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EVALUATION OF ELECTROSTATIC PARTICLE IONIZATION AND BIOCURTAIN™ TECHNOLOGIES TO REDUCE AIR POLLUTANTS FROM BROILER HOUSES

S. B. Jerez, S. Mukhtar, W. Faulkner, K. D. Casey, M. S. Borhan, R. A. Smith

ABSTRACT. *The continuing growth of poultry production, along with the increasing urbanization of rural areas, is leading to more odor-related complaints from neighboring communities and more scrutiny from policy makers. It is, therefore, in the best interest of poultry producers to look at control methods for abating odors. Previous studies have shown that substantial amounts of volatile and odorous compounds are adsorbed and transported by dust particles. Thus, by reducing the amount of dust emitted from poultry facilities such as broiler houses, odor may be reduced as well. The objective of this study was to evaluate the effectiveness of two commercially available control technologies (BioCurtain™ and electrostatic particle ionization (EPI) system) in reducing the total suspended particulate matter (TSP), particulate matter* $\leq$*10 µm in diameter (*PM_{10}*), ammonia (*NH_3*), and hydrogen sulfide (*H_2S*) emitted from a broiler facility in Texas. The study was conducted at a broiler production facility in two identically designed, ventilated, and managed broiler houses where one served as the treatment house and the other, the control. Measurements were done on two consecutive days each in September and December 2010. BioCurtain™ was tested independently on the first day and in combination with and the EPI on the second day. Reductions in the* NH_3 *and* H_2S *emission rates by as much as 8% (1040 vs. 943 g/h for* NH_3 *and 9.2 vs. 8.4 g/h for* H_2S*) and by as much as 43% (396 vs. 227 g/h) for the TSP emission rates were achieved with the BioCurtain™. The EPI system reduced the* NH_3*,* H_2S*, and TSP emission rates by as much as 17%, 34% and 39%, respectively. Economic analysis showed that operating the automated EPI and BioCurtain™ system for one 14 m wide and 152 m long broiler building housing an average of 23,000 birds will cost $0.06 per bird.*

Keywords. *Ammonia, BioCurtain™, Electrostatic charging, Ionization Odor, Particulate matter, Poultry housing.*

Although the number of animal farms in the United States has declined since reaching its peak in 1935 at about 6.5 million, the annual production of poultry has risen steadily over the past decades due to the increased farm size and the number of birds raised per farm (NAS, 2003). In terms of broiler production, the 25.6 billion lb produced in 1990 almost doubled at 49.1 billion lb in 2010, while the total value grew from $8.4 billion to $23.7 billion during the same time period (USDA-NASS, 2011). Texas ranked sixth in the nation in broiler production, producing 3.6 billion lb and generating $1.8 billion in revenue in 2010. Texas broiler production has grown approximately 150% since 1990, second only to Mississippi (USDA-NASS, 2011).

The continuing growth of poultry production in Texas, and intensive animal production systems in general, led to increased number of odor-related complaints from communities in close proximity to these facilities. In an effort to address the increasing odor complaints, the 81st Regular Session of Texas Legislature passed Senate Bill 1693 (2009), which required the Texas Commission on Environmental Quality (TCEQ) to investigate odor complaints concerning a poultry facility or the land application of litter by a poultry facility within 18 h for a second consecutive complaint against the same facility. Given the increasing attention from policy makers and the public, it is in the interest of the poultry producers to look at control methods for abating odors as well as other environmental pollutants from their facilities.

Odorous compounds are disseminated in vapor phase or may be carried by dust particles. Cai et al. (2006) identified 50 different volatile organic compounds (VOCs), 21 of which have been reported present in swine dust for the first time. Das et al. (2004) found significantly higher amounts of hydrogen sulfide, octanal, and nonanal in small particles (5 to 20 µm) than the medium (20 to 40 µm) and large (40 to 75 µm) particles from swine operations. Thus, by reduc-

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ing the amount of dust emitted from the building, odor may be reduced as well. Hangartner (1990), for example, reported that filtering dust from the exhaust air reduced VOC-odor emissions from swine buildings by up to 65% - evidence that VOC-odor is associated with airborne dust particles.

