CONCENTRATION AND EMISSIONS OF AMMONIA AND PARTICULATE MATTER IN TUNNEL–VENTILATED BROILER HOUSES UNDER SUMMER CONDITIONS IN TEXAS

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ABSTRACT. *Total suspended particulate (TSP) concentrations, ammonia (NH_3) concentrations, and ventilation rates were measured in four commercial, tunnel–ventilated broiler houses in June through December of 2000 in Brazos County, Texas. TSP and NH_3 concentrations ranged from 7,387 to 11,387 $\mu g\ m^{-3}$ and 2.02 to 45 ppm, respectively. Ammonia concentration exhibited a correlation with the age of the birds. Mass median diameters (MMD) of the TSP samples were between 24.0 and 26.7 μm aerodynamic equivalent diameter. MMD increased with bird age. The mass fraction of PM_{10} in the TSP samples was between 2.72% and 8.40% with a mean of 5.94%. Ventilation rates were measured between 0.58 and 89 $m^3\ s^{-1}$. Measured concentrations of PM_{10} and ammonia were multiplied by the measured ventilation rates to calculate emission rates for PM_{10} and ammonia. Ammonia emission rates varied from 38 to 2105 g hr^{-1}. TSP emission rates and PM_{10} emission rates ranged from 7.0 to 1673 g hr^{-1} and 0.58 to 99 g hr^{-1}, respectively. Emission rates for ammonia and particulate matter increased with the age of the birds. Most of the PM in the commercial broiler houses was large enough to be captured by the human or poultry respiratory system prior to being inhaled into the lungs.*

Keywords. *Air quality, Ammonia, Dust, Emission, Particulate matter, Poultry housing, Ventilation.*

Emissions of particulate matter (PM) and ammonia are of particular concern to broiler producers. The U.S. Environmental Protection Agency (USEPA) regulates PM in the ambient air in the U.S. The primary and secondary National Ambient Air Quality Standards (NAAQS) for particulate matter less than 10 μm in diameter (PM_{10}) are 150 $\mu g\ m^{-3}$ for a 24–h average and 50 $\mu g\ m^{-3}$ annual arithmetic mean. The primary and secondary standard for particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) is 65 $\mu g\ m^{-3}$, calculated as a 3–year average of the 98th–percentile reading. The annual standard is 15 $\mu g\ m^{-3}$ as the 3–year average of annual arithmetic means (USEPA, 1999).

Atmospheric nitrogen compounds emitted from livestock operations, primarily in the form of ammonia, have been implicated as causing nitrogen enrichment and eutrophication of surface waters, as contributing to the formation of acid precipitation (ApSimon et al., 1987), and as precursors to the formation of secondary PM (Barthelmie and Pryor, 1998). Additionally, ammonia is an odorant, and conditions conducive to the production of ammonia may result in the emission of other odorants. Ammonia release from broiler litter has been modeled from empirical observations (Carr et al., 1990) and determined based on equilibrium principles (Elliott and Collins, 1982). Both models agree that litter pH, litter temperature, and litter moisture are the primary factors in determining ammonia release from broiler litter and that increased ventilation rates result in decreased ammonia concentration in the building.

Few data were found in the scientific literature that document PM_{10} and ammonia concentrations in or emission rates from broiler houses in the Southern U.S. Thus, the objectives of this study were to:

1. Determine concentrations of total suspended particulates (TSP) in the air within tunnel–ventilated broiler houses.
2. Characterize the PM in tunnel–ventilated broiler houses by mass mean diameter (MMD) and PM less then 10 μm (PM_{10}).
3. Determine the concentration of ammonia (NH_3) in tunnel–ventilated broiler houses.
4. Estimate the emission rates for PM_{10} and NH_3 from a tunnel–ventilated broiler house. The emission rate from the building for any specific contaminant is defined as the rate at which the pollutant is expelled into the surrounding atmosphere in units of mass per time and is the calculated product of the measured concentration of the contaminant exiting the building and the measured ventilation rate.

MATERIALS AND METHODS

This study was implemented in four commercial tunnel–ventilated broiler houses in north Brazos County, Texas. The houses were less than one year old and had housed two flocks prior to this study. Sampling was conducted once per week at the site during June, July, August, and December of 2000.

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Samples collected during June, July, and August were considered summer samples, and those collected during December were considered winter samples. Sampling was conducted at different ages of the birds for three different flocks during summer and one flock during winter.

The site contained four identical tunnel–ventilated broiler houses with evaporative cooling pads. The houses were 152.4 m × 13.4 m × 2.6 m with the long axis oriented east–west. The center roof height was 4.85 m. The sidewalls had ventilation openings 2.1 m in height that ran the length of the house and were equipped with moveable curtains. The sidewalls of each house contained tunnel ventilation openings, 18.3 m in length, that housed the evaporative cooling pads. Six air baffles were spaced evenly down the length of the house at approximately 3 m above the floor level. A schematic of the plan view of the buildings is shown in figure 1. A 24–hour reduced lighting scheme was employed.

Approximately 27,500 birds were placed in the houses immediately after hatching and grown until the market age of 49 days with a final body weight of approximately 2.4 kg. The housing space was divided into three sections. The two end sections were each 25% of the floor space, and the middle section was 50% of the floor space. During the brooding period (0–18 days) the birds were confined to the middle section of the house. After the brooding period, the birds occupied the entire length of the building at a stocking density of 13.5 birds m^{-2}.

