Particulate Matter Concentrations and Emissions of a High-Rise Layer House in Iowa

Shuhai Li  
*SUNY Morrisville*

Hong Li  
*University of Delaware*

Hongwei Xin  
*Iowa State University, hxin@iastate.edu*

Robert T. Burns  
*University of Tennessee*

Follow this and additional works at: [http://lib.dr.iastate.edu/abe_eng_pubs](http://lib.dr.iastate.edu/abe_eng_pubs)  
Part of the [Agriculture Commons](http://lib.dr.iastate.edu/abe_eng_pubs), and the [Bioresource and Agricultural Engineering Commons](http://lib.dr.iastate.edu/)

The complete bibliographic information for this item can be found at [http://lib.dr.iastate.edu/abe_eng_pubs/187](http://lib.dr.iastate.edu/abe_eng_pubs/187). For information on how to cite this item, please visit [http://lib.dr.iastate.edu/howtocite.html](http://lib.dr.iastate.edu/howtocite.html).
Particulate Matter Concentrations and Emissions of a High-Rise Layer House in Iowa

Abstract
Particulate matter (PM) associated with animal feeding operations is a concern for the occupants and the surrounding community. Baseline measurements of PM concentration and emission rate are the first step toward assessing the magnitude of concentrations and emissions and evaluating effectiveness of dust control strategies. This study presents the results of PM measurements at a high-rise layer house (approx. 250,000 hens) in central Iowa using tapered element oscillating microbalance (TEOM) equipment. Daily average concentrations of PM10 and PM2.5 over a 17-month measurement period were 393 (±257 SD) and 44 (±36 SD) µg m⁻³, respectively. Daily average PM10 and PM2.5 emission rates during the same monitoring period were, respectively, 26.1 (±15.8 SD) and 3.6 (± 3.7 SD) mg bird⁻¹ d⁻¹, or 8.16 (±4.94) and 1.13 (±1.16) g AU⁻¹ d⁻¹ (AU = animal unit = 500 kg body weight). PM emission rate was positively related to ventilation rate but was negatively related to relative humidity.

Keywords
Air quality, Laying-hen house, Particulate matter, PM25, PM10

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
This article is from Transactions of the ASABE 54, no. 3 (2011): 1093–1101.
PARTICULATE MATTER CONCENTRATIONS AND EMISSIONS OF A HIGH-RISE LAYER HOUSE IN IOWA

S. Li, H. Li, H. Xin, R. T. Burns

ABSTRACT. Particulate matter (PM) associated with animal feeding operations is a concern for the occupants and the surrounding community. Baseline measurements of PM concentration and emission rate are the first step toward assessing the magnitude of concentrations and emissions and evaluating effectiveness of dust control strategies. This study presents the results of PM measurements at a high-rise layer house (approx. 250,000 hens) in central Iowa using tapered element oscillating microbalance (TEOM) equipment. Daily average concentrations of PM$_{10}$ and PM$_{2.5}$ over a 17-month measurement period were 393 ($\pm$257 SD) and 44 ($\pm$36 SD) $\mu$g m$^{-3}$, respectively. Daily average PM$_{10}$ and PM$_{2.5}$ emission rates during the same monitoring period were, respectively, 26.1 ($\pm$15.8 SD) and 3.6 ($\pm$3.7 SD) mg bird$^{-1}$ d$^{-1}$, or 8.16 ($\pm$4.94) and 1.13 ($\pm$1.16) g AU$^{-1}$ d$^{-1}$ (AU = animal unit = 500 kg body weight). PM emission rate was positively related to ventilation rate but was negatively related to relative humidity.

Keywords. Air quality, Laying-hen house, Particulate matter, PM$_{2.5}$, PM$_{10}$.

Particulate matter (PM) associated with animal feeding operations is a concern for the occupants and the surrounding community. The adsorbed odorants and bacteria on PM may pose health hazards and environmental contamination. Baseline measurements of concentration and emission rate (ER) of PM are the first step toward assessing the environmental impact of animal feeding operations and evaluating effectiveness of dust control strategies.