A variety of strategies and control technologies are available for controlling odor and other air pollutants from confined animal structures. There are those technologies that can capture and treat air pollutants such as biofilters, biotrickling filters, and air scrubbers (Kennes and Veiga, 2002; Melse and Mol, 2004; Melse and Ogink, 2005; Chen et al., 2009; Park et al., 2011). The aforementioned technologies rely on the use of filter media to entrain and remove pollutants from exhaust air. Their use for removing gaseous pollutants (i.e., ammonia, hydrogen sulfide, odorous compounds) has found varying degree of success. However, these technologies, although commercially available, have not been tested in the United States.

Two approaches for reducing emissions of particulate matter (PM) are a BioCurtain™ and an electrostatic precipitator. A BioCurtain™ relies on filtration mechanisms of impaction, interception, and gravitational settling, to separate PM from the exhaust air stream. An electrostatic precipitator charges the particles to move them out of the gas stream and deposit them onto collector plates (Zhang, 2005). Studies have also shown that another function of an electrostatic precipitator system can be to kill airborne and surface microorganisms (Mitchell et al., 2004). They used an electrostatic space charge system (ESCS) in a broiler breeder house to effectively reduce airborne dust, ammonia, and airborne bacteria by an average of 61%, 56%, and 67%, respectively. In a related study, the ESCS was also effective in reducing the airborne dust and gram-negative bacteria in an experimental room containing broiler breeder pullets by an average of 37% and 64%, respectively (Richardson et al., 2003). The Electrostatic Particle Ionization (EPI) systems used in a pilot broiler house reduced PM_{10} and $PM_{2.5}$ by 36% and 10%, respectively (Cambra-Lopez et al., 2009).

The objective of this study was to test the effectiveness of a patented Electrostatic Particle Ionization (EPI) system and a BioCurtain™, used separately and simultaneously, in reducing PM and gases (ammonia and hydrogen sulfide) in the exhaust air stream of a broiler facility. Although the use of an EPI has been reported before (e.g., Cambra-Lopez et al., 2009), there is very limited evaluation data that would help producers make informed decisions about purchasing the system. In addition, there has been no reported research data on the effectiveness of a combined EPI system and BioCurtain™ in reducing PM and gases from the exhaust air streams of poultry buildings in the United States. The economic analysis for the use of both systems is also included in this article.

METHODOLOGY

EXPERIMENTAL DESIGN AND DESCRIPTION OF THE BROILER HOUSES

The study was conducted in two identically designed, ventilated, and managed broiler houses located in east central Texas. The EPI system and BioCurtain™ were installed in one of the houses, which served as the treatment house; the other adjacent house served as the control. Measurements were done on two consecutive days in September 2010 (23 and 24 September) to represent warm weather conditions, and another two consecutive days in December 2010 (7 and 8 December) represented cold weather conditions in the area. On day one of each sampling period, the EPI system was turned off so that the effectiveness of the BioCurtain™ alone was tested; on the second day, the performance of the combined EPI and BioCurtain™ was evaluated.

The farm chosen for this study had 12 broiler buildings with a 15 m distance in between the buildings. Because of the prevailing southerly winds, the two adjacent buildings located on the south end of the farm were selected so that the exhaust air from fans on the south side of the treatment building could be sampled with minimum interference from exhaust air from fans of other buildings. Both broiler houses were bedded with new litter about 10 to 15 cm consisting of Pineywood shavings at the beginning of the September study period. The bedding was not replaced with new litter for the next 290 days that included the December study period. This eliminated the effect of the bedding material age on emissions of gases (particularly ammonia or NH_3, and hydrogen sulfide or H_2S) between the buildings. Each of the buildings was 152 m long, 14 m wide, with a peak ceiling height of 3.7 m, and the long axis oriented east-west. They were tunnel-ventilated with nine 137 cm and two 122 cm axial exhaust fans by Chore-Time, CTB Inc. (six on the south sidewall and five on the north sidewall (fig. 1) near the east side of the buildings). Additionally, two minimum ventilation, 91 cm fans were installed on the east end wall of each building. Two sidewall tunnel air inlets, one on the south sidewall and one on the north sidewall (1.5 m high and 26 m long with a 15 cm thick cooling pad) were located on the west end of each building. There were drop-down ceiling inlets installed against both sidewalls to provide fresh air into the building. All fans had discharge diffuser cones. Each building had alternating water (four) and feed (three) lines that ran along the length of the building starting and ending at about 3 m from each end of the building.

