

Seasonal variations and spatial distribution of particulate matter emissions from a ventilated laying hen house in Northeast China

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Abstract: With the development of concentrated animal feeding operations in China, the air pollution problem has drawn widespread public attention. Residents living near farms are suffering from the emissions of particulate matter (PM) and odors. However, scientific data on the characteristics of these emissions are limited to the establishment and evaluation of mitigation strategies in China. This study was conducted to provide fundamental information on the concentrations of PM inside and outside a typical ventilated laying hen house in northeastern China. The results showed that outdoor PM concentrations of this laying hen house did not meet the requirements of the environmental quality standard of China's livestock and poultry farms in the two days out of six sampling days in summer, while indoor PM concentrations met the environmental requirements during this study. The indoor and outdoor PM concentrations were highly correlated in summer, and over 60% of particles indoor were emitted outside via mechanical ventilation. There were more fine particles dominated both inside and outside of the laying hen house. Besides, twelve and nine elements were measured from the PM sources inside and outside laying hen house, respectively. PM control strategies may be adjusted based on the status of exhaust fans, the ages of laying hens, atmospheric conditions, and routine house management to well reduce PM emissions and improve control efficiency.

Keywords: particulate matter, ventilated laying hen house, air emission, animal feeding operation

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1 Introduction

The high concentration of particulate matter (PM) can affect environmental sustainability as well as human and animal health and well-being^[1]. Long-term exposure to air pollutants increased the risk of lung disease, mortality, and respiratory system or heart failure hospitalization^[2-5]. The air pollution emitted from livestock and poultry breeding industry contained high levels of particulate matter, endotoxin, toxic gases, and other microbial components^[6]. The PM concentration in livestock and poultry houses was 10-200 times higher than in other indoor environments^[6]. Carrying odorous compound, bacterial and virus, the PM from poultry houses may be dispersed to the environment and surrounding communities^[1,7]. Residents near poultry farms were more likely to develop pneumonia^[8]. Patients with chronic obstructive pulmonary disease were at increased risk of worsening the disease by exposure to the emissions from livestock farms^[9].

It was indicated that PM concentration in a poultry house was higher than that in pigsty and dairy farms^[10]. The average number of microbiota and gram-negative bacteria in domestic poultry houses was 2.5 times and 1.3 times higher than that in pig houses, respectively^[11]. Excessive PM affected the feeding, weight gain and production performance of chickens, led to various respiratory diseases^[12]. Moreover, higher PM concentration determined a higher concentration of endotoxin^[13]. Fine particles in poultry houses had long residence time and can be transported over long distances^[14]. Once inhaled, fine particles can be trapped in the respiratory system^[15]. Housing and climate conditions influenced the state of poultry by affecting the intake and utilization of food, which affected the PM concentrations in chicken coops^[16,17].

Currently, for the livestock and poultry industry, the data on PM emission sources, levels, sampling methods, simulation evaluation and estimation, and mitigation strategies are available mainly from developed countries. It cannot be directly used to reflect the status of PM emission from livestock and poultry in China since there are great differences in the farming systems between China and developed countries^[18]. Compared to developed countries, improving pollutant treatment facilities, environmental regulation of livestock and poultry houses is still demanded in China^[19]. Nevertheless, there are few detailed studies on seasonal variations and spatial distribution of PM from poultry houses in China, which may contribute to constructing strategies to control air pollution from poultry breeding. Especially in northeastern China, the production of livestock and poultry pollutants was significantly higher than that in other regions of China, and public attention on livestock and poultry environment is low^[20]. It is necessary to conduct experiments to investigate the current situation of livestock and poultry pollution

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and provide technical support for formulating policies, standards, and guidelines related to environmental protection.

In this study, PM inside and outside a ventilated laying hen house was sampled to investigate the influencing factors of PM emissions and their characteristics in spring and summer. These results will contribute to optimizing the management of poultry farming to reduce the adverse effects of PM on the growth and production of laying hens as well as the ambient environment.