Wood shavings were used for litter. After four flocks, the litter in the middle section and one end section of the house is removed and replaced with fresh litter. After the next four flocks, the litter in the middle section and the opposite end section is removed and replaced. Thus, the litter in the center section is changed every four flocks, and the litter in the end sections is changed every eight flocks.

The broiler houses were ventilated to maintain a temperature to maximize bird performance. The target temperature for the house was 31° C on day 1 and was decreased by 0.26° C per day until 20° C was reached. A programmable controller was used to control ventilation. Three different ventilation schemes were used to maintain the target temperature in the house. They were, in increasing order of ventilation rate, natural ventilation, sidewall ventilation, and tunnel ventilation. The natural ventilation rate was controlled by varying the area of the sidewall openings with the moveable curtains. Sidewall and tunnel ventilation used the sidewall exhaust fans and tunnel exhaust fans, respectively. When the sidewall exhaust fans were in use, the ventilation rate was controlled by operating the fans intermittently. For instance, the sidewall fans may be on for two minutes and off for five minutes. Variations in tunnel ventilation rate were accomplished by controlling the number of fans in operation (2, 3, 4, 5, or 11).

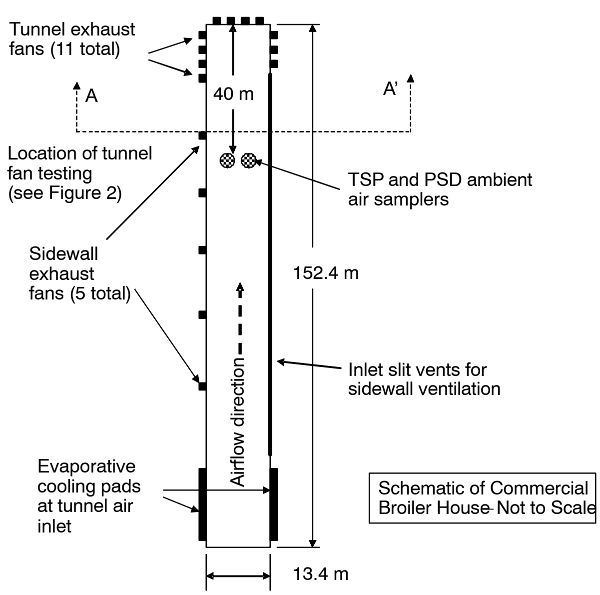

Figure 1. Schematic of the plan view of commercial boiler houses used in the study showing the location of the air samplers and ventilation fans.

Five 0.91 m diameter exhaust fans with gravity–controlled shutters were mounted on the north sidewall. Eleven 1.2–m diameter tunnel fans with discharge diffuser cones were mounted on the west end. Four of the eleven fans were on the west end wall, and the remaining seven were mounted on the ends of the north and south sidewalls, three on one side and four on the other. Additionally, eight 0.91–m diameter fans were mounted approximately 2.1 m above the litter and directed from the center of the building toward each end of the house. The mixing fans were used for short time periods during sidewall ventilation when the exhaust fans were not running.

Particulate Matter Measurements

Concentrations of PM in the houses were determined using gravimetric sampling. High–volume TSP samplers (Graseby GMW, Smyrna, Ga.) were used for all samples. The samplers draw air through glass–fiber filters (Graseby GMW 6810) that collect the PM suspended in the ambient air. The mass of the PM collected is divided by the standard volume of air sampled to determine the mass concentration of PM in the ambient air. These samplers were designed to mimic the human respiratory system, capturing particles less than approximately 44 μm aerodynamic equivalent diameter (AED) (Parnell et al., 1999).

Each sampler used a vacuum motor to draw air downward through the filter. The speed of the motor was controlled manually with a rheostat. An orifice meter was mounted on the sampler motor. The pressure drop across the orifice meter was measured with a pressure transducer and used to calculate instantaneous volumetric airflow. The output from the transducer was recorded with a data logger (HOBO H8 RH/Temp/2x External, Onset Computer Corporation, Pocasset, Mass.) at 7–sec intervals. A split–core AC current transformer (CT–A, Onset Computer Corporation) was used in conjunction with the data logger to measure current to the sampler motor and to determine total run time (i.e., sampling time). A second data logger with a 12–sec sampling interval (HOBO H8 RH/Temp, Onset Computer Corporation) was used to record temperature and relative humidity during the sampling period. The accuracy of the data loggers was ±0.8° C, and ±5% RH. The data loggers were mounted on the outside of the sampler housing.

Barometric pressure was recorded at the beginning and end of the sampling period using a digital barometer (EW–997700, Cole–Parmer, Vernon Hills, Ill.) with an accuracy of ±3.75 mm Hg. It was assumed that the barometric pressure varied minimally from these two values during the sampling period, and the mean of the two values was used in the calculation of airflow rate. The mean temperature, relative humidity, and barometric pressure for each individual sampling period were used to calculate the mean air density for that particular sampling period.

The mean air density and the instantaneous pressure drop across the orifice meter at each 7–sec interval were used to determine instantaneous flow rate. This flow rate was assumed to be constant over the 7–sec interval and was used to calculate total airflow during that interval. The total actual flow rate for the sampling period was calculated by summing the flow rates for all of the intervals. This total actual flow was corrected to total flow at standard conditions of temperature, relative humidity, and pressure.

