometers (Fancom Model FMS 50, Techmark, Lansing, MI) were mounted in the exhaust shrouds of nine ventilation fans belonging to the first two stages.

Since dust buildup, belt wear, and shutter degradation causes less airflow than predicted by fan rating curves, fan airflow capacities were measured in the field with a fan airflow numeration system (FANS), a calibrated anemometer system (Becker, 1999) consisting of multiple traversing impellers. The FANS and the vane anemometers were calibrated with an accuracy of ±2% at the

University of Illinois Bioenvironmental Systems and Simulations (BESS) Laboratory with two fans temporarily removed from the caged-layer house.

Adjustment factors were assigned to each fan stage based on tests of 22 fans with the FANS conducted between May 17 and June 7. Airflow rates of each fan stage were the number of fans times the adjustment factor and airflow based on static pressure and the BESS fan curve. Total building ventilation rate was the summation of airflows from each stage.

PM Measurements

The TEOM (Model 1400a Ambient Particulate (PM_{10}) Monitor, Rupprecht and Patashnick, Albany, NY) is designated by USEPA as an equivalent method (EPA Designation No. EQPM-1090-079) for continuously measuring PM_{10}. The instrument draws aerosol through an exchangeable filter attached to a hollow tapered oscillating glass rod at a constant flow rate. The real-time PM concentration is based on sample flow rate coupled with gains in mass on the filter measured by its effect on oscillation frequency (Rupprecht and Patashnick, 1991).

Each TEOM system consists of controller and sensor units (Figure 1). The sensor unit contains a mass transducer and is heated to 50 °C to minimize moisture effects. The PM_{10} sample inlet is attached to the sensor unit and can be replaced with TSP and $PM_{2.5}$ inlets. Sample flow is split isokinetically into a main flow passing through the filter and a bypass flow, each controlled by a mass flow controller.

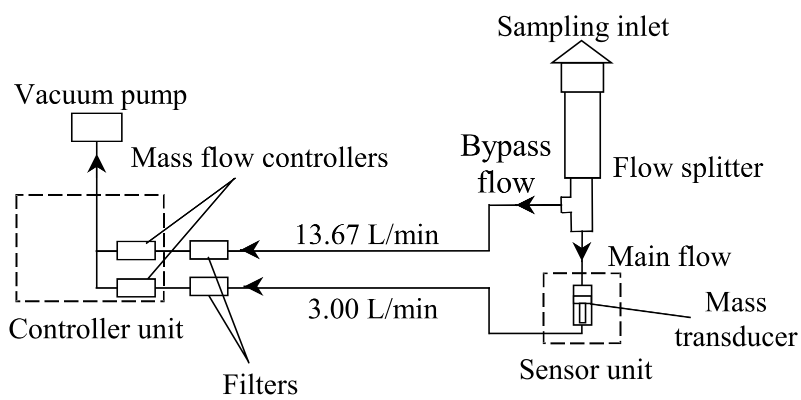

Figure 1. Flow schematic of the TEOM.

Four TEOM sampling inlets and sensor units were collocated on either side of the PREF between it and adjacent fans (Figure 2). They were located far enough away from the PREF to avoid concerns about anisokinetic sampling (air speed < 2.03 m/s) while still inside the exhaust air stream of the fan. Air speeds near the sampling head were measured once with a hot wire anemometer (Model 440, Kurz, Inc., Monterey, CA). TEOMs were used to measure $PM_{2.5}$, PM_{10}, and TSP at sampling locations A, B, and C, respectively; TEOM of location D was not operated. Each sensor unit was housed in a plywood cabinet for protection against the manure storage environment. A 7.5 m wide, 1.2 m high plywood manure wall was located 1.18 m from the side wall to stop manure from spilling into the sampling area.