2 Materials and methods

2.1 Experimental site

One typical ventilated poultry house, located in the suburban area of Changchun (43.9°N, 125.3°W), China, was selected as the experimental site for monitoring PM emissions. The poultry house was 53 m × 10 m × 4 m (length × width × height) and east-west oriented, equipped with four exhaust fans (Model DS-1380, Lanhao Ventilation and Cooling Equipment Company, Dongguan, with a diameter of 1.38 m) on the west sidewall with a spacing of 0.9 m between adjacent edges (Figure 1). Besides, it had windows on the north and south side. Fans and windows were regularly closed in winter and spring in order to keep the house warm. Only when the indoor temperature was above 25 °C, would the fans be turned on. In this study, these fans worked at all sampling times in summer and about 4 hours of each sampling day in spring. The house had also two wet curtains installed in the east-side wall in case the temperature was too high to reduce the heat stress of animals^[21]. There were 4 cages in the house, each of which had 3 layers equipped with an automatic feeder and a nipple drinking water dispenser. The laying hen dung was cleared with a mechanical scraper. Workers collected eggs at 8:30, and the feeding time was 10:00 and 16:00 in one day.

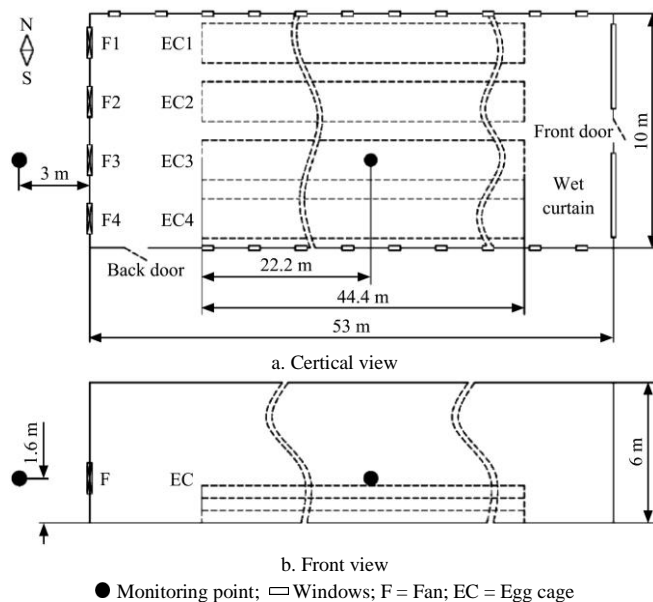


Figure 1 Schematic diagram of monitoring points inside and outside laying hen house (not to scale)

2.2 Field sampling

The field sampling was concentrated in two typical seasons of spring (3 d in 2016 and 4 d in 2017) and summer (6 d in 2016). In order to reduce the impact of the natural environment, the sampling campaign was chosen in the days with no rain and breezes. There were 8000 laying hens of Hy-Line Variety Brown with the age of 10-74 d in 2016, and 7800 with the age of 54-76 d in 2017. It was reported that the PM concentration inside the poultry house is higher in the daytime than that at night^[22]. Therefore, the

sampling time was set between 10:00 and 16:00 daily with potential high PM concentration. Particle concentration, ambient humidity and temperature were synchronously monitored at the same locations, as shown in Figure 1. In addition, to investigate the PM sources, dust particles accumulated on the ground of the house and the blades of ventilation fans were collected in summer for analyzing elements composition of PM.

Real-time particle concentrations were monitored using DustTruck™ DRX (Model 8533, TSI Incorporated, U.S.A.), which can simultaneously monitor size segregated mass fractions of PM_{2.5} and PM₁₀ (particulate matter with an aerodynamic diameter of 2.5 μm and 10 μm or less, respectively) as well as for TSP (total suspended particulate)^[23]. The sampling range is 0.001-150 mg/m³ with a ±0.1% resolution. Before each test, the instruments were regularly checked and calibrated with its zero filters^[24]. Moreover, AOSONG monitor (Model AH200, AOSONG, Guangzhou, China) was used to monitor ambient temperature (range: -40 °C-80 °C; resolution: ±3 °C at 25 °C) and relative humidity (RH) (range: 0-99.9%; resolution: ±2%). During each test, the sampling data was recorded per 1 min. In addition, two anemometers were originally set up with these two aerosol monitors to measure the wind speed. However, the data was not able to be collected because of the data logger malfunction during some of these sampling days. Therefore the rest of wind speed data was not reported in this study though it might be one of the major factors affecting PM emissions. Based on the estimation from the literature^[25-27] and our previous tests on-site, the wind speed from the fan should be around 3-6 m/s. The components of particles were analyzed by using an energy dispersive x-ray detector (EDX) (Model INCA, Oxford instrument, UK).