Glass–fiber filters (G810, Graseby GMW, Smyrna, Ga.) were used for collection of PM. They are relatively inert and nonhygroscopic. The filters were weighed before and after sampling with a high–precision analytical balance (AG245, Mettler Toledo, Greifensee, Switzerland). The weighing was conducted in a controlled environment room (temperature ~25° C, relative humidity ~50%). It was essential that weighing of the filters was conducted under the same conditions before and after PM exposure, since relative humidity has a significant influence on the analysis accuracy. The filters were kept in the weighing room for at least 24 hours before weighing for acclimatization. During pre– and post–weighing, each filter was weighed three times and the mean of the three measurements was used.

The filters were held to the samplers using standard filter–holder cartridges (Graseby GMW, Smyrna, Ga.). The filters were placed in the cartridges in the laboratory, covered, and transported to the broiler houses in watertight protective containers for testing. The cartridge covers were kept in place while the cartridges were attached to the sampler and then removed immediately before the samplers were started. Immediately after sampling, the covers were replaced. The filters were kept in the cartridges inside the watertight containers during transport back to the laboratory for analysis. Each filter was examined carefully before placement in and after removal from the cartridge for defects. On each day of sampling, one control filter was transported to the site and back along with the other filters, but was not used to collect PM. This filter was weighed before and after sampling along with the other filters. The change in mass was recorded and used to monitor background changes in mass.

Window screen material with a 0.16 cm mesh size was placed over each filter cartridge to prevent large feathers from being collected on the filters. During sampling, the screens were monitored and cleaned, if necessary, to remove feathers.

The samplers were placed near the center of the house approximately 40 m from the end wall where the tunnel fans were located, as shown in figure 1. Sampling was conducted once a week for one complete production cycle and two partial production cycles during summer, and one partial production cycle during winter. Samplers were covered when not in use. The samplers were placed in the house at least 3 hours before measurements were taken to avoid errors caused by disturbance of the birds during setup. On each day of measurement, three consecutive samples were taken in each of the four houses. Measurements were conducted between 7:00 a.m. and 6:30 p.m. Sampling times were chosen with a target PM mass collection of 1 gram per filter and were approximately three hours during summer and two hours during winter. The shorter sampling time in winter was necessary because of the higher concentrations of PM.

A second high–volume TSP sampler (Graseby GMW, Smyrna, Ga.) was placed in two of the four broiler houses approximately 2 m from the TSP sampler. This sampler was used to collect samples for the particle size distribution (PSD) measurement. A poly–web filter media (Grade 7120, Web Dynamics, E. Stroudsburg, Pa.) was used to collect PSD samples because it had a low associated particulate count and minimized errors during analysis. The filters were held to the sampler using cartridges with screens identical to the ones used for TSP sampling, and the same procedure was used to prepare, handle, and transport the filters as for TSP sampling.

A Coulter Counter Multisizer (CCM) (Beckman–Coulter, Coulter Multisizer II, Miami, Fla.) was used for particle size analysis. The electrolyte used for particle size analysis with the CCM was 5% lithium chloride in methanol. The electrolyte was pre–filtered using a filtration system that removed all particles larger than 0.2 μm. A background count of the filtered electrolyte was made with the CCM to ensure there was no particulate contamination of the electrolyte. A background count of less than 400 particles per three cm^3 was acceptable.

The results of a CCM particle size analysis are a PSD in the form of PM volume versus equivalent spherical diameter (ESD). To change these results to PM mass versus aerodynamic equivalent diameter (AED), the particle density for the different size particles was assumed to be 1.4 g cm^{-3} (Parnell et al., 1986), and the shape factor was assumed to be 1 (i.e., spherical particles).

Three different samples from each exposed filter were analyzed with the CCM. The mean of the mass fraction in each of the 64 particle size ranges reported by the CCM for the three samples was computed. These means were used to obtain a representative PSD for each filter. A lognormal distribution was fit to the PSD for each filter. The mass median diameter (MMD) and geometric standard deviation (GSD) for each PSD was computed from the lognormal distribution. The MMD for a PSD is defined as the particle size where 50% of the PM is larger or smaller. The GSD is defined as the ratio of the 84.1% (d_{84}) and 50% (d_{50}) particle sizes, or the 50% and 15.9% ($d_{15.9}$) particle sizes. The mass fraction of particles less than 10 μm AED was determined from the best–fit lognormal distribution. The mean of these values was calculated to find the mean mass fraction of particles less than 10 μm.

Ammonia Measurements

Measurement of ammonia concentrations inside the broiler houses was accomplished using a chemical analyzer (Dräger CMS, Dräger, Lubeck, Germany) that uses colorimetric analysis of the chemical reaction of ammonia with a reagent. The reagent is precisely defined and encapsulated in glass capillaries contained in a chip. The instrument opens the glass capillary and draws a constant volume of air through the exposed reagent with an internal pump. The chemical reaction that occurs between the ammonia in the sampled air and the reagent is detected optically by the analyzer and is indicated on the digital display of the analyzer. Since higher concentrations of ammonia require a shorter period of time than lower concentrations for the complete chemical conversion, measurement time varied from 15 to 140 sec. The chips used for this study (6406130, Dräger, Lubeck, Germany) had a range of 2 to 50 ppm and a stated accuracy of ±8% of the measured value.

