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Spatial and Diurnal Variations of Particulate Matter Concentration of a Pilot-Scale Aviary Layer House in Winter

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ABSTRACT. *Laying hen production plays an important role in particulate matter (PM) emissions which potentially cause air pollution and adverse health effect on animals and workers. Aviary cage-free (CF) egg production systems have been attracting increasing attention due to concerns over animal welfare and increased market demand. While studies have been conducted to characterize PM concentrations and emissions of aviary CF houses with litter floor, few reports are available of this information for aviary CF layer houses equipped with slat floor. In this study, PM concentrations – both spatial and diurnal patters inside a pilot-scale aviary CF layer house (1,800 laying hens, L×W×H of 28.2 × 9.0 × 3.0 m) in northern China were measured under winter conditions. Daily mean $PM_{2.5}$, PM_{10}, and TSP levels were found to be 0.19±0.11, 1.05±0.65, 2.90±2.07 mg/m^3, respectively, which were considerably lower than those reported in previous studies of aviary CF houses with litter floor in cold weather. Daytime PM concentrations were significantly higher than those at night primarily due to differences in animal activity and feed supply. The average PM_{10} and TSP concentrations during light period (5:00-21:00 h) were 1.34 mg/m^3 and 3.75 mg/m^3, amounting to 279% and 304% of those during the dark period (21:00-5:00h), respectively. Spatial variations for PM_{10} and TSP were observed in the experimental hen house due to non-uniform distribution of ventilation air and localized generation of the constituents. Higher TSP concentrations (4.26 mg/m^3) were found at worker respiratory level (2.0 m) as compared to floor level (0.5 m, 3.00 mg/m^3). TSP concentration at one end of the house (west) was found to be 28.3% and 86.9% higher than the middle and the opposite (east) end. This spatial variation characteristic points out the importance of multi-location sampling when assessing indoor air quality and aerial emissions (for cross ventilation). Data from this study will be useful for future improvement of the housing ventilation design and operation. Future study should also assess PM concentrations of the housing style under warm seasons.*

Keywords. *Air quality; aviary cage-free hen housing; PM concentration; worker health;*

Introduction

Concerns have been rising about production housing systems in connection with animal welfare. Conventional cages (CC), the dominant model for egg production since the 1950s, were banned in the European Union effective 2012. In other developed countries, pressure from animal welfare non-governmental organizations or other food system stakeholders (e.g., retailers) is similarly resulting in a large-scale move-away from CC toward other systems (Mench and Rodenburg, 2018). There are also growing pledges of shifting toward cage-free (CF) eggs in the United States (Xin, 2016). Alternative CF housing systems feature a larger living space and amenities to better accommodate hens' natural behaviors, where cages are replaced with shelf-like platforms at various heights, with birds living at every level. A significant proportion of the floor in an aviary CF system is covered with litter for birds to dustbathe and forage in. High perches are also provided for hens to roost on at night (Zhao et al., 2015).

However, environmental challenges posed in single- or multi-level aviary CF housing systems remain to be addressed, such as much higher concentrations and emissions of ammonia (NH_3), particulate matters ($PM_{2.5}$, PM_{10}), and airborne bacteria than manure-belt cage or enriched colony houses that have been shown in studies (Green et al., 2009; Hayes et al., 2012; Zhao et al., 2015; Shepherd et al., 2015; Zhao et al., 2016). PM levels and emissions of CF houses were found to be 6-8 times higher than those in CC or enriched colony houses (Xin, 2016), which arises from accumulation of manure on the floor and activities of the hens (scratching, dustbathing, wing-flapping, etc.) on the litter floor.

A modified aviary system (MAS) for housing CF laying hens was developed to significantly mitigate the environmental risks of PM and NH_3 generation while attempting to accommodate natural behaviors of the hens in a CF setting (Zheng et al., 2015). The MAS had no litter area; instead it was equipped with a slat floor that allowed the manure to fall through and be collected on a manure belt below. To assess the efficacy of the new system design on the indoor air quality, the objectives of this study were to (1) quantify airborne PM concentrations and size distributions in an experimental henhouse in winter (when air quality tends to be the worst), and (2) delineate diurnal and spatial variations of PM concentrations in the layer house under winter ventilation conditions.