2.3 Data analysis

The daily average PM concentrations were reported with standard error (SE). Since PM ratios may reflect particle size distribution and provide an estimation of fine PM concentrations using available TSP or PM₁₀ data, the percentage of segregated PM (PM₁₀-TSP, PM_{2.5}-PM₁₀, and PM_{2.5}) in TSP were calculated and provided in this study, such as PM₁₀-TSP means the percentage of the concentration difference of TSP and PM₁₀ divided by the concentration of TSP, i.e. $(TSP - PM_{10}) \times 100 / TSP, \%$ ^[28,29]. The ratios of indoor to outdoor PM_{2.5}, PM₁₀ and TSP concentration were also given, which can reflect, to some extent, the amount of PM transmitted from the laying hen house. Statistical analysis on PM concentrations at two sampling points was calculated with a 1% level of significance based on *t*-Test (Paired Two Sample for Means). The matrices of correlation coefficients of indoor and outdoor PM concentrations, PM concentrations and temperature, PM concentrations and relative humidity were analyzed using SPSS (IBM, USA).

3 Results and discussion

3.1 Particle concentration

The daily mean concentration of indoor PM_{2.5} had a range of 0.067-0.609 mg/m³ with averages of 0.118±0.082 mg/m³ in spring 2016, 0.342±0.173 mg/m³ in summer 2016, and 0.289±0.174 mg/m³ in spring 2017. Indoor PM₁₀ concentration had a range of 0.118-1.145 mg/m³ with averages of 0.213±0.158 mg/m³ in spring 2016, 0.596±0.340 mg/m³ in summer 2016, and 0.534±0.242 mg/m³ in spring 2017. Indoor TSP concentration had a range of 0.168-1.585 mg/m³ with averages of 0.295±0.229 mg/m³ in spring 2016, 0.814±0.490 mg/m³ in summer 2016, and 0.819±0.383 mg/m³

in spring 2017, as shown in Figure 2a. It indicates that the indoor PM concentration during our sampling days met the requirements of the environmental quality standard of China’s livestock and poultry farms (EQSF, the number of laying hens raised at the site exceeds 5000), which requires PM₁₀ and TSP concentration inside the house area should be controlled to be less than 4 mg/m³ and 8 mg/m³, respectively^[30].

The daily mean concentration of outdoor PM_{2.5} had a range of 0.026-0.364 mg/m³ with averages of 0.041±0.020 mg/m³ in spring 2016, 0.205±0.098 mg/m³ in summer 2016, and 0.071±0.059 mg/m³ in spring 2017. Outdoor PM₁₀ concentration had a range of 0.038-0.720 mg/m³ with averages of 0.054±0.024 mg/m³ in spring 2016, 0.363±0.214 mg/m³ in summer 2016, and 0.079±0.060 mg/m³ in spring 2017. Outdoor TSP concentration had a range of 0.049-1.049 mg/m³ with averages of 0.070±0.029 mg/m³ in spring 2016, 0.518±0.322 mg/m³ in summer 2016, and 0.085±0.062 mg/m³ in spring 2017, as shown in Figure 2b. The results show that there were 4 d out of 6 d of sampling time in summer that the outdoor PM concentration met the requirements of EQSF, which requires PM₁₀ and TSP concentration in the buffer zone (within 500 m around the farm) should be controlled to be less than 0.5 mg/m³ and 1 mg/m³, respectively^[30].