PM comes in a spectrum of sizes and shapes. Based on their sizes, particles can be categorized into different groups. PM$_{10}$ refers to the PM that passes through a size-selective inlet with a 50% cut-off at 10 $\mu$m aerodynamic equivalent diameter, whereas PM$_{2.5}$ refers to the PM that passes through a size-selective inlet with a 50% cut-off at 2.5 $\mu$m aerodynamic equivalent diameter. This scale classification is used mostly in studies of ambient air quality in the U.S. European studies used to report PM as respirable and inhalable particles, being occupational health parameters, but increasingly use PM$_{10}$ and PM$_{2.5}$ for outside air quality related studies. Inhalable particles refer to those smaller than 100 $\mu$m, and respirable particles are those smaller than 4 $\mu$m. More details on particle size categories can be found in Zhang (2005).

Various techniques have been used in measuring PM concentration. Gravimetric filtration is the most common method used in the early PM studies of livestock buildings. The principle of this method is to pump air samples through a filter and collect the dust on the filter. Dust concentration can be calculated with the airflow rate and the mass gain on the filter. Another method, using tapered element oscillating microbalance (TEOM) equipment, collects dust on a filter that is attached to an oscillating element. The element oscillates at a frequency depending on the mass of the element, as governed by the law of spring-mass systems. The oscillation frequency can be readily measured with an electronic counter. TEOM is the PM monitor recommended by the U.S. Environmental Protection Agency (EPA) in the nationwide Air Compliance Agreement study. Particle concentration can also be measured with various optical methods based on light scattering and attenuation. Some of the early studies reported dust concentration as the number of particles per unit volume (Gleennon et al., 1989; McQuitty et al., 1985; Nakaue et al., 1981; van Wicklen and Allison, 1989; Yoder and van Wicklen, 1988), making it difficult to compare these studies with recent studies that reported PM concentration as mass per unit volume.

Measurement of PM in poultry production facilities started in the 1980s. Several reviews were made of PM measurements in poultry houses (Auvermann et al., 2006; CIGR, 1994; Ellen et al., 2000; Pearson and Sharples, 1995). The measurements in early years focused on PM concentrations inside poultry houses because the indoor environment was the primary concern. In addition to the health hazards that PM poses to the occupants inside animal buildings, PM emitted to the surroundings is also a recognized public hazard. However, data on PM emissions from poultry facilities are still scant. The recent advancement

Submitted for review in August 2010 as manuscript number SE 8747; approved for publication by the Structures & Environment Division of ASABE in May 2011.

Mention of company or product names is for presentation clarity and does not imply endorsement by the authors or Iowa State University nor exclusion of other suitable products.

The authors are Shuhai Li, ASABE Member, Research Scientist, Renewable Energy Training Center, SUNY Morrisville, New York; Hong Li, ASABE Member, Assistant Professor, Department of Biosystems Engineering, University of Delaware, Newark, Delaware; Hongwei Xin, ASABE Fellow, Professor, Director of Egg Industry Center, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa; and Robert T. Burns, ASABE Member, Professor and Assistant Dean, Agriculture, Natural Resources, and Resource Development, University of Tennessee Extension, Knoxville, Tennessee. Corresponding author: Hongwei Xin, Department of Agricultural and Biosystems Engineering, 3204 NSRIC, Iowa State University, Ames, IA 50011-3310; phone: 515-294-4240; e-mail: hxin@iastate.edu.
in determination of building ventilation rate (VR) of mechanically ventilated facilities and the corresponding dynamic PM concentrations has enabled researchers to tackle PM emissions with improved certainty. It should be noted that the highly diurnally varying nature in both PM concentration and VR calls for the use of instantaneous (e.g., 10 min) values of the concentration and VR, as opposed to the daily mean values, in determination of daily PM emissions. Use of the daily mean concentration and VR to determine daily emissions would be adequate when at least one of the two variables remain constant throughout the day.

Different production systems are used to raise egg-laying hens. Hens are raised in: (1) cages that are arranged in multiple tiers, or (2) perchery (also referred to as aviary) systems where hens have access to several tiers of platforms for their natural activities and nesting space for laying eggs, or (3) free-range systems where hens have access to outdoor space in addition to the amenities in a perchery system. Since a major source of PM is from chickens’ natural activities and their activity levels vary in these production systems, different PM concentrations and emission rates are expected from these production systems given the same conditions of other factors.