Material and Methods

Housing System and Animals

This study of quantifying PM and ammonia concentrations was conducted in an experimental pilot-scale modified aviary system (MAS), measuring 28.2 × 9.0 ×3.5 m (L × W × H) and oriented west to east, in Beijing, China. A total of 1800 Jingfen Brown layers were reared in the experimental henhouse and they were transferred from conventional cages at 13 weeks of age. The house had two rows (the row on the south side of the house comprised a half side structure of the MAS and slat floor) and each row was divided by wire-mesh into 3 pens along the length of the house (fig. 1). Each pen measured 6.0 × 3.0 × 2.6 m (L × W × H) and comprised two tiers of nest boxes (upper tier and lower tier), stair-step perches, plastic slat floor and two elevated platforms for feeding, drinking, and other activities. A schematic view of the experimental henhouse is shown in Figure 2, and a more detailed description of the MAS developed by China Agricultural University can be found in (Zheng et al., 2015). The resource allowance for hens in the housing system is presented in Table 1. Hens were kept in the system with no litter area provided, and a manure belt placed under the plastic slat floor of the entire length of the system was used to remove the accumulated manure from the house every 2 days. Feed was provided twice per day at 08:00 h and again 14:00 h. The feed was formulated using a commercial source for the housing system based on egg production level, feed consumption, and ingredient costs. Drinking water was available all the time in the house. The photoperiod was 16-h light and 8-h dark, with lights on at 05:00 h and off at 21:00 h. The caretakers performed daily routine tasks of checking laying hen health, removing mortalities, collecting system eggs (eggs laid in system structure but outside the nest box), and equipment operation of water lines, feed lines, lights, egg belts, manure belts, and ventilation equipment. Fresh air entered the house from continuous eave inlets and their openings were controlled by static pressure. Two 0.61m (24") exhaust fans were installed in the west end wall. The minimum ventilation rate (VR) was 0.3 $m^3 h^{-1} hen^{-1}$ and the maximum VR was 7.5 $m^3 h^{-1} hen^{-1}$. The fans operation was controlled based on the indoor temperature and its setpoint.

Sampling Devices and Protocols

Size-segregated PM mass concentrations, including PM1, $PM_{2.5}$, PM_4, PM_{10} and total suspended particulate (TSP) were measured with an optical PM monitor DustTrak DRX (Model 8533, TSI, Inc., Shoreview, MN). The DustTrak DRX measured mass concentrations using a photometric method combined with single particle detection signal pulsing for size segregation. Additionally, ambient and indoor temperature (T) and relative humidity (RH) were measured using Testo 175H1 temperature and RH data loggers (Testo SE & Co. KGaA, West Chester, PA). The DustTrak DRX was manufacture calibrated (multi-points) right before the experiment and zero calibrated every 3 days. Cleaning routines and filter change were followed according to the procedures and schedules in the operating manuals of the monitor.