Data Analysis

Emission rates were calculated every minute as the product of 60-s PM concentration and ventilation rate, neglecting unmeasured background PM concentration. For analysis purposes, a day was further divided into 24 (hourly) or 144 (10-min) sampling periods, with a mean calculated for each. The terms day and daytime or night in this paper refer to artificial light or darkness in the house. Period means of both day (from 04:00 to 20:00) and night were used to study effects of lighting.

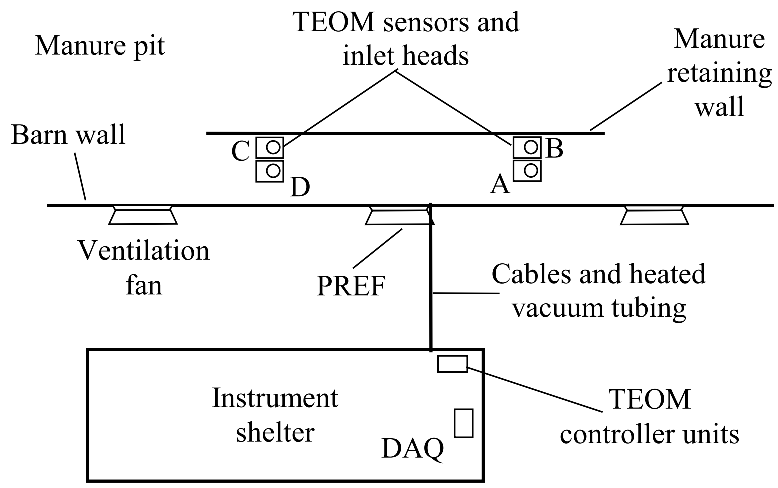

Figure 2. Schematic of monitoring plan, DAQ=data acquisition, PREF=primary representative exhaust fan.

RESULTS AND DISCUSSION

A total of 709 10-min data sets were collected during the 6-d test, during which the mean barn inventory was 243,628 birds, and the average bird mass was 1.6 kg. The total live mass was equivalent to 780 animal units (AU=500 kg). Air speeds around the TEOM sampling heads ranged from 1.3 to 2.0 m/s.

Exhaust air temperatures during day and night periods were similar (Table 1) indicating the ventilation system maintained stable temperatures. Mean FANS-measured airflows were 5% lower than that estimated by measured static pressure and the BESS fan curve, and generally indicated that fans of lower stages were less efficient than fans of higher stages. Adjustments to BESS fan curves based on in-field tests with the FANS ranged from 0.858 for stage 1 to 1.024 for stage 8. The overall mean 24-hr ventilation rate was 288 m^3/s, and the ventilation rate was 66% higher ($P<0.05$) in the day than at night.

Table 1. Means (±95% confidence interval) of environmental variables.

Variable	**24-hr mean**	**Day***	**Night***
Temperature, ^{o}C			
Ambient	20±1.2	21±1.4	18±1.1
Attic	18±1.3	19±1.6	15±0.8
Cages	26±0.6	26±0.7	24±0.4
Exhaust fan	25±0.6	25±0.7	24±0.5
Relative humidity, %			
Ambient	80±4.7	77±5.8	89±2.9
Attic	71±4.0	68±4.9	79±1.2
Cages	56±1.5	54±1.9	58±0.9
Exhaust fan	62±1.9	60±2.4	65±0.7
Ventilation rate, m^3/s	288±37	326±38	196±22
PM concentration, μg/m^3			
$PM_{2.5}$	39±8.0	47±7.7	19±8.7
PM_{10}	518±74	611±44	293±103
TSP	1887±563	2268±718	961±214
PM emission, mg/s			
$PM_{2.5}$	10±2.5	13±2.5	3.7±2.4
PM_{10}	143±31	179±27	293±103
TSP	566±139	719±133	192±71
PM emission, g/d-AU			
$PM_{2.5}$	1.1±0.3	1.4±0.3	0.4±0.3
PM_{10}	16±3.4	20±2.9	6.3±3.4
TSP	63±15	80±15	21±7.9

* Day = period with artificial indoor light, night = period without artificial lights