Some of the findings from early studies are: (1) PM concentration and ER increase with bird weight and age (Martensson and Pehrson, 1997). (2) PM concentration and ER increase with bird activity; since hens are more active during the day (light hours) than at night (dark hours), PM concentration and ER is generally higher during the day than at night (Lim et al., 2003). (3) ER during winter is generally lower than during summer (Wathes et al., 1997). (4) Perchery systems usually have higher PM concentration and ER than cage systems (Takai et al., 1998; Wathes et al., 1997). (5) PM emission from house sources is greater when manure is stored in-house (e.g., high-rise houses) than when using moving belts (Fabbri et al., 2007). (6) Certain daily operational and management events, such as house cleaning, feed conveying, and disturbance of birds caused by workers lead to much higher PM concentrations (Guarino et al., 1999).

Limited data on PM emissions from poultry houses have been reported in the literature, and there exist large differences among the reported values, possibly due to different measurement techniques, different production systems, and different manure management practices (Auvermann et al., 2006; Ellen et al., 2000). The reported studies generally involve short-period, intermittent measurements. Hence, the objectives of this study were: (1) to conduct a long-term assessment of PM concentrations and emissions of a commercial high-rise layer barn in central Iowa, and (2) to compare PM emission values of this study with the literature values.

**MATERIAL AND METHODS**

This study was conducted on a laying-hen farm in central Iowa. The original project involved three side-by-side identical high-rise layer houses (27.4 m W x 180.4 m L each), and each received a different diet (one control or standard diet and two experimental diets). The house with the control diet was monitored for PM concentrations and emissions. The east-west oriented high-rise houses had in-house manure storage. The house was equipped with 72 exhaust fans (1.2 m diameter) installed on the north and south sidewalls of the manure storage level. Evaporative pads were installed on the north roof and the pad served as the ventilation air inlet. Baffles on the ceiling were controlled automatically to regulate the barn static pressure (fig. 1).

The number of laying hens (Hy-Line W-36) housed in the barns was calculated by subtracting the daily mortality from the previous inventory number. The hen population varied from 248,814 at the onset of the monitoring (July 12, 2008) to 245,069 at the end of the monitoring (Dec. 31, 2009).

Two TEOM PM monitors (model 1400a, Rupprecht & Patashnick Co., Inc., Albany, N.Y.) were placed downstream of one of the minimum ventilation fans on the south sidewall and covered with a shelter (fig. 2). One TEOM monitor measured PM$_{10}$ concentration, while the other measured PM$_{2.5}$ concentration. They were 0.9 m and 2 m, respectively, from the discharge cone of the exhaust fan. The concentrations were reported under the standard conditions of temperature (0°C) and pressure (1 atm). A wooden shelter was built to protect the PM monitors from weather and to help direct the airflow. Each TEOM monitor consisted of a sensor unit, control unit, and sample head. Each TEOM monitor consisted of a sensor unit, control unit, and sample head. The size of PM being measured depends on the sample head being used. The sampling interval was set as 30 s, and the smoothing time was 300 s. The concentration data were logged using a LabVIEW data acquisition system developed by our research group. The filters in the sensor units were replaced and the sampling...
head were cleaned weekly. Due to the dust accumulation on the sampling head screen and the balance filter, the data of the first day following filter replacement and head cleaning were considered valid and used in the concentration and emission determination.

Four thermocouples were placed at four locations in the manure storage area to measure air temperatures, and the average of these was taken to represent the indoor air temperature. A relative humidity (RH) sensor (model HMW60U, Vaisala, Helsinki, Finland) was placed in the center of the house to measure RH. The air temperature and RH were taken at 5 min intervals. A barometric (model WE100, Global Water Instrumentation Inc., Gold River, Cal.) pressure sensor was used to measure the ambient atmospheric pressure, which was logged every 30 s.