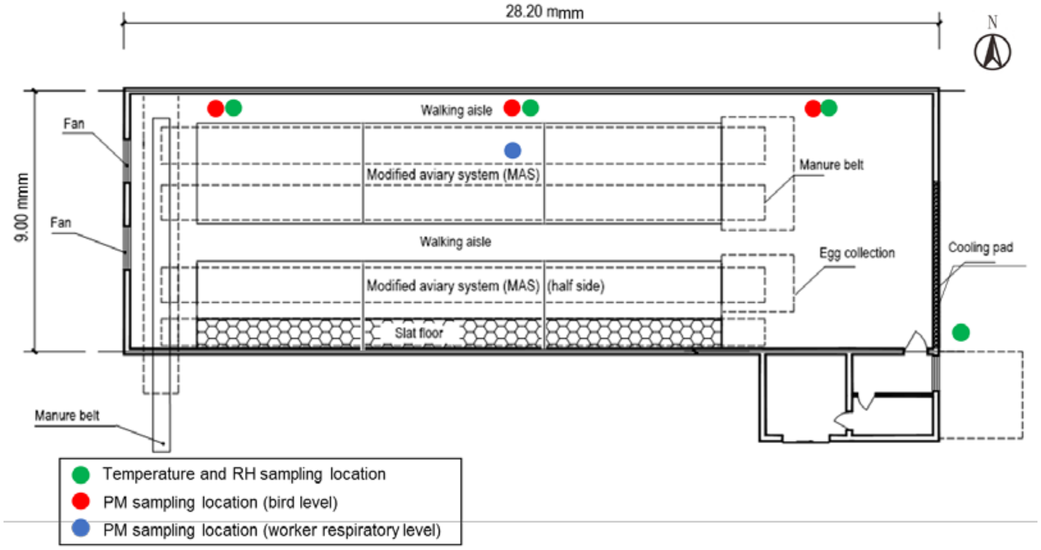


Figure 1. Schematic layout views of experimental MAS housing system and sampling locations for environmental monitoring.

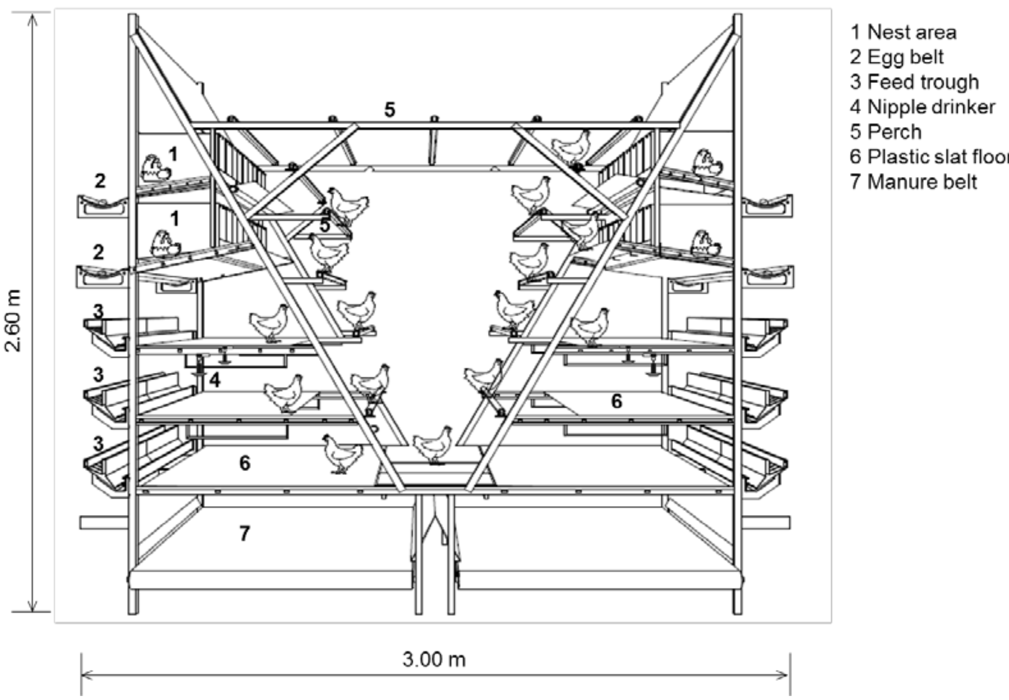


Figure 2. Schematic illustration of modified aviary system (MAS).

Figure 3. TSI monitor (a) at 2.0 m in the experimental modified aviary system (MAS) housing system (b).

Table 1. Resource allowances for hens in experimental aviary cage-free house.

Hens per colony unit (CU)	400 (per CU) *
Slat floor area (cm^2/hen)	986.6
Solid surface floor area (cm^2/hen)	-
Forage area (cm^2/hen)	-
Nest space (cm^2/hen)	96.0
Perch space (cm/hen)	23.0
Feeder space (cm/hen)	8.0
Nipple drinker (hens per drinker)	4.6

* The experimental MAS house had 2 colony rows and the house was partitioned into 3 pens along the length of the house with wire mesh.

Three PM concentration samples were taken at west, middle, and east locations of the house at a 0.5 m height (lower bird level in walking aisle), and one PM concentration sample were taken in the middle of the house at 2.0 m height (upper bird level), as shown in Figure 1 & Figure 3. The distances between west/middle/east sampling points and the west end wall of the house were 1.5, 14.0, 25.0 m, respectively. All the air samples were taken sequentially from four in-house locations. Environmental and indoor T and RH were measured at the same sampling locations as PM measurement locations. Measurements of PM concentrations, air temperature and RH were taken at 5-min intervals.