PM Concentration

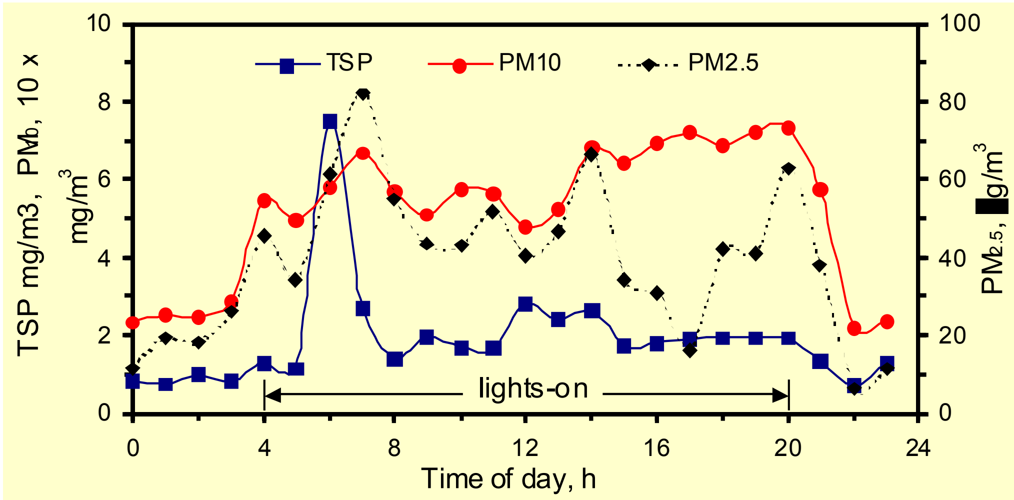

Figure 3. Average time-of-day hourly mean PM concentrations.

Overall 24-hr mean TSP, PM_{10}, and $PM_{2.5}$ concentrations were 1887±563, 518±74, and 39±8.0 $\mu g/m^3$, respectively. The PM concentrations were comparable to a European study where overall mean inhalable (TSP) and respirable (PM_5) dust concentrations were 3800 and 700 $\mu g/m^3$ in cattle buildings, 2190 and 230 $\mu g/m^3$ in pig buildings, and 3600 and 450 $\mu g/m^3$ in poultry buildings, respectively (Hinz and Linke, 1998). Large diurnal variations occurred (Figure 3) as mean daytime concentrations were 2.51, 2.08, and 2.36 times higher than at night for $PM_{2.5}$, PM_{10}, and TSP, respectively, similar to the 2:1 ratio reported by Hinz and Linke (1998). The combination of increased animal activities, operation of feed delivery equipment, worker activities (floor and equipment cleaning, etc.) were apparent causes of higher daytime concentrations.