The buildings were populated with approximately 24,300 birds per flock during warm weather of June through September and 25,700 birds per flock during all other months. The birds in each flock were approximately 50% males and 50% females. Birds were placed immediately after hatching and grown until the market age of 63 days with an approximate weight of 3.6 kg. Sampling was done when the birds were 59-60 days old in September and 60-61 days old in December. The birds were fed through automatic feeders and a nipple drinking system (Chore-Time, CTB Inc., Milford, Ind.) that ran the entire length of the house.

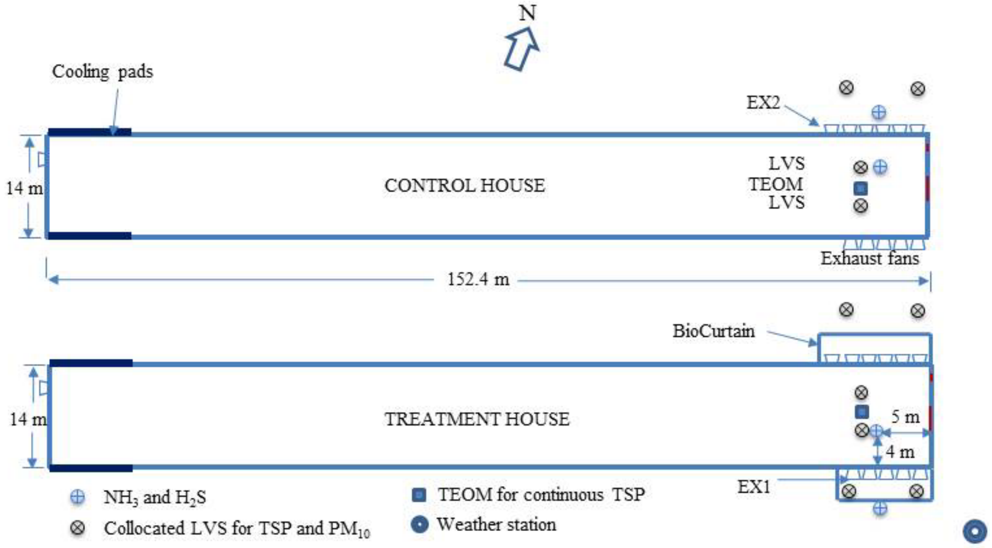


Figure 1. Schematic of the plan view of the broiler houses showing the sampling locations for TSP, PM_{10}, NH_3, and H_2S. LVS = Low volume sampler, TSP = total suspended particulate matter, TEOM = Tapered Element Oscillating Microbalance. Not drawn to scale.

Description of the Electrostatic Particle Ionization (EPI) System

The EPI system (Baugmgartner Environics Inc., Olivia, Minn.) installed inside the treatment house consisted of four rows of inline, negative ionization units (consisting of conductive wires with discharge electrodes) that were suspended 30 cm from the ceiling and ran along the entire length of the house (fig. 2). Each of these ionization units was attached to a high voltage power supply to generate -30kV DC at a low current level (up to 2 mA) to ensure safety. The high-voltage negative corona discharge occurs at the stainless-steel electrodes, which are located at 2.54 cm intervals and are pointed toward the litter as shown in figure 3. The negative corona imparts negative charge to the airborne particles as they move through the charging field causing them to be attracted to grounded surfaces such as floor, walls, ceilings, and other surfaces in the building.