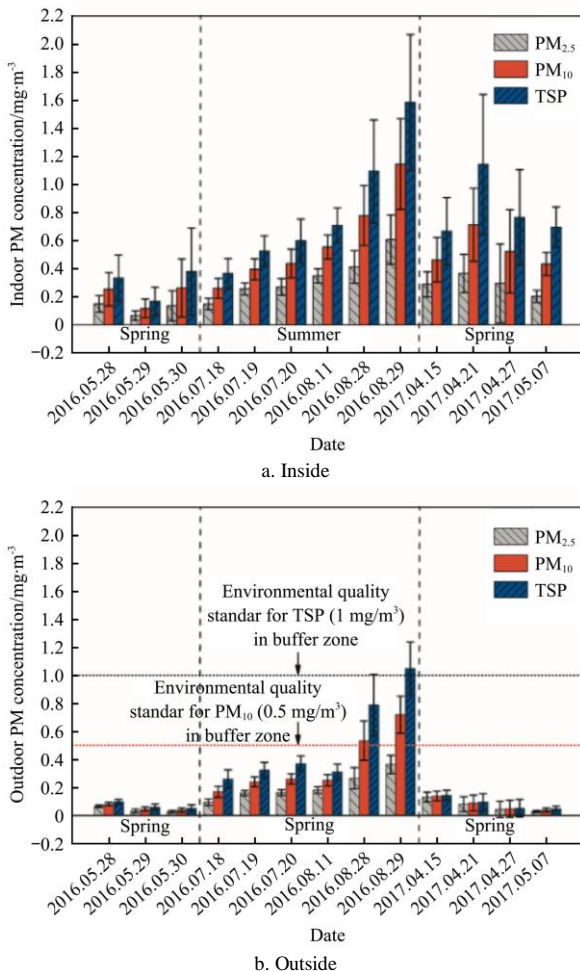


Figure 2 Concentrations of particles (a) inside and (b) outside the laying hen house

3.2 Correlation between indoor and outdoor particulate matter concentrations

From the matrix of correlation coefficient of indoor and outdoor PM concentrations in spring and summer (Table 1), it can be seen that all of the indoor and outdoor particle concentrations in summer were in good correlation ($p<0.01$), yet in spring were poor. This

should be caused by the ventilation fans, which exhausted PM suspended indoor to the outdoor atmosphere in summer. Another notable phenomenon observed was that the correlation between the concentration of outdoor PM_{2.5} and the concentration of indoor PM_{2.5} was the highest compared with others in spring, while the correlation between the concentration of outdoor PM_{2.5} and the concentration of indoor TSP was the highest compared with others in summer. It indicated that more fine particles can be emitted outside from the house and the ventilation fans brought more large particles to the outside from the laying hen house in summer. As expected, the closure of windows and exhaust fans significantly reduced the transportation of indoor particulates to outside.

Table 1 Correlation coefficients (r) between indoor and outdoor particulate matter concentrations.

	Outdoor PM in spring			Outdoor PM in summer		
	PM _{2.5}	PM ₁₀	TSP	PM _{2.5}	PM ₁₀	TSP
Indoor PM _{2.5}	0.545			0.979 ^a		
Indoor PM ₁₀	0.402	0.341		0.992 ^a	0.966 ^a	
Indoor TSP	0.351	0.290	0.182	0.994 ^a	0.980 ^a	0.962 ^a

Note: ^a Correlation was significant at the 0.01 level.

3.3 Ratio of outdoor to indoor particulate concentration

The ratios of outdoor PM_{2.5}, PM₁₀ and TSP concentration to the corresponding indoor PM, as listed in Table 2, can partly reflect the amount of particle emitted from the laying hen house to the ambient atmosphere. The larger the value is, the bigger the percentage of PM transmitted from the interior to the exterior. The results indicated that during summer sampling time, more than 60% of particles from the poultry house had been transported to the outside atmosphere, and quantities of coarse particles were larger in the PM emitted from the house. On the contrary, the ratios became very small, especially in spring 2017, and the outdoor TSP concentration was only 10% of indoor TSP concentration when all of the fans were closed. Moreover, relatively more fine particles emitted from the poultry house. These findings were consistent with the results of the above correlation analysis between the concentration of indoor and outdoor particles.