Statistical Analysis

The original experimental data were statistically analyzed using the JMP 14 (SAS Institute, Inc., Cary, NC). Analysis of variance (ANOVA) was used to analyze difference, and statistically significant difference was defined when the p-value was less than 0.05 ($p < 0.05$). Experimental data were expressed by mean ± standard deviation (SD).

Results and Discussion

Indoor Thermal Conditions

Air temperature (T) and RH of the house along with the ambient are shown in Figure 4. During the experiment, ventilation rate was maintained at about 0.3 m^3/h/hen. Ambient temperature varied from -8.9°C to 10.0°C, and RH varied from 16% to 82% (averaging 61%). The indoor temperature ranged from 13.0°C to 19.1°C (averaging 15.0°C), and RH varied from 22% to 100% (averaging 71%). High RH occurred when spray disinfecting the house.

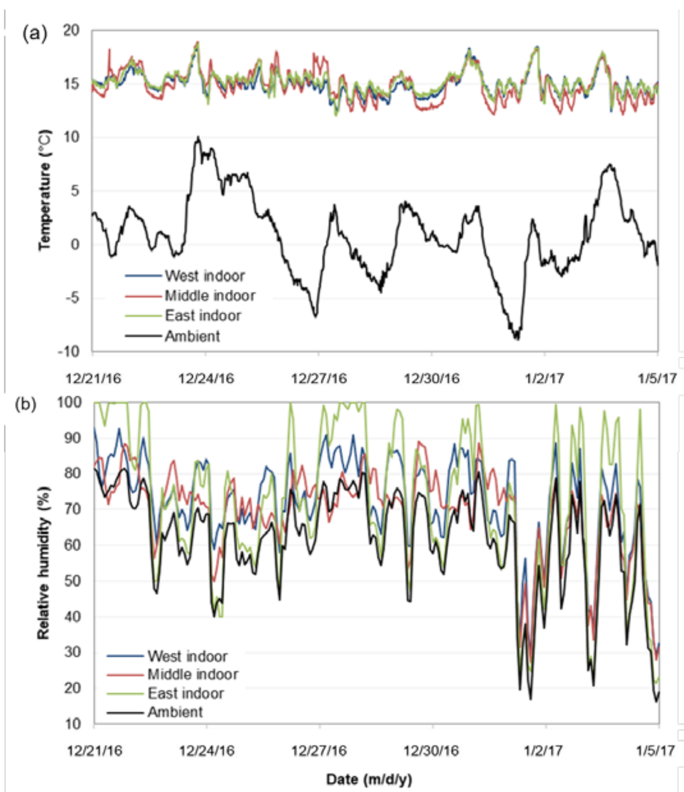


Figure 4. Ambient and indoor air temperature (a) and RH (b) during the experiment

PM Mass Concentrations and Diurnal Variations

During the sampling period (late December 2016), the overall PM concentrations ranged from 0.02 to 0.99, 0.14 to 3.42, and 0.34 to 12.80 mg/m^3 for $PM_{2.5}$, PM_{10}, and TSP, respectively. TSP concentrations averaged 2.90 mg/m^3, followed by PM_{10} at 1.05 mg/m^3 and $PM_{2.5}$ at 0.19 mg/m^3 over the sampling periods (Table 2). Based on review of previous PM monitoring in aviary laying-hen housing systems, the $PM_{2.5}$ and PM_{10} concentrations in the MAS house (no litter) from the current study were considerably lower than those reported for litter-based aviary CF houses (Table 3). As is known that PM levels are closely related to animal activities in livestock and poultry houses (Takai et al., 1998; Zhao et al., 2014). When floor bedding or litter is provided in housing systems (such as litter-based CF housing) to accommodate animal natural behaviors (e.g., dustbathing and foraging for laying hens), PM generation can be higher by a pronounced amount (Chai et al., 2018).