The 72 ventilation fans were grouped into seven stages. Cumulative VR from low to high stages accounted for 21%, 41%, 56%, 73%, 88%, 98%, and 100% of the total ventilation capacity. Each stage of fans was temperature controlled. Their working status was monitored with two inductive current switches (Muhlbauer et al., 2011). A static differential pressure sensor was mounted on the supporting beams near both sidewalls, with the high-pressure terminal tubing extended to the outside of the building. Fan calibration was performed in situ using fan assessment numeration systems (FANS) units to develop VR vs. static pressure curves (Gates et al., 2004). These curves were used to calculate the building VR based on the working status of individual fans and static pressure of the building.

Instantaneous ER of PM was calculated using the following equation:

$$ER_{pm} = Q \cdot C_{pm} \cdot \frac{273.15}{t_i + 273.15} \cdot \frac{P}{101325} \cdot 10^{-3}$$

where $ER_{pm}$ is PM emission rate (mg s$^{-1}$), $Q$ is building ventilation rate (m$^3$ s$^{-1}$), $C_{pm}$ is concentration of PM ($\mu$g m$^{-3}$), $t_i$ is indoor air temperature ($^\circ$C), and $P$ is atmospheric pressure (Pa). Daily ER was calculated by integrating instantaneous $ER_{pm}$ over the day and dividing by the number of hens or animal units (1 animal unit or AU = 500 kg live body weight).
Seasonal patterns of VR, PM concentrations, and ER were examined by season-grouped data. Seasons are divided on the basis of spring (March to May), summer (June to August), fall (September to November), and winter (December to February).

To test the effects of indoor air temperature, RH and VR on ER, linear multivariate regressions were run on hourly ER of PM$_{10}$ and PM$_{2.5}$ against hourly VR, indoor air temperature, and RH using the GLM procedure of SAS (SAS, 2008). Season was set as class variable. Significance of the factors was checked using F tests. All possible combinations of the independent variables were examined. Those with p < 0.05 were regarded being significant.

**RESULTS AND DISCUSSION**

**ENVIRONMENTAL CONDITIONS**

Environmental conditions inside the barn, especially RH, are regarded as an important factor that affects PM generation (CIGR, 1994). Over the monitoring period, daily average air temperature in the manure storage area of the barn ranged from 12.4°C to 26.6°C with an overall mean of 21.6°C. The corresponding daily average RH ranged from 39% to 71% with an overall mean of 55%. The average temperature and RH along with the variation are shown in figure 3.

**PM CONCENTRATIONS**

Daily mean and standard deviation (SD) of PM$_{10}$ and PM$_{2.5}$ concentrations are shown in figure 4. PM$_{10}$ concentration ranged from 90 to 1387 μg m$^{-3}$ with an overall mean of 393 μg m$^{-3}$ and SD of 257 mg m$^{-3}$. PM$_{2.5}$ concentration ranged from 11 to 168 mg m$^{-3}$ with an overall mean of 44 mg m$^{-3}$ and SD of 36 mg m$^{-3}$. It can be seen that concentrations of PM$_{10}$ and PM$_{2.5}$ varied greatly with seasons. Presented in figure 5 are the corresponding VR, whose mean had an inverse pattern relative to the mean PM concentrations.

Diurnal patterns of PM$_{10}$ and PM$_{2.5}$ concentrations on a selected day (March 5, 2009) are presented in figure 6. It can be seen that the concentrations were higher during the day or light period (4:00 to 20:00 h) than during the night or dark period (20:00 to 4:00 h). Several spikes of PM concentration occurred throughout the day, at 3:00, 8:45, and 13:45 h, which corresponded to the times of feeding, manure scraping, and housing cleaning.

It is worth mentioning that despite the advantages (e.g., continuous measurement) of the TEOM technique, this method may underestimate PM concentration, possibly due to sampling efficiency and loss of some semivolatile substances during the heating process. Sampling efficiency of TEOM inlets is believed to be related to mass median diameter of the air sampled, according to Wang et al. (2003) and Wanjura et al. (2008). Nevertheless, at the present time, TEOM seems the best available option to provide real-time, dynamic quantification of concentrations that, when combined with the dynamic VR data, lead to the determination of dynamic and daily PM emissions.