Measurements were taken in the center of each of the four houses, approximately 40 m from the end wall where the tunnel fans are located. The sampler was held approximately 1 m above the litter, with the inlet perpendicular to the airflow in the building. Measurements were taken 2 to 3 hours apart (at the beginning of each TSP sampling period and at the end of the third TSP sampling period) between 7:00 a.m. and 6:30 p.m. for a total of four samples per day. Ambient air outside the houses near the inlets was also sampled to obtain background concentrations.

Ventilation Rate Measurements

Ventilation rate measurements were made using a vane thermo–anemometer (451126, Extech, Waltham, Mass.) that had an accuracy of ±3% of the reading. Analysis was conducted when no birds were present in the house. This study was concerned with mechanical ventilation only, so no estimates for natural ventilation rates were developed.

Sidewall ventilation rates were estimated from airflow rates measured individually for each sidewall fan. The anemometer was used to measure air velocity at four points 15 cm upstream from each fan. The mean velocity was calculated from these points and multiplied by the area of the fan to estimate ventilation rate for each fan. The total ventilation rate was calculated by taking the sum of the flow rates from each of the five fans. The effective ventilation rate for each stage was calculated by multiplying the total ventilation rate for the sidewall exhaust fans by the duty cycle.

Tunnel ventilation rates were estimated from air velocity measurements made with the fans operating in each of the operator–defined stages. Air velocity was measured at 15 locations in a grid perpendicular to the airflow, as shown in figure 2. The mean velocity was calculated and multiplied by the cross–sectional area of the house to obtain the actual ventilation rate. During each sampling period for PM and ammonia, the ventilation stage was recorded. This information was used with the ventilation rate measurements corrected for differences in temperature, pressure, and relative humidity to determine the total ventilation rate for each sampling period. All ventilation during summer sampling periods was in tunnel mode, while winter ventilation was either sidewall or tunnel. No natural ventilation occurred during the testing.

Table 1 describes the duty cycle for the exhaust fans and the effective ventilation rate for each fan stage of sidewall ventilation. Ventilation rates for each stage of tunnel ventilation are listed in table 2. Sidewall ventilation rates were between 0.56 and 17 dry standard cubic meters per second (dscm s^{-1}). Tunnel ventilation rates were between 11 and 89 dscm s^{-1}.

Emission Rate Calculations

TSP emission rates were calculated by taking the product of the TSP concentration and the ventilation rate for each sampling period. PM_{10} emission rates were calculated from TSP emission rates and the mass fraction of PM_{10} in the PSD. Ammonia emission rates were calculated from the product of the ammonia concentration and the ventilation rate for each sampling period.

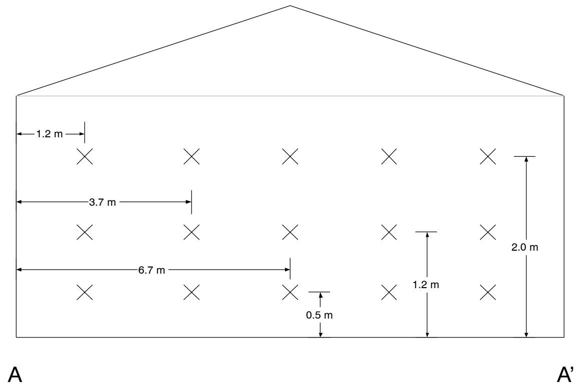

Figure 2. Sampling positions for measurement of ventilation rates during tunnel ventilation of commercial broiler houses. Each "×" marks a location where the air velocity was recorded. The ventilation rate for a given set of operating fans was calculated from the mean air velocity at the 15 points times the cross–sectional area of the building.

Table 1. Sidewall fan ventilation stages and rates for modern mechanically ventilated broiler houses in central Texas.

Stage	On Time (min)	Off Time (min)	On Time per Hour (min)	Effective Ventilation Rate ($m^3 s^{-1}$)
1	0.5	14.4	2.4	0.67
2	0.5	15.0	2.0	0.56
3	1.0	5.0	10.0	2.8
4	2.0	5.0	18.0	5.1
5	2.0	2.0	30.0	8.4
6	2.0	0.0	60.0	17

Table 2. Tunnel fan ventilation rates for modern mechanically ventilated broiler houses in central Texas.

Number of Fans Operating	Ventilation Rate ($m^3 s^{-1}$)
2	11
3	27
4	38
5	48
11	89

Results and Discussion

TSP concentrations measured versus the age of the birds are shown in figure 3. The overall range of TSP was 737 μg per cubic meter (μg m^{-3}) to 11,387 μg m^{-3}. Concentrations during summer ranged from 737 μg m^{-3} to 5,245 μg m^{-3}, while winter concentrations were between 2,102 μg m^{-3} and 11,387 μg m^{-3}. TSP concentrations appeared to be greater during winter conditions when ventilation rates were lower.

TSP concentrations increased with bird age. The composition of the PM was expected to be made up of litter, dried fecal matter, feed, and dried particles of skin and feathers (Koon et al., 1963; Madelin and Wathes, 1989). As the birds grew, they produced more manure, developed a greater area of skin and feathers, and were switched from a moist "starter" feed to a dry feed during the grow–out period. Feed intake also increased as the birds grew, which increased the frequency of operation of the feed–delivery system. All of these changes would contribute to increased concentrations of TSP. As the birds became heavier, their movement on the litter imparted more energy and presumably suspended more PM.