Table 2. Summary of particulate matter (PM) concentrations

Period of Day	$PM_{2.5}$ Mean ± SD (mg/m^3)	PM_{10} Mean ± SD (mg/m^3)	TSP Mean ± SD (mg/m^3)
Light period (5:00-21:00)	0.21±0.10	1.34±0.57	3.75±1.90
Dark period (21:00-5:00)	0.16±0.11	0.48±0.35	1.23±1.18
Daily mean concentration	0.19±0.11	1.05±0.65	2.90±2.07

Table 3. Comparison of this study and published data on particulate matter (PM) concentrations in aviary CF hen housing systems.

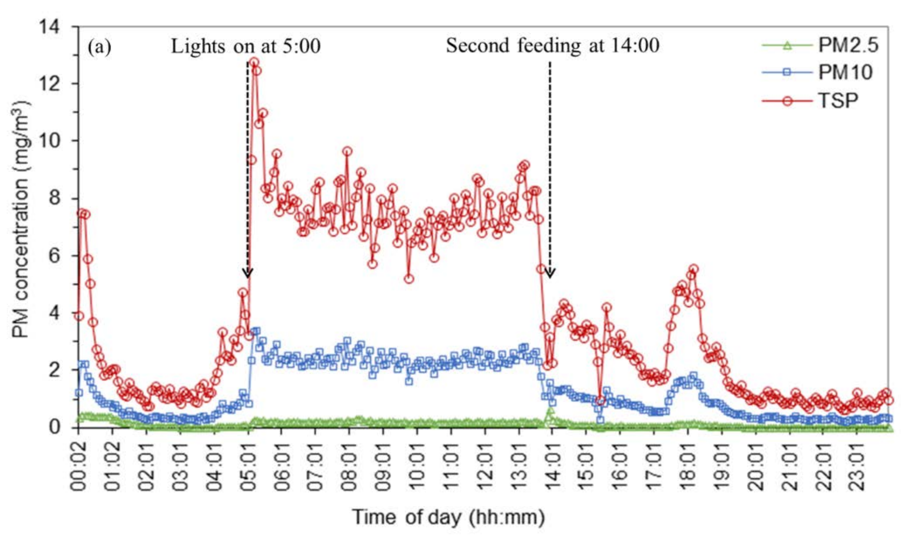
Daily mean ambient temperature range (°C)	$PM_{2.5}$ Mean ± SD (mg/m^3)	PM_{10} Mean ± SD (mg/m^3)	TSP Mean ± SD (mg/m^3)	Country/Region	Manure System*	Measurement Technique†	Number of days with valid data for $PM_{2.5}$/ PM_{10}/TSP‡	Reference
−10 to 0 0 to 10	0.76 ± 0.04 0.71 ± 0.12	7.38 ± 1.69 6.80 ±1.66	-	United States	MB and L	TEOM	63/87/-	(Zhao et al., 2015)
<7.2	0.40±0.26	3.35±1.60	-	United States	MB and L	TEOM	14/14/-	(Hayes et al., 2013)
-8.9 to 10.0	0.19±0.11	1.05±0.65	2.90±2.07	China	MB	DustTrak	15/15/15	This study

* MB = manure belt; L = litter.

† Manufacture information of PM measurement equipment: TEOM (Model 1400a, Thermo Fisher Scientific Inc., Waltham, MA), DustTrak DRX (Model 8533, TSI Inc., Shoreview, MN).

‡ Valid day must have 75% or greater of the continuously recorded dynamic data passing the quality assurance and quality control (QA/QC).

The PM levels within a day varied over time, especially during feeding and lights on/off time periods. Figure 5 shows a spike of PM_{10} and TSP concentrations at 05:00 h when lights were turned on in the henhouse and induced chicken activities. This was consistent with the results of previous study (Guarino et al., 1999) that the sudden variation of light intensity could induce strong stimuli. In addition, there were similar viewpoints reported by Kwon et al. (2016) in a nursery pig house who found the activity of animals and the feed supply contributed significantly to dust generation. The results mirrored those reported by Hayes et al. (2013) and Zhao et al. (2015) for litter-based aviary CF houses. The averaged TSP and PM_{10} concentrations during light period (05:00-21:00 h) were 3.75 mg/m^3 and 1.34 mg/m^3 amounting to 304% and 279% of those during the dark period (21:00-05:00 h), respectively (Table 2). PM concentrations returned to lower levels after the lights were turned off.