**EMISSION RATE (ER) OF PM**

ERs of PM$_{10}$ and PM$_{2.5}$ from July 12, 2008 to December 31, 2009 (one daily ER data point per week) are
shown in figure 7. PM$_{10}$ ER ranged from 1.9 to 89.1 mg bird$^{-1}$ d$^{-1}$, averaging 26.1 mg bird$^{-1}$ d$^{-1}$ with a SD of 15.8 mg bird$^{-1}$ d$^{-1}$, which is equivalent to an average of 8.16 g AU$^{-1}$ d$^{-1}$ with a SD of 4.94 g AU$^{-1}$ d$^{-1}$. PM$_{2.5}$ ER ranged from 0.4 to 16.3 mg bird$^{-1}$ d$^{-1}$, averaging 3.6 mg bird$^{-1}$ d$^{-1}$ with a SD of 3.7 mg bird$^{-1}$ d$^{-1}$, which is equivalent to an average of 1.13 g AU$^{-1}$ d$^{-1}$ with a SD of 1.16 g AU$^{-1}$ d$^{-1}$.

As shown in figure 7, from July 2009 when the old flock was replaced with a new flock, there were remarkable increases in ER of PM$_{10}$ and PM$_{2.5}$ compared with the same period of 2008. It was observed that young hens were more active and sensitive to disturbance and hence tended to produce more dust than old hens. Diurnal patterns of PM$_{10}$ and PM$_{2.5}$ ER on a selected day (March 5, 2009) are pre-
Figure 8. Diurnal patterns of PM$_{10}$ and PM$_{2.5}$ emission rates of the high-rise layer barn on a typical day.

The patterns of ER were similar to those of concentration, where ER during light hours was higher than that during dark hours.

Results of multivariate regressions relating ERs of PM$_{10}$ and PM$_{2.5}$ to VR, indoor air temperature, and RH suggest that VR was the dominant factor affecting ER, with higher VR leading to higher ER. RH was negatively correlated with ER, indicating that a humid environment tended to suppress dust generation. Air temperature was shown to be insignificant (p > 0.05). This can be attributed to two possible reasons. One is that the inside air temperature was kept within a narrow range; hence, its effects were not manifested. The other is that the effect of air temperature was overshadowed by VR and RH.

VR, PM concentrations, and ERs of PM$_{10}$ and PM$_{2.5}$ exhibited seasonal variations, as presented in table 1. ERs were highest during summer, followed by fall, spring, and winter. The order of ER magnitudes matches that of VR, i.e., the higher VR, the higher ER. This outcome seems reasonable considering that the greater airflow in summer tends to disturb and carry away more dust than in winter, when ventilation was kept to minimal and indoor air was relatively stagnant and humid.

Ambient PM concentrations are normally much lower than those in laying-hen facilities. To assess the effects of ambient PM concentration on the net emission rates, the data for the nearest EPA monitoring site, Des Moines, Iowa (EPA, 2009), were utilized, where the annual mean concentration of PM$_{10}$ and PM$_{2.5}$ for 2008 was 21 and 9.6 μg m$^{-3}$, respectively. The net ER of PM$_{10}$ and PM$_{2.5}$ became 25.0 and 3.0 mg bird$^{-1}$ day$^{-1}$, respectively, when accounting for the ambient PM concentrations, as compared to 26.1 and 3.6 mg bird$^{-1}$ day$^{-1}$, respectively. The difference was 4% for PM$_{10}$ ER and 17% for PM$_{2.5}$ ER. However, considering that the farm monitored in this study was approximately 64 km (40 mi) from the EPA monitoring site and was located in a rural area, the real ambient PM concentrations at the monitoring farm should be less than the EPA values, and their effects on the net ER presumably were quite minor and negligible.

### COMPARISON WITH LITERATURE VALUES

Table 2 lists the experimental conditions and measurements of some previous studies on PM emissions and concentrations in laying-hen houses. The experimental conditions include study location, production systems, bird age and weight ranges, manure removal interval, and ventilation system. Measurements included VR, PM concentration, measurement duration or period, and frequency. The most common hen houses were cage systems, while perchery systems were used in three studies. No reported studies were found on free-range systems. Mechanical ventilation systems were used in almost all the studies, presumably due to the fact that building VR could be determined with relative ease, as compared to natural ventilation systems. As for PM concentration measurement, gravimetric filter was the most common technique used in the early studies, while TEOM has been increasingly used in recent studies, which makes continuous measurement possible and less onerous.