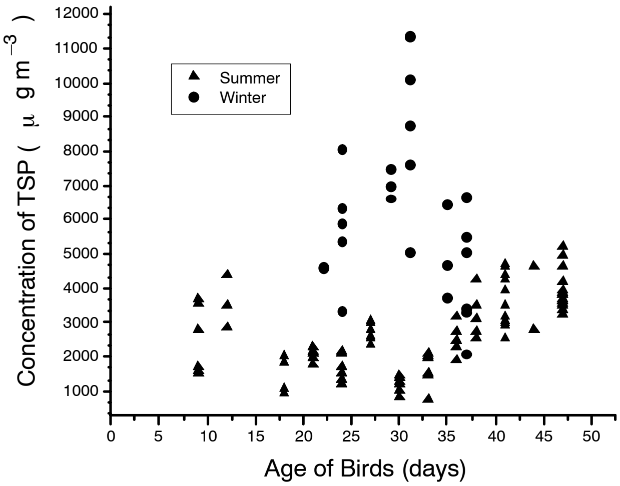

Figure 3. Concentration of total suspended particulate matter (µg m^{-3}) versus age of birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000.

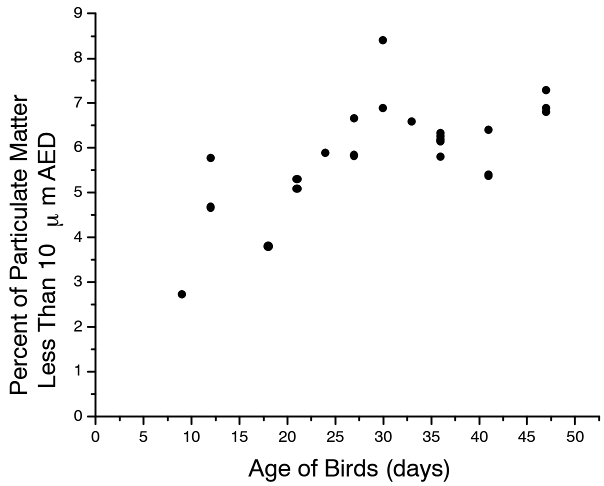

Figure 5. Mass percentage of particulate matter classified as PM_{10} versus age of birds (days) determined from particle size distributions calculated with a Coulter Counter Multisizer and sampled in four tunnel–ventilated commercial broiler houses in central Texas during June–December 2000.

The MMD for the PSD of the PM collected in the houses versus age of the birds is shown in figure 4. The minimum MMD was 24.0 µm and the maximum was 26.7 µm. The MMD of the PM showed a slight increase with bird age. Koon et al. (1963) and Madelin and Wathes (1989) reported that most of the PM in broiler house air originates from skin and feathers, with the rest originating from the feed and litter. Madelin and Wathes (1989) reported that the percentage of the PM from feed and litter increased with bird age.

The MMD of the PM sampled were considerably larger than PM from other livestock production facilities. The MMD was found to be between 24.0 and 26.7 µm. A MMD for TSP from beef cattle feedyards has been reported as 9.54, 12.3, and 14.2 µm AED (Sweeten et al., 2000). Barber et al. (1991) reported mean MMD for PM from a swine production facility as 17.97 µm AED. The large particle sizes of the broiler house PM have larger settling velocities and will fall out of exhausted air more quickly than the smaller particles.

The mass percentage of TSP classified as PM_{10} versus age of the bird is shown in figure 5. The percentage of the TSP with AED less than or equal to 10 µm (PM_{10}) varied from 2.72% to 8.40% with a mean of 5.94%. Particles with an AED of less than 10 µm can be inhaled into the human or animal lung, where they can lodge into the alveoli. Particles larger than 10 µm AED can be inhaled into the nose or mouth but are usually trapped by the nose and upper respiratory tract and do not reach the lungs (Parnell et al., 1999). Thus, most of the particles in the PM are large enough to be filtered by the human or poultry respiratory system.

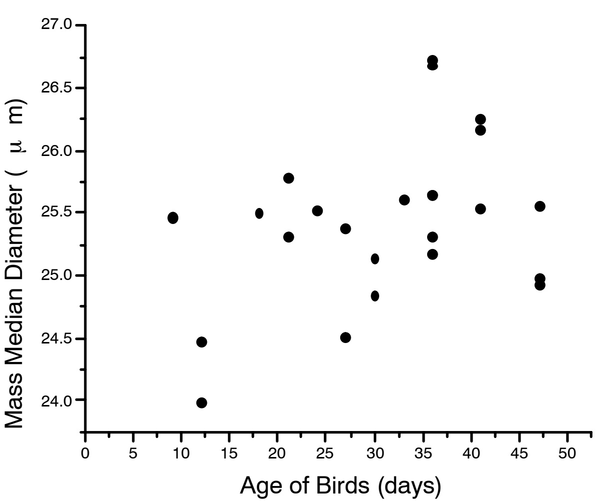

Figure 4. Mass median diameter of particulate matter (µm) versus age of birds (days) for particulate matter sampled in commercial tunnel–ventilated broiler houses in central Texas during June–December 2000.