Table 2 Ratio of indoor particulate concentration to that of outdoor

	Outdoor /Indoor		
	PM _{2.5}	PM ₁₀	TSP
Spring, 2016	35%	25%	24%
Summer, 2016	60%	61%	64%
Spring, 2017	25%	15%	10%

3.4 Particle size distribution

Indoor and outdoor percentages of different sized PM in the TSP, presented in Figure 3, indicated that PM_{2.5} was relatively high in TSP both in spring and summer. The outdoor percentage of PM_{2.5}/TSP in spring was almost always greater than 50%. The highest percentage (90.5%) of PM_{2.5}/TSP occurred in spring 2017. These indicated that there were more fine particles dominated in and out of the laying hen house. Compared to indoor particle size distribution, the outdoor percentages of different sized PM in the TSP had greater variation. In the last two sampling days of summer 2016, the ratio of PM_{2.5}/TSP decreased. This may be caused by high PM concentration during these two days and more large-diameter particles were exhaled by the fans. However, fine particles had very high percentages in spring. This may be attributed to less coarse particles emitted from the house.

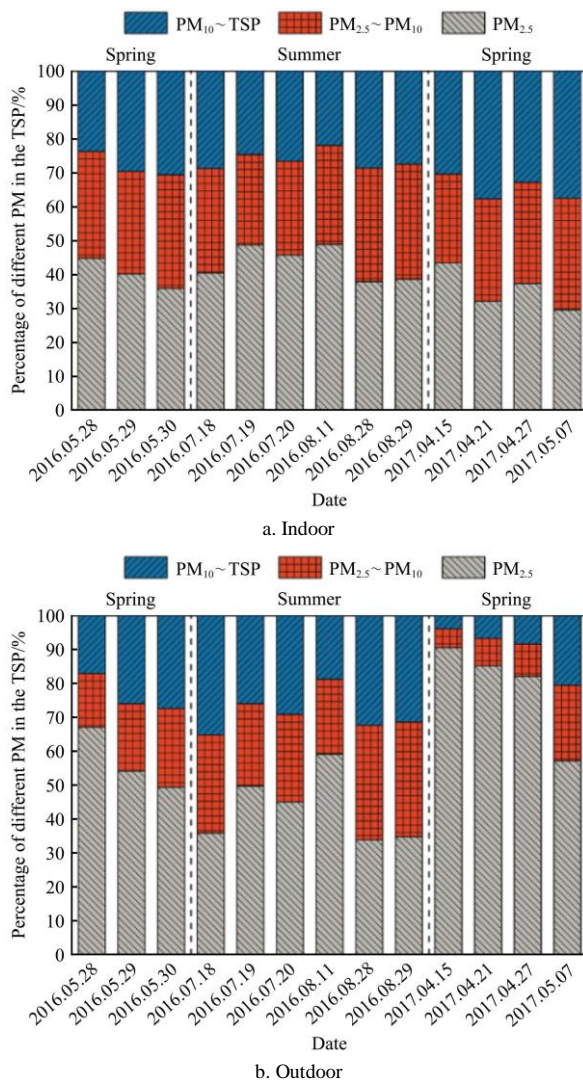


Figure 3 Percentages of different PM in the TSP: (a) indoor, and (b) outdoor

3.5 Particle composition

The data from EDX tests, as shown in Table 3, indicated that there were 12 different elements (C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe) in the indoor PM sources and only 9 of them were detected outside of the house. The reason that the elements of Na, P, Cl were not found may be attributed to 1) the house was cleaned every morning, and some of the indoor dust including these elements was cleared away; 2) some coarse particles containing these elements settled down before they were transported to outside.

Indoor and outdoor particles had a very high content of C, O (Table 3). Particulates emitted from laying hen house were mainly from feathers, epidermal debris, feed particles, feces, and so on^[31]. These contained proteins, which were mainly composed of C, H, O, and N. However, elements of indoor and outdoor PMs did not have N. One possible reason was that the content of N was too little to be detected in samples. The results also showed that indoor PM had higher relative levels of Ca, and Si than outside PM. It is because these two elements in the feed were high, and the activity of laying hens caused plenty of feed falling near the indoor sample collection point^[4]. The reason for the highest content of Ca except for C and O in the laying hen house may be due to the high Ca content in the feed. Besides, the particles outside the house had a higher content of C, S, and Fe compared with that from the indoor PM. The mass percentage of Fe outside the house was almost two times that of the inside, this may be because some particles from the fan blades might

be mixed with the samples.