Table 3 lists the reported values for PM concentrations and emissions of laying-hen houses. Total suspended particulate (TSP) concentration ranged from 0.75 to 8.78 mg m$^{-3}$. PM$_{10}$ concentration ranged from 0.03 to 2.2 mg m$^{-3}$. PM concentration is inversely related to VR for a constant ER. Since both ER and VR are affected by various factors and they tend to change constantly, it is not surprising to see such wide ranges of PM concentrations.

ER of TSP ranged from 14 to 74 g AU$^{-1}$ d$^{-1}$. The highest ER of TSP (74 g AU$^{-1}$ d$^{-1}$) was reported for a perchery system (Takai et al., 1998). On a per bird basis, the ERs of TSP were 168 and 300 mg bird$^{-1}$ d$^{-1}$ for the two perchery systems. The ER for cage systems ranged from 44 to 147 mg bird$^{-1}$ d$^{-1}$. For PM$_{10}$ the ER range was 2.20 to 16.59 g AU$^{-1}$ d$^{-1}$. On a per bird basis, those ER values translate into 9 to 66 mg bird$^{-1}$ d$^{-1}$.

Excluding perchery systems, PM$_{10}$ ERs from the two European studies (Takai et al., 1998; Wathes et al., 1997) were lower than the rest of the studies, probably because the measurements were taken in different barns for a short period (2 d); therefore, the values would not have reflected the

Table 1. Seasonal ventilation rate (VR), PM concentrations, and emission rates of the high-rise layer house (SD in parentheses).

<table>
<thead>
<tr>
<th>Season</th>
<th>VR (m$^3$ s$^{-1}$ barn$^{-1}$)</th>
<th>Concentrations (μg m$^{-3}$)</th>
<th>Emission Rate (mg bird$^{-1}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PM$_{10}$</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Spring</td>
<td>189 (104)</td>
<td>328 (129)</td>
<td>23 (11)</td>
</tr>
<tr>
<td>Summer</td>
<td>458 (119)</td>
<td>236 (163)</td>
<td>46 (40)</td>
</tr>
<tr>
<td>Fall</td>
<td>200 (140)</td>
<td>483 (319)</td>
<td>60 (43)</td>
</tr>
<tr>
<td>Winter</td>
<td>87 (25)</td>
<td>503 (227)</td>
<td>39 (18)</td>
</tr>
</tbody>
</table>
Table 2. Production and measurement conditions of studies on PM concentrations and emissions in laying-hen houses.[a]