Researchers in Europe tend to use "respirable" and "inhalable" as indicators of particle size rather than an AED. Respirable data generally correspond to PM_5 and inhalable data correspond to TSP. Reported concentrations of PM for broilers on litter are summarized in table 3, where respirable dust ranges from 0.4 to 9.7 mg m^{-3}. The data in this study show PM_{10} concentrations ranging from 0.1 to 0.3 mg m^{-3} as the birds grow, which is slightly less than comparable data from European studies. However, in the warmer climate of Texas, higher ventilation rates are typically used, and evaporative cooling systems are common. Higher ventilation rates may dilute the PM, and the evaporative coolers may suppress PM emissions by maintaining a higher relative humidity in the buildings.

Ammonia concentrations measured versus age of the birds are shown in figure 6. The overall range of the ammonia concentrations observed was 2.0 to 45.0 ppm and increased with the age of the bird. Summer ammonia concentrations were between 2.0 ppm and 9.6 ppm, while winter concentrations were between 12.0 and 45.0 ppm. The higher concentrations of ammonia in the winter corresponded to the lower ventilation rates. All background ammonia concentrations measured were below the range of the sampler (less than 2 ppm).

Ammonia concentrations reported in the literature are shown in table 4. They range from less than 1 ppm to near 50 ppm. As with the data in this study, periods of lower ventilation (i.e., winter conditions) were characteristically the times of higher ammonia concentration. The data for the Texas broiler houses in this study are comparable to that reported in the literature.

Table 3. Dust concentrations (mg m^{-3}) reported in the literature for broilers grown on deep litter.

Reference	Size Range	Mean Concentration (mg m^{-3})	Concentration Range (mg m^{-3})	Stocking Density (birds m^{-2})	Ventilation
Willis et al., 1987	Respirable	5.43 (28 days of age) 9.71 (49 days of age)		18.5	Mechanical
Conceicao et al., 1989	Inhalable	8.9	2.0 – 13.2	23.3 11.7	Mechanical
	Respirable		0.6 – 1.63	23.3 11.7	Mechanical
Morrison et al., 1993	0.1 – 1.0 μm	0.78 (week 1–3) 2.10 (week 4–6)	0.0 – 5.7	9.6–13.6	
Wathes et al., 1997	Inhalable	10.1	7 – 11	20.8 – 23.4	Mechanical
	Respirable	1.19	0.9 – 1.3	20.8 – 23.4	Mechanical
Hinz and Linke, 1998	Inhalable		1 – 14	22	Natural/Mixed
Takai et al., 1998	Inhalable	9.92 (England) 10.36 (Netherlands) 3.83 (Denmark) 4.49 (Germany			
	Respirable	1.14 (England) 1.05 (Netherlands) 0.42 (Denmark) 0.63 (Germany)			

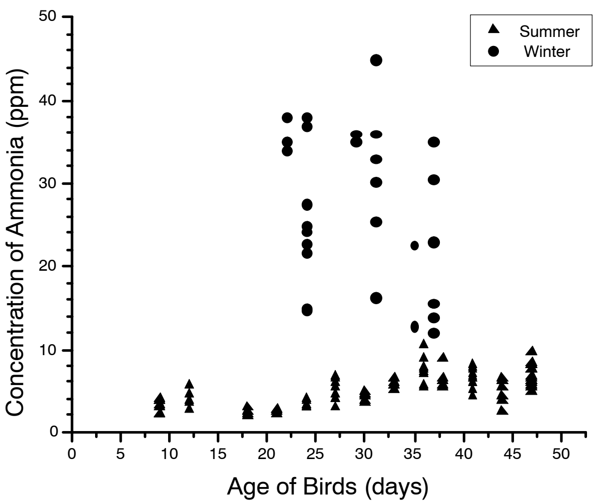

Figure 6. Ammonia concentration (ppm) versus age of birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000.

PM_{10} emission rates for the building (27,500 birds) are shown versus bird age in figure 7 and were between 3.7 and 99 g hr^{-1} during summer and 0.58 and 57 g hr^{-1} during winter. Ammonia emission rates for the building versus the age of the birds are shown in figure 8 and varied between 59 and 2105 g hr^{-1} during summer and between 38 and 1893 g hr^{-1} during winter. Figure 9 shows the TSP emission data compared to data from the literature in cases where sufficient data for comparison was available. Figure 10 shows the data for ammonia emissions compared to the data from Groot Koerkamp et al. (1998). Both TSP and ammonia emissions were similar to that reported in the literature despite differences in building design, ventilation methods, and climate. PM_{10} and ammonia emission rates showed an increase with bird age. This was attributed to the higher ventilation rates necessary to obtain the desired temperature as the birds mature and the fact that the PM and ammonia concentrations increased with bird age.

Measurements during this study were conducted during daytime hours. The assumption was made that diurnal effects from bird activity on concentration and emission rates were minimal because of the reduced lighting scheme. Temperature and relative humidity data were collected during each test and are shown in figures 11 and 12, respectively. Because of the large amount of data, only mean values are shown. All ventilation rates were corrected to account for the difference between temperature and relative humidity on test day and the values during calibration of the fans. Production schedules and local weather limited sampling during cooler weather to three days. Seasonal effects on concentration and ventilation rate should be more closely evaluated by collecting additional data during cooler weather.