Table 3 Mean relative element content of collected particles

Elements	%			
	Indoor		Outdoor	
	Weight	Atomic	Weight	Atomic
C	44.19	54.76	55.94	64.44
O	41.51	38.61	38.76	33.52
Na	1.37	0.89	-	-
Mg	1.23	0.76	0.37	0.21
Al	0.49	0.27	0.44	0.23
Si	1.49	0.79	0.66	0.32
P	2.65	1.27	-	-
S	0.61	0.28	0.72	0.31
Cl	0.58	0.24	-	-
K	1.11	0.42	0.85	0.30
Ca	4.14	1.54	1.13	0.39
Fe	0.63	0.17	1.13	0.28
Totals	100.00	-	100.00	-

3.6 Factors affecting particulate emissions

The concentrations of indoor PM gradually increased from spring to summer in 2016 as shown in Figure 2, and the PM concentrations in spring 2017 were greater than that in 2016. These variations might be caused by the positive correlation between dust concentration and poultry age^[4] since the laying hens in spring 2016 was the same batch of that in summer and their age was much younger, and the age of laying hens in 2017 was similar with that in summer 2016. Moreover, both in spring and summer, indoor PM concentrations were higher than those outside. The greatest difference occurred in spring 2017 and the differences were lesser in spring 2016. It should be mainly caused by the closure of the exhaust fans in spring which resulted in less particulate emitted to outside, and the age of lay hens in spring of 2017 which was older and active to produce more particles. The minimum difference of indoor and outdoor PM concentrations appeared in the summer of 2016, which indicated that the working of the ventilation fans significantly enhanced the transmission and diffusion of particles to the atmosphere. Therefore, the outside PM concentrations might be a higher possibility to exceed the related standard. These results indicated that for well control PM emissions from the poultry house, farmers may adopt and adjust PM control strategies: 1) with the age of laying hens, enhancing control intensity and/or frequency when they become older; 2) with the status of exhaust fans, applying PM mitigation methods to reduce ambient environmental impact when the fans are turned on.

In addition, the following factors may also cause a variation of PM emissions.

3.6.1 Temperature and relative humidity

The indoor and outdoor daily average temperature in summer 2016 ranged from 27.6 °C to 29.7 °C and 26.9 °C to 32.5 °C, respectively, while daily average temperatures in spring 2017 were relatively low for both indoors (20.5 °C to 23.3 °C) and outdoors (22.8 °C to 28.3 °C) (Figure 4). In summer 2016, the daily average RH inside and outside the laying hen house was 39.0% to 77.7% and 40.4% to 64.1%, respectively. For laying hens, the upper limit of RH in China's environmental quality standard is 75%^[30]. The indoor RH during the study was able to meet this standard almost every day in summer. Owing to the dry and windy spring in Changchun, the daily average RH was at a low level for both indoors (19.2% to 31.0%) and outdoors (12.3% to 17.5%).