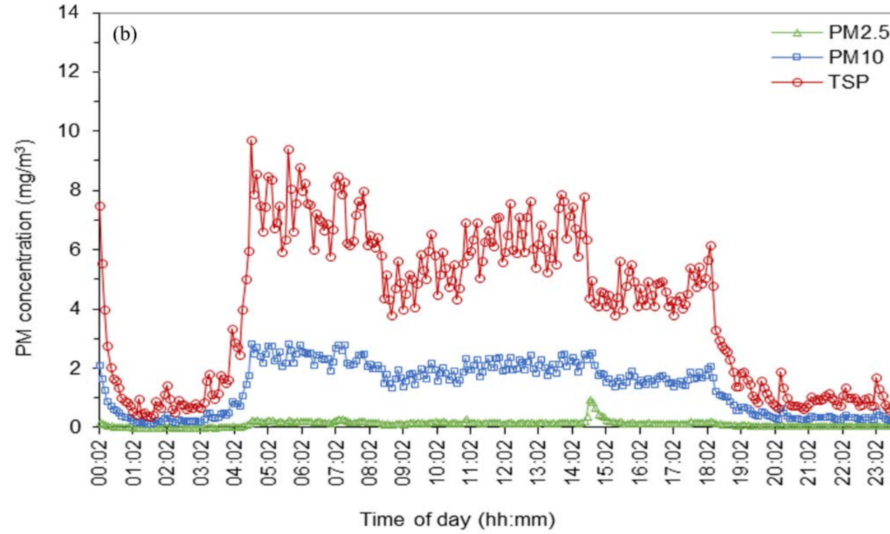


Figure 5. Diurnal particulate matter (PM) concentrations at (a) floor bird level (0.50 m) and (b) worker respiratory level (2.0m) in the experimental perforated-floor cage-free henhouse (Dec. 23, 2016).