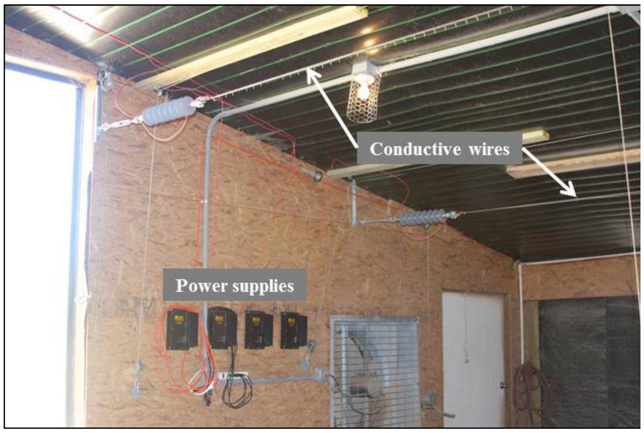


Figure 2. The ionization units hanging from the ceiling of the broiler treatment house and connected to the power supplies.

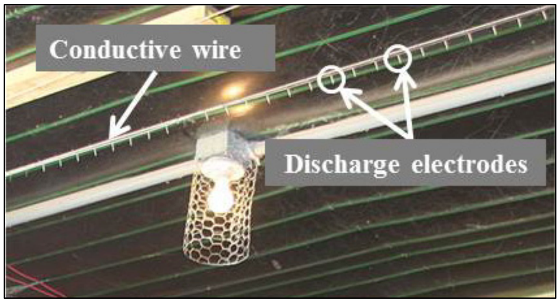


Figure 3. Detail of the discharge electrodes attached to the conductive wire of the EPI system.

Description of the BioCurtain™ with an EPI System

The BioCurtain™ system (Baugmgartner Environics Inc., Olivia, Minn.) is comprised of a metal frame structure, covered with a woven geotextile fabric used to enclose a group of ventilation fans. It was installed about four fan diameters away from the exhaust fans covering the entire exhaust area on both sides of the building (fig. 4). Each curtain was 12.2 m long and 5.5 m wide.

The BioCurtain™ functions by directing exhausted air toward the geotextile fabric and down into the bottom corner of the structure, where dust settles out of the air stream. The treated air is then exhausted out vertically and through the opening near the bottom corner of the structure (fig. 4). An EPI system was also installed inside the BioCurtain™ (fig. 5) enclosure to enhance the collection of suspended particles before the treated air leaves the structure but it was functional only during the winter sampling when the EPI system and the Biocurtain™ operated simultaneously.

Measurement of TSP and PM_{10} Concentrations

Concentrations of the total suspended particulate matter (TSP) in both the treatment and control houses were measured using gravimetric samplers. A Tapered Element Oscillating Microbalance (TEOM) monitor (Series 1400a, Rup-

Figure 4. Biocurtain covering the entire exhaust area on both sides of the treatment house. Treated air leaves vertically and through the opening near the bottom corner of the structure.

precht and Patashnick Co., Inc., Albany, N.Y.) mounted in an environmentally controlled cabinet and fitted with a TSP inlet was used for continuous measurement of the mass concentration inside the two houses. The TEOM monitor inlet (at a 2m height) was collocated with two low-volume TSP and PM_{10} samplers (LVS; SSI25; BGI Inc.; Waltham, Mass.) (Wanjura et al., 2005) at a 1 m height with 47 mm Teflon filters. Leak checks and mass flow controller calibration checks were performed in the laboratory two days prior to both sampling events in accordance with manufacturer instructions. All measurements inside the treatment and control buildings were taken at a height equivalent to the center of the fan hubs of EX1 and EX2 in figure 1 and at three fan diameters (4 m) upstream of EX1 and EX2. Outside the houses, LVS samplers fitted with TSP and PM_{10} inlets were used for the measurements inside of the biocurtain enclosing EX1 in the treatment house and at about 7 m away from EX2 of the control house (fig. 1). The measured PM_{10} concentrations reported in this article were compared with estimates obtained using the procedures outlined in Lacey et al. (2003)