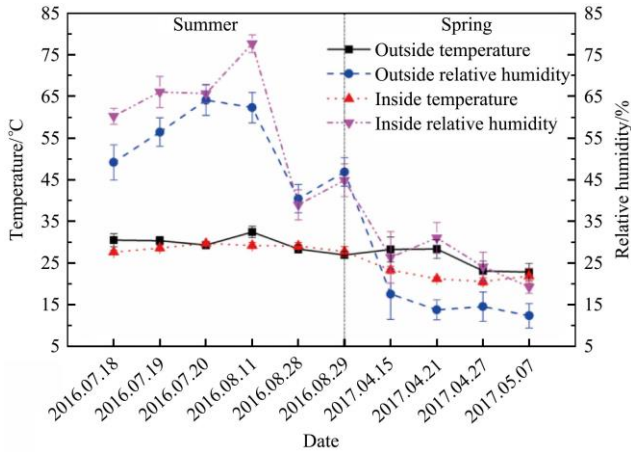


Figure 4 Variety of temperature and relative humidity during the test

Correlation coefficients between PM concentrations and temperature and RH (Table 4) showed that PM concentration outside the house was significantly and positively correlated with temperature and RH at $p < 0.01$ level in spring. It indicated that the change of temperature and RH in spring had a significant impact on the outdoor PM concentration. Moreover, the correlations between $PM_{2.5}$, PM_{10} and TSP concentrations and temperature were basically the same. Therefore, the temperature had a similar effect on the concentration of outdoor PMs with different sizes in spring. The correlation between indoor $PM_{2.5}$ concentration and temperature in spring was not statistically significant. Indoor PM concentrations in spring had little correlation with temperature (excluding $PM_{2.5}$) and were positively correlated with RH ($p < 0.01$). It can be seen that the increase of RH in spring did not reduce PM concentrations. From reference [1], only if the RH was large enough, the PM concentrations may be reduced due to the high water content of the environment. As can be seen from Figure 4, the RH was relatively

low in the spring, so the particle concentration didn't rise as its value increased.

Table 4 Correlation coefficients between particulate matter concentrations and temperature and relative humidity

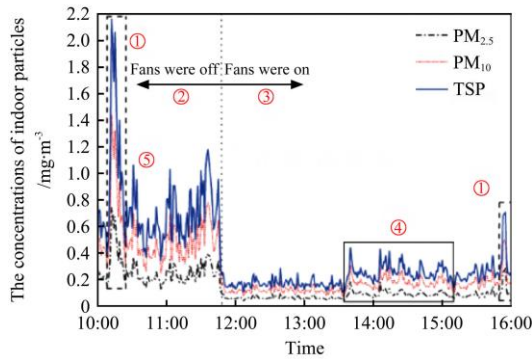
	Outdoor PM			Indoor PM		
	$PM_{2.5}$	PM_{10}	TSP	$PM_{2.5}$	PM_{10}	TSP
Temperature in spring	0.567 ^b	0.563 ^b	0.533 ^b	-0.123	-0.207 ^b	-0.205 ^b
Relative humidity in spring	0.499 ^b	0.512 ^b	0.543 ^b	0.337 ^b	0.465 ^b	0.503 ^b
Temperature in summer	-0.133 ^b	-0.284 ^b	-0.366 ^b	0.007	-0.045	-0.055 ^b
Relative humidity in summer	-0.003	-0.186 ^b	-0.263 ^b	-0.383	-0.491	-0.514

Note: ^b Correlation was significant at the 0.01 level.

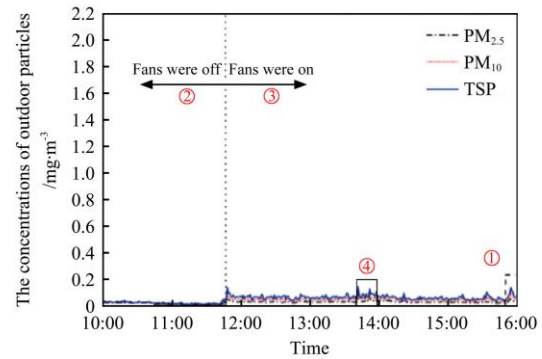
In summer, the correlations between indoor $PM_{2.5}$ concentration and temperature, outdoor $PM_{2.5}$ concentration and RH were not statistically significant. During this period, indoor concentrations of PM_{10} , TSP and outdoor concentrations of PMs had little correlation with temperature, and the correlations were negative. Moreover, outdoor concentrations of PM_{10} , TSP and indoor PM concentrations were negatively correlated with RH. Therefore, an appropriate increase of RH in summer contributed to decreasing PM concentrations. By comparing the correlation coefficient between the concentration of different sized particles and RH, it can be found that RH had a stronger effect on the settlement of particles with the larger size.

3.6.2 Factors affecting the diurnal change of particulate matter

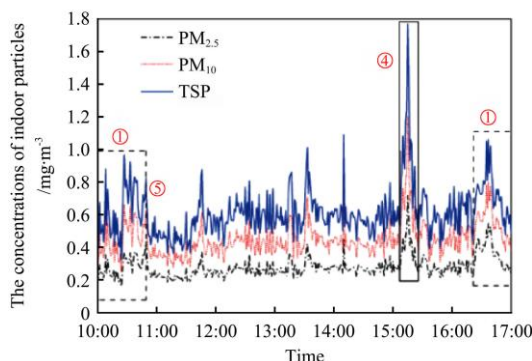
To find out the factors influencing daily variation of PM concentration inside and outside the laying hen house, two typical dates (May 30 of 2016 and July 20 of 2017) which had a great variation of PM concentrations were selected to further check the reasons for their diurnal PM changes.