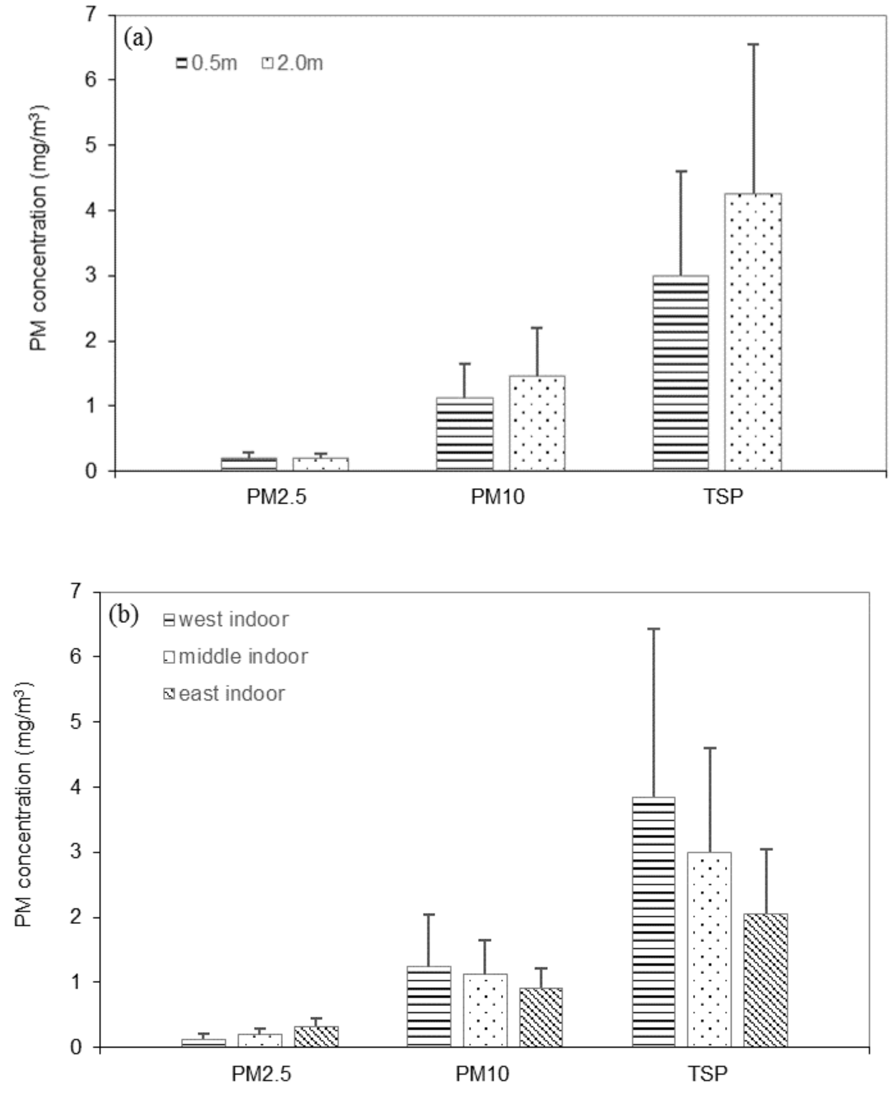


Figure 6. Comparison of particulate matter (PM) concentration at different height (a) and locations (b) in the experiment MAS layer house.

PM Spatial Variations

PM concentrations (mg/m^3) over the sampling periods averaged 3.00 for TSP, 1.12 for PM_{10}, and 0.20 for $PM_{2.5}$ at floor bird level (0.5 m height) and averaged 4.26, 1.46 and 0.19, respectively at worker's respiratory level (2.0 m height) (fig. 6). TSP concentrations were significantly higher ($p < 0.05$) in the upper locations of the experimental henhouse. In general, coarse particles (PM_{10}, TSP) readily settle when the chickens are quiet, while fine particles ($PM_{2.5}$) will stay in the air for a long time. The higher concentrations in the upper locations observed in the current study could have resulted from more perching and movement activities of the hens in the upper area – a natural tendency when given the choice (Brendler & Schrader, 2016; Campbell, Makagon, Swanson, & Siegford, 2016; Liu, Xin, Shepherd, & Zhao, 2018).

The mean TSP concentrations (mg/m^3) at the west end wall (near the exhaust fans), middle of the house, and the east end wall (near the cooling pad) were 3.85 (±2.57), 3.00 (±1.59), and 2.06 (±0.99), respectively. The corresponding mean PM_{10} concentrations (mg/m^3) were 1.24 (±0.80), 1.12 (±0.53), and 0.91 (±0.31), respectively. TSP concentration at the west (exhaust) end was 28.3% and 86.9% higher than the middle and the east end, respectively ($p<0.05$) (fig. 6). A probable reason for the longitudinal stratification presumably could be the cumulative effect of the PM as it traveled to the exhaust.

Sumary and Conclusions

A modified aviary system (MAS) for housing CF laying hens – featuring a perforated floor (*vs.* traditional litter floor) was evaluated for its thermal, ammonia and PM conditions – both spatial and temporal patterns during cold weather season. Based on 15-day continuous monitoring in winter, the following observations were made and conclusions drawn.

- Daily mean (±SD) $PM_{2.5}$, PM_{10}, and TSP levels were 0.19 (±0.11), 1.05 (±0.65), and 2.90 (2.07) mg/m^3, respectively, which were considerably lower than those reported in previous studies of litter-based aviary houses in cold weather.
- Daytime PM concentrations were significantly higher than at night due to hen activities and feeding. The averaged TSP and PM_{10} concentrations during light period (05:00-21:00 h) were 3.75 mg/m^3 and 1.34 mg/m^3, which was 304% and 279% of those during dark period (21:00-05:00 h), respectively.
- Spatial variations for the PM_{10} and TSP were observed in the experimental MAS henhouse due to differences in ventilation air distribution and localized generation of the constituents. TSP concentrations were found higher (4.26 mg/m^3) at worker respiratory level (2.0 m height) than at floor bird level (0.5 m height; 3.00 mg/m^3) were found. TSP concentration at the exhaust end of the experimental henhouse was 28.3% and 86.9% higher than those at the middle and the opposite end. This characteristic points out the importance of multi-location sampling when assessing indoor air quality.
- Data from this study provide useful insight for improving the MAS ventilation design and operation. While winter represents the most air quality and ventilation distribution challenges, similar assessment of the MAS performance should be conducted under different weather conditions.

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