<table>
<thead>
<tr>
<th>Study</th>
<th>Reference</th>
<th>Location</th>
<th>Production System</th>
<th>Bird Age and Weight Range</th>
<th>Vent. Mode</th>
<th>Manure Removal Freq.</th>
<th>PM Mea.</th>
<th>Ventilation Measurement</th>
<th>Measurement Duration</th>
<th>Measurement Frequency[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Takai et al. (1998)[c]</td>
<td>Northern Europe</td>
<td>Perchery</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>GF</td>
<td>Tracer gas</td>
<td>2 d</td>
<td>Intermittent (note 1)</td>
</tr>
<tr>
<td>2</td>
<td>Takai et al. (1998)[c]</td>
<td>Northern Europe</td>
<td>Caged</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>GF</td>
<td>Tracer gas</td>
<td>2 d</td>
<td>Intermittent (note 2)</td>
</tr>
<tr>
<td>3</td>
<td>Wathes et al. (1997)[c]</td>
<td>U.K.</td>
<td>Perchery</td>
<td>20-69 wk, 1.82-2.3 kg</td>
<td>MV</td>
<td>--</td>
<td>GF</td>
<td>Tracer gas</td>
<td>2 d</td>
<td>Intermittent (note 3)</td>
</tr>
<tr>
<td>4</td>
<td>Wathes et al. (1997)[c]</td>
<td>U.K.</td>
<td>Caged</td>
<td>18-69 wk, 1.94-2.18 kg</td>
<td>MV</td>
<td>--</td>
<td>GF</td>
<td>Tracer gas</td>
<td>2 d</td>
<td>Intermittent (note 3)</td>
</tr>
<tr>
<td>5</td>
<td>Fabbri et al. (2007)</td>
<td>Italy</td>
<td>Caged</td>
<td>--</td>
<td>MV</td>
<td>2 years</td>
<td>GF and optical</td>
<td>Fan status / RPM sensor</td>
<td>1 year</td>
<td>Continuous</td>
</tr>
<tr>
<td>6</td>
<td>Fabbri et al. (2007)</td>
<td>Italy</td>
<td>Caged</td>
<td>--</td>
<td>MV</td>
<td>3-4 d</td>
<td>GF and optical</td>
<td>Fan status / RPM sensor</td>
<td>1 year</td>
<td>Continuous</td>
</tr>
<tr>
<td>7</td>
<td>Qi et al. (1992)[c]</td>
<td>Pennsylvania</td>
<td>Caged</td>
<td>217 d</td>
<td>MV</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>10 mo (June-Mar.)</td>
<td>Intermittent (note 4)</td>
</tr>
<tr>
<td>8</td>
<td>Lim et al. (2007)</td>
<td>Ohio</td>
<td>Caged</td>
<td>1.65 kg</td>
<td>MV</td>
<td>1 year</td>
<td>TEOM</td>
<td>Fan status</td>
<td>10 mo (Apr.-Jan.)</td>
<td>Continuous</td>
</tr>
<tr>
<td>11</td>
<td>Guarino et al. (1999)[c]</td>
<td>Italy</td>
<td>Caged</td>
<td>34-42 wk</td>
<td>MV</td>
<td>--</td>
<td>GF</td>
<td>--</td>
<td>3 mo (Apr-June)</td>
<td>Intermittent (note 6)</td>
</tr>
<tr>
<td>12</td>
<td>Davis and Morishita (2005)</td>
<td>Ohio</td>
<td>Caged</td>
<td>--</td>
<td>MV</td>
<td>--</td>
<td>Optical</td>
<td>--</td>
<td>9 wk</td>
<td>Intermittent (note 7)</td>
</tr>
<tr>
<td>13</td>
<td>Vucemilo et al. (2007)</td>
<td>Croatia</td>
<td>Caged</td>
<td>--</td>
<td>MV</td>
<td>--</td>
<td>GF</td>
<td>--</td>
<td>Winter</td>
<td>Intermittent (note 8)</td>
</tr>
<tr>
<td>14</td>
<td>This study (2011)</td>
<td>Iowa</td>
<td>Caged</td>
<td>50-90 wk</td>
<td>MV</td>
<td>1 year</td>
<td>TEOM</td>
<td>Calibrated fan running status</td>
<td>17 mo</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

[a] GF = gravimetric filtration, TEOM = tapered element oscillating microbalance, MV = mechanical ventilation, and NV = natural ventilation.

[b] The following notes apply: 1 = 22 buildings surveyed, each measured over a summer day and winter day; 2 = 26 buildings surveyed, each measured over a summer day and winter day; 3 = four buildings surveyed, each measured over a summer day and a winter day; 4 = measured one day per week; 5 = measured three to four times a day; 6 = measured three times a day, five days each week, one week each month; 7 = measured once a week; and 8 = measured 15 times a day.

[c] Inhalable and respirable fractions of PM were reported.

Table 3. Particulate matter emissions and concentrations of laying-hen houses.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Emission Rate</th>
<th>Concentration (mg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TSP (g AU⁻¹ d⁻¹)</td>
<td>TSP (mg bird⁻¹ d⁻¹)</td>
</tr>
<tr>
<td>1[a][b]</td>
<td>Northern Europe</td>
<td>74</td>
<td>300</td>
</tr>
<tr>
<td>2[b]</td>
<td>Northern Europe</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>3[a][b]</td>
<td>U.K.</td>
<td>44</td>
<td>168</td>
</tr>
<tr>
<td>4[b]</td>
<td>U.K.</td>
<td>22</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>Italy</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>Italy</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>Pennsylvania</td>
<td>14[c]</td>
<td>44</td>
</tr>
<tr>
<td>8</td>
<td>Ohio</td>
<td>44.5</td>
<td>147</td>
</tr>
<tr>
<td>9</td>
<td>Sweden</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>10[d]</td>
<td>Sweden</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>11[b]</td>
<td>Italy</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>Ohio</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>Croatia</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>Iowa</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

[a] Perchery systems.