Conclusion

Data was collected in four commercial tunnel–ventilated broiler houses with deep litter during June–December of 2000 in Brazos County, Texas. Stocking density was 13.5 birds m^{-2} and birds were housed from hatching to approximately 50 days of age.

TSP concentrations measured were between 737 μg m^{-3} and 11,387 μg m^{-3} and increased with bird age. The MMD was between 24.0 and 26.7 μm AED. This was larger than reported for PM from cattle feedyards and swine feeding facilities and increased slightly with bird age. Mass fractions of the TSP with AED less than 10 μm were between 2.72% and 8.40% with a mean of 5.94%. This indicated that most of the PM in the commercial broiler houses was large enough to be captured by the human or poultry respiratory system prior to being inhaled into the lungs. Ammonia concentrations were measured between 2.0 and 45.0 ppm and increased with bird age.

Table 4. Ammonia concentrations (ppm) reported for the air inside deep litter broiler houses.

Reference	Mean Concentration (ppm)	Concentration Range (ppm)	Stocking Density (birds m^{-2})	Ventilation	Growth Cycle (days)	Final Bird Weight (kg)
Leonard et al., 1984		1.8 – 12.1	14.4	Mechanical	44	1.71
			12.3		46	
Willis et al., 1987	1.3		18.5	Mechanical	49	1.8
	25.0					
Conceicao et al., 1989	5.4	0.19 – 27.5	23.3	Mechanical	126	
			11.7			
Madelin and Wathes, 1989	7.93	4 – 23	12.6	Mechanical	63	
Morrison et al., 1993	10.7 (week 1–3) – 41.8 (week 4–6)	0.5 – 110	9.6 – 13.6		49	
Elwinger and Svensson, 1996	9.6 (28 days of age, shavings)		13.5	Mechanical	42	
	10.4 (28 days of age, straw)					
	43 (35 days of age)		13.5	Mechanical	42	
Wathes et al., 1997	Winter: 28 (day), 35 (night)	20 – 52	20.8 – 23.4	Mechanical		
	Summer: 14 (day), 18 (night)	12 – 25	20.8 – 23.4	Mechanical		
Groot Koerkamp et al., 1998	27.1 (England)					
	11.2 (Netherlands)					
	8.0 (Denmark)					
	20.8 (Germany)					
Hinz and Linke, 1998		1 – 50	22	Natural or mixed	32	1.1
Jiang and Sands, 2000	6	1 – 18	11.3 – 13.4	Natural	42	2

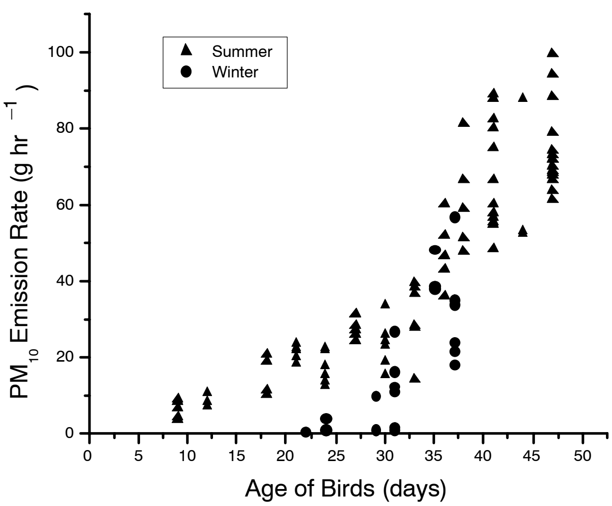

Figure 7. PM_{10} emission rate (g hr^{-1}) per building (27,500 birds) versus age of the birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000.

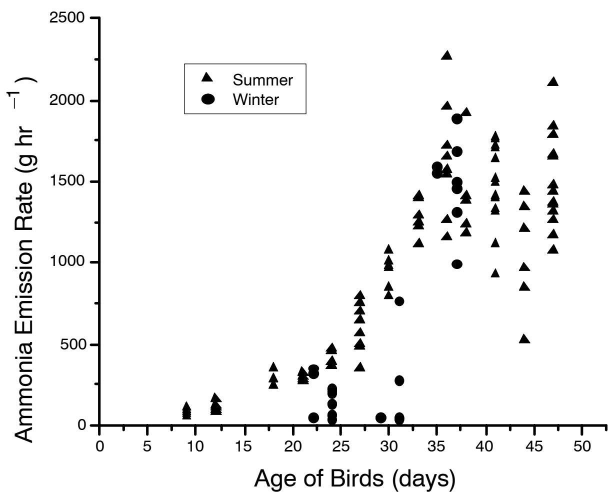

Figure 8. Ammonia emission rate (g hr^{-1}) per building (27,500 birds) versus age of birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000.

PM_{10} emission rates were calculated using PM_{10} fractions of TSP and were between 3.7 and 99 g hr^{-1} during summer and 0.58 and 57 g hr^{-1} during winter. Ammonia emission rates were between 59 and 2105 g hr^{-1} during summer and between 38 and 1893 g hr^{-1} during winter. Emission rates for both PM_{10} and ammonia increased with bird age.