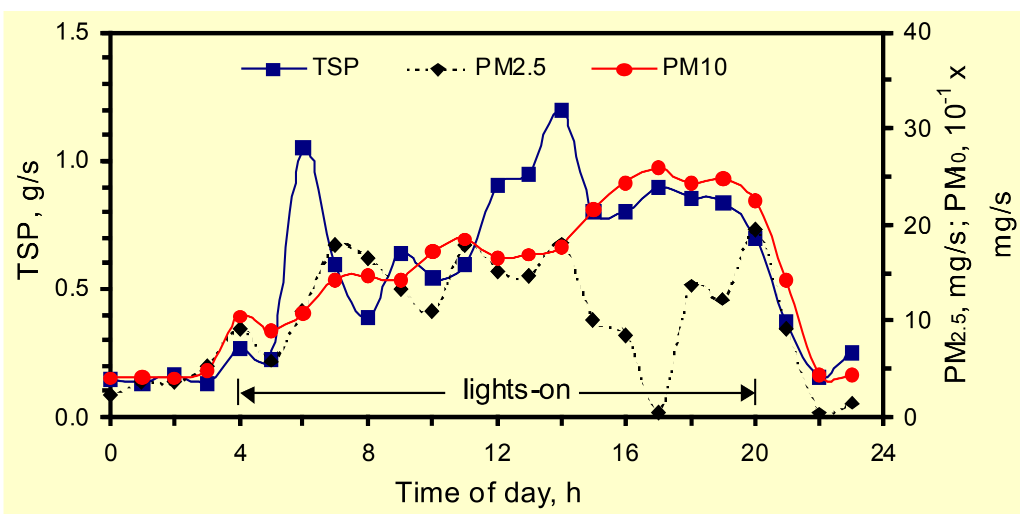

Figure 4. Average time-of-day hourly mean PM emission rates.

Several peaks in PM were recorded, particularly when lights were turned on or off, and at around 07:00. The first large TSP peak of hourly means (Figure 4) occurred slightly earlier than PM_{10} and $PM_{2.5}$ and was contributed to mostly by strong peaks (>8 mg/m^3) at 06:00 on June 6 and 7, and a 6.4 mg/m^3 peak at 07:00 on June 8. The hourly mean $PM_{2.5}$ concentration decreased to less than 20 $\mu g/m^3$ at 17:00, similar to nighttime concentrations. The causes of the early morning TSP peaks, and the large decrease of $PM_{2.5}$ in the afternoon are not known since animal activity, feeding, worker activity, and other process variables were not monitored. However, it is likely that worker activity and operation of the feed conveyer may have caused the early morning TSP peaks.

PM Emission

Building $PM_{2.5}$, PM_{10}, and TSP emission rates were 10±2.5, 143±31, and 566±139 mg/s (1.91, 27.3, and 108 lb/d) and were 246, 213, and 274% higher during the day than at night, respectively. Diurnal variations of emissions were greater than concentration variations due to higher airflow rates during the day. The airflow peaked at about 16:00 causing emission rate to peak as well (Figure 4), except for PM 2.5. The amplifying effects of ventilation on emissions can be observed by comparing PM concentration (Figure 3) with PM emission (Figure 4). The mean 24-h live-mass specific emission rates were 1.1±0.3, 16±3.4, and 63±15 g/d-AU (46, 661, and 2610 mg/h-AU) for $PM_{2.5}$, PM_{10}, and TSP, respectively, and were comparable to mean respirable and inhalable PM emissions of 504 and 3165 mg/h-AU, respectively (Takai et al., 1998).

Effects of Ventilation Rates on PM and Other Variables

Building ventilation rate, PM, RH, and exhaust air T exhibited significant sinusoidal patterns on a diurnal basis (Figure 5). Higher frequency and simultaneous undulations of 10-min means of ventilation, PM_{10}, and RH were caused by fans cycling on and off. Ventilation rate apparently affects PM concentrations, T, and RH almost instantaneously because short-term fluctuations of PM_{10} and RH were most frequently inversely related to ventilation. However, these effects were only seen at small time scales and relatively low magnitudes. On a larger time scale, the diurnal pattern of ventilation rate did not exhibit lower PM concentrations in the afternoon (except for $PM_{2.5}$) when airflow rate was highest. PM_{10} was occasionally inversely proportional to RH, indicating that PM concentrations were affected by other factors, such as anticipatory feeding around 20:30 before the lights went out (Heber et al., 2002).