[b] Inhalable PM regarded equivalent to TSP. Values of respirable PM corrected to PM₁₀ based on the PM mass distribution by Roumeliotis and Van Heyst (2007).

[c] Bird weight assumed to be 1.6 kg.

[d] Average of PM emission from two houses.
annual mean ER. With the two European values excluded, PM$_{10}$ ER averaged 31.5 mg bird$^{-1}$ d$^{-1}$ (9.56 g AU$^{-1}$ d$^{-1}$). The ERs of PM$_{2.5}$ from previous studies were 14.20 mg bird$^{-1}$ d$^{-1}$ (Farribi et al., 2007) for barns with in-house manure storage and 6.20 mg bird$^{-1}$ d$^{-1}$ for barns with manure belt systems (Farribi et al., 2007). The current study resulted in PM$_{2.5}$ ER of 3.6 mg bird$^{-1}$ d$^{-1}$.

From the results presented above, it can be said that ER of laying hen houses is dependent on housing system (perchery or cage), climate (affecting VR), and manure management (long term in-house storage or rapid cleaning with manure belt). The current study provided additional, year-round measurement data on concentrations and ER of PM$_{10}$ and PM$_{2.5}$ for high-rise laying-hen houses with in-house manure storage, which represents the majority of existing laying-hen houses in the U.S. The information generated will contribute to the national inventory on PM emissions from animal feeding operations. The information will also provide comparative data for environmental assessment of alternative hen housing systems and management practices.

**CONCLUSIONS**

Concentrations and emission rates of particulate matter (PM$_{10}$ and PM$_{2.5}$) for a commercial high-rise laying-hen house in central Iowa were continually monitored for 17 consecutive months (one full day per week). PM concentrations were measured using tapered element oscillating microbalance (TEOM) PM monitors. Ventilation rate of the barn was determined by continuously monitoring the runtime of *in situ* calibrated ventilation fans. Average concentrations of PM$_{10}$ and PM$_{2.5}$ over the measurement period were 393 and 44 µg m$^{-3}$, respectively. The concomitant average PM$_{10}$ and PM$_{2.5}$ emission rates were, respectively, 26.1 (±15.8 SD) and 3.6 (±3.7 SD) mg bird$^{-1}$ d$^{-1}$, or 8.16 (±4.94) and 1.13 (±1.16) g AU$^{-1}$ d$^{-1}$. Emission rates of PM$_{10}$ and PM$_{2.5}$ increased with ventilation rate and decreased with relative humidity. PM concentrations and emission rate varied remarkably during a diurnal cycle and with season, which justifies full-day continuous, long-term monitoring to increase the representativeness of the measurement. PM concentrations and emission rate were higher in the light hours than in dark hours.

The literature values for PM$_{10}$ emission rate ranged from 9 to 66 mg bird$^{-1}$ d$^{-1}$ (2.20 to 16.59 g AU$^{-1}$ d$^{-1}$), as compared to 26.1 mg bird$^{-1}$ d$^{-1}$ (8.16 g AU$^{-1}$ d$^{-1}$) in the current study. PM$_{2.5}$ emission rates of previous study ranged from 6.2 to 14.2 mg bird$^{-1}$ d$^{-1}$ (1.45 to 4.73 g AU$^{-1}$ d$^{-1}$), as compared to 3.6 mg bird$^{-1}$ d$^{-1}$ (1.13 g AU$^{-1}$ d$^{-1}$) in the current study.

**ACKNOWLEDGEMENTS**

Collaboration and generous support demonstrated by the cooperative farm throughout the study are acknowledged. Financial support for this study was provided in part by a USDA-NRCS Conservation Innovation Grant (Award NRCS 69-3A75-7-91).

**REFERENCES**