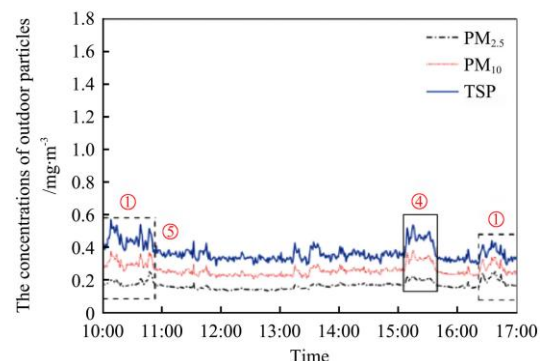
a. Indoor PM concentration on May 30th, 2016



b. Outdoor PM concentration on May 30th, 2016



c. Indoor PM concentration on July 20th, 2016



d. Outdoor PM concentration on July 20th, 2016

Note: 1= Feeding; 2= Fans off; 3= Fans on; 4= Staff working; 5= Activity decrease of the laying hens.

Figure 5 Diurnal variation of PM concentrations inside and outside the laying henhouse:

As we can see from Figure 5a, on May 30 of 2016, the highest indoor PM concentration appeared at 10:15, which was attributed to the feeding operation. When the automatic feeding machine passed the indoor monitoring point, the process of unloading feed would levitate the PM and also increase the activity of the laying hens nearby, generating more suspended dust. With the completion of feeding, the activity of layers gradually reduced, resulting in the PM decrease in the house. At noon, to decrease the temperature in the house, the exhaust fan was turned on. Then, the indoor concentration of the particles was obviously reduced and the outdoor PM concentration increased. From 13:35 to 15:10, the PM concentrations in the house fluctuated, which might be attributed to the working of staff and also caused the fluctuation of outdoor PM concentrations between 13:45 and 13:58. The short fluctuation time between 13:58 and 15:10 may be due to that the staff worked quite close to the monitoring equipment. At approximately 16:00, indoor and outdoor PM concentrations tended to increase during the feeding. On July 20, the exhaust fan was on during the whole sampling time, and the variation trend of indoor and outdoor PM concentration was basically the same. It is clear from Figure 5d that the PM concentration on July 20 also fluctuated correspondingly due to the effects of feeding, the activity of laying hens and staff working.

Many factors might have caused the change of PM concentrations inside and outside the laying hen house, including feeding, egg collection, cleaning, working state of the fans, age and activity of the chicken, temperature and relative humidity, etc. Although feeding and cleaning of the chicken coop were unavoidable, the state of the fans, indoor temperature and RH can be changed without affecting the health and the rate of egg production to reduce PM suspension and transmission.

4 Conclusions

To investigate the emission status of PM_{2.5}, PM₁₀ and TSP from the typical laying hen house in the northeastern area of China, the PM concentrations inside and outside a laying hen house in Changchun, China, were monitored and the potential factors affecting the variation of PM concentration were analyzed. The following conclusions were drawn from this study.

1) During this study, indoor PM concentrations in the laying hen house met the requirements of the environmental quality standard of China's livestock and poultry farms. However, in two days out of six sampling days in summer with exhaust fans working, outdoor PM concentration did not meet the requirements of the standard for a buffer zone.

2) The particle concentrations of indoor and outdoor were highly correlated in summer, and more than 60% of indoor PM may be transported to the outdoor environment. In addition, there were more fine particles dominated both inside and outside of the laying hen house; there were 12 different elements found in the indoor PM sources, and three of them were not detected in the outdoor particle sources.

3) The exhaust fans, age of laying hens, ambient temperature, relative humidity, feeding, house cleaning and egg collection all had influenced on PM concentrations. PM control strategies may be adjusted based on these factors to well reduce PM emissions and improve control efficiency.

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