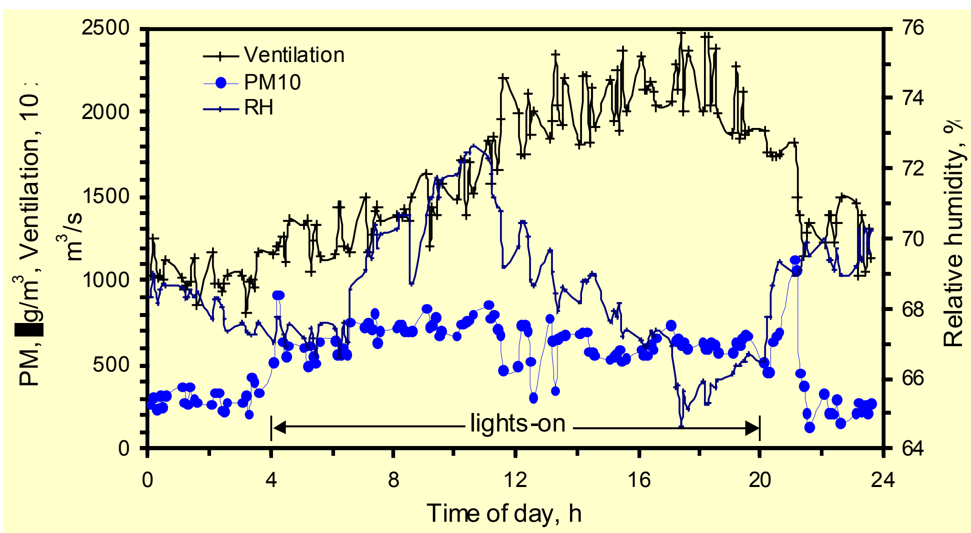

Figure 5. A 24-h record of 10-min mean PM_{10} concentrations, ventilation rates, and RH, on June 6, 2002.

The hourly means of several variables were subjected to a correlation analysis (Table 2). Results showed that the ventilation rate was directly proportional to exhaust and outdoor temperatures due to the temperature-based ventilation control system. Ventilation rate was inversely proportional to exhaust and outdoor RH (Table 2).

The dilution of PM concentrations by ventilation (r = -0.14, 0.01, and 0.04 for $PM_{2.5}$, PM_{10}, and TSP, P>0.05) was not as apparent as dilution of gas concentrations (Ni et al., 2000). Many other sources contribute to PM generation since higher ventilation rates did not always reduce PM concentrations by itself. However, PM emission was directly proportional to ventilation rate (r = 0.33, 0.84, and 0.62 for $PM_{2.5}$, PM_{10}, and TSP, P<0.05) because emission is the product of concentration and ventilation rate and thus the variables are not independent of each other. Large diurnal variations in PM and ventilation rate confirm the need for long sampling times, covering both day and night periods.

Table 2. Correlation coefficients (r) of hourly means of environmental variables.

Variables	1*	2	3	4	5	6	7	8	9	10
1. Exhaust temperature	-									
2. Exhaust RH	-0.68†									
3. Ambient temperature	0.97†	-0.70†								
4. Ambient RH	-0.77†	0.95†	-0.83†							
5. Ventilation	0.94†	-0.69†	0.95†	-0.80†						
6. $PM_{2.5}$ concentration	-0.18	0.06	-0.15	0.09	-0.14					
7. PM_{10} concentration	-0.01	-0.05	-0.04	-0.03	0.01	0.58†				
8. TSP concentration	-0.02	-0.10	-0.03	-0.06	0.04	0.15	0.19†			
9. $PM_{2.5}$ emission rate	0.29†	-0.35†	0.32†	-0.37†	0.33†	0.74†	0.26†	0.08		
10. PM_{10} emission rate	0.79†	-0.71†	0.77†	-0.76†	0.84†	0.11	0.45†	0.13	0.44†	
11. TSP emission rate	0.56†	-0.62†	0.55†	-0.61†	0.62†	0.00	0.18†	0.69†	0.22†	0.63†

* Numbers correspond to the variables listed in the first column

† $P<0.05$

CONCLUSIONS

- Mean $PM_{2.5}$, PM_{10}, and TSP levels were 39±8.0, 518±74, and 1887±563 $\mu g/m^3$, respectively.
- Emissions of $PM_{2.5}$, PM_{10}, and TSP were 1.1±0.3, 16±3.4, and 63±15 g/d-AU, respectively.
- Daytime PM concentrations and emissions were significantly higher than at night.
- Ventilation influenced PM concentrations, temperature, and RH in relatively short time scales.
- Long measurement periods are required to evaluate representative poultry building PM emission.

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