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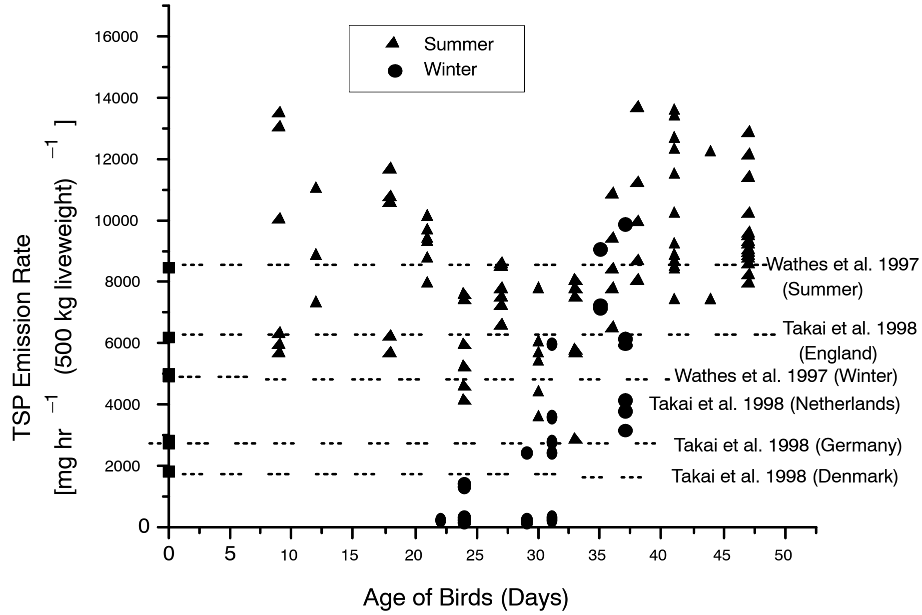

Figure 9. Calculated emissions of total suspended particulates (mg hr^{-1} 500 kg^{-1}) versus age of the birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000 compared to concentrations reported in the literature.

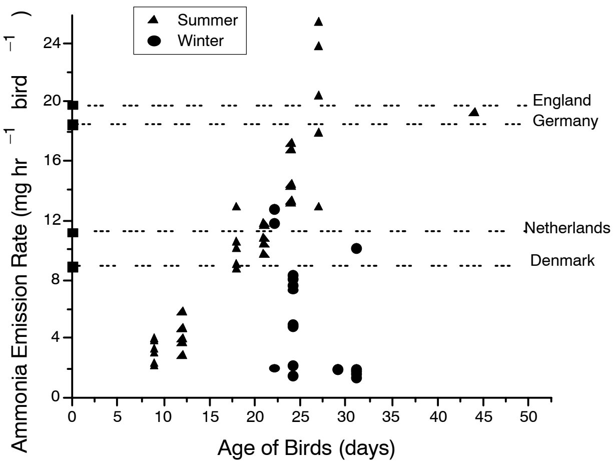

Figure 10. Ammonia emission rates (mg hr^{-1} bird^{-1}) versus age of the birds (days) measured in four commercial tunnel–ventilated broiler houses in central Texas during June–December 2000 compared to mean emission rates (represented by dotted lines) reported by Groot Koerkamp et al. (1998).

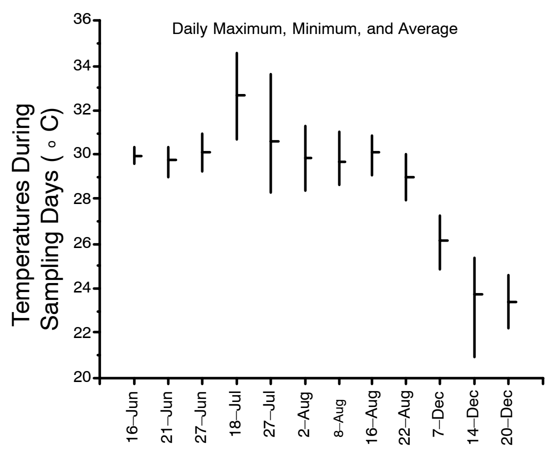

Figure 11. Dry–bulb temperature during sampling periods in four commercial tunnel–ventilated broiler houses in central Texas, showing maximum, minimum, and mean values. Samples were taken every 12 seconds during PM sampling, for approximately 10,000 data points per day.

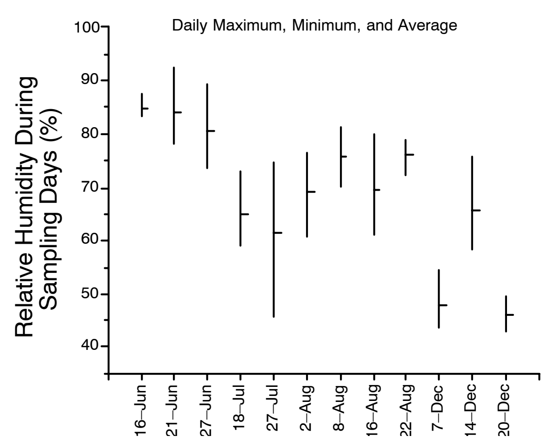

Figure 12. Relative humidity during sampling periods in four commercial tunnel–ventilated broiler houses in central Texas, showing maximum, minimum, and mean values. Samples were taken every 12 seconds during PM sampling, for approximately 10,000 data points per day.

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