MEASUREMENT OF AMMONIA AND HYDROGEN SULFIDE CONCENTRATION

Ammonia (NH_3) and hydrogen sulfide (H_2S) concentrations were measured continuously using a chemiluminescence NH_3 analyzer (Model 17i, Thermal Environmental Instruments (TEI), Franklin, Mass.) for NH_3 concentrations and a pulsed fluorescence SO_2 detector (TEI Model 45C, Thermal Environmental Instruments (TEI), Franklin, Mass.) connected to a converter (TEI Model 340, Thermal Environmental Instruments (TEI), Franklin, Mass.) for the H_2S concentrations. Both analyzers were calibrated in the laboratory using standard gases (10, 30, 80 ppm, ±2% accuracy, Nitrogen balance, Coastal Specialty Gas, Beaumont, Tex.) prior to measurements. They were connected to the gas sampling system (GSS) shown in figure 6 that allowed the analyzers to be housed in a mobile trailer parked at the site. The GSS consisted of a set of three-way isolation valves that were controlled by a datalogger (Model 850, Campbell Scientific, Logan, Utah), a pump (Model no. 420-1901, Thermo Scientific, Franklin, Mass.), and a separate datalogger (Model CR3000, Campbell Scientific, Logan, Utah) for the analyzers. The sampling lines connected to the intake port of the isolation valves were 6.35 mm (O.D.) diameter Perfluoroalkoxy (PFA) tubing and insulated to minimize condensation inside the tubing. A 47-mm PFA filter holder containing polytetrafluoroethylene (PTFE) membrane filters (5 µm pore size, Savillex Corp., Minnetonka, Minn.) was located at the intake side of all four sampling lines to filter out dust in the sampled air.

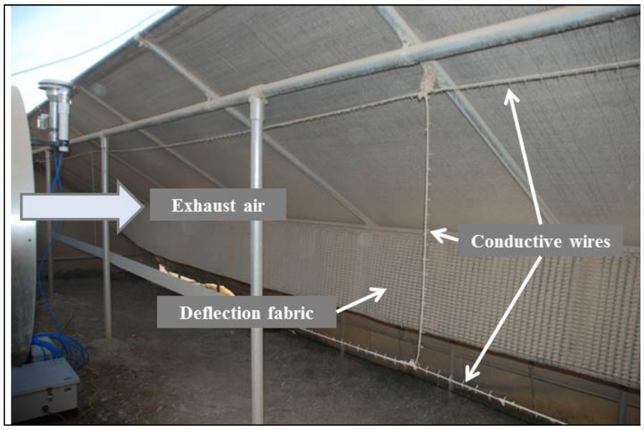


Figure 5. An EPI system installed in the BioCurtain™ enclosure to enhance the removal of PM.

Similar to the TSP measurements, NH_3 and H_2S concentrations were measured 4 m upstream of EX1 and EX2 and at a height equivalent to the center of the fan hubs. To determine the concentrations at the exhaust, measurements were taken immediately outside and at the center of the BioCurtain™ opening in the treatment house (fig. 1) and immediately downstream of EX2 in the control buildings (fig. 1). Concentrations were monitored sequentially, switching from one location to the next every 15 min. Concentrations were measured every 15 s and the averages were recorded using the CR3000 datalogger every minute.

MEASUREMENTS OF VENTILATION RATES AND ENVIRONMENTAL PARAMETERS

The performance curves of fans in both buildings were determined prior to sampling using a Fan Assessment Numeration System (FANS) (Gates et al., 2004), which is a portable fan system consisting of multiple traversing impellers. The FANS measured volumetric flow rates that corresponded to a range of static pressure. During sampling, the ventilation rate in each building was measured by manually recording the exhaust fans that were in operation and measuring the static pressure drop in the building using differential pressure tranducers (Model 260, Setra Systems, Inc., Boxborough, MA) with output scanned at 1 Hz and averaged every minute by a datalogger (Model CR1000, Campbell Scientific, Inc., Logan, UT) . The pressure transducers were calibrated before deployment and checked following recovery using a low pressure calibrator (MicroCal™ Model 869, Setra Systems, Inc., Boxborough, Mass.).The performance curves generated with the FANS were used to determine the corresponding fan flow rates.

The temperature and relative humidity in the buildings were measured every 3 min using Hobo dataloggers (HOBO® RH Temp, Onset Computer Corporation, Pocasset, Mass.) that were positioned at five locations in the building spaced about 30 m apart starting from the center of the exhaust fan hub. A portable weather station that recorded the weather data every 15 min was installed SE of the treatment house (fig. 1). Temperature, relative humidity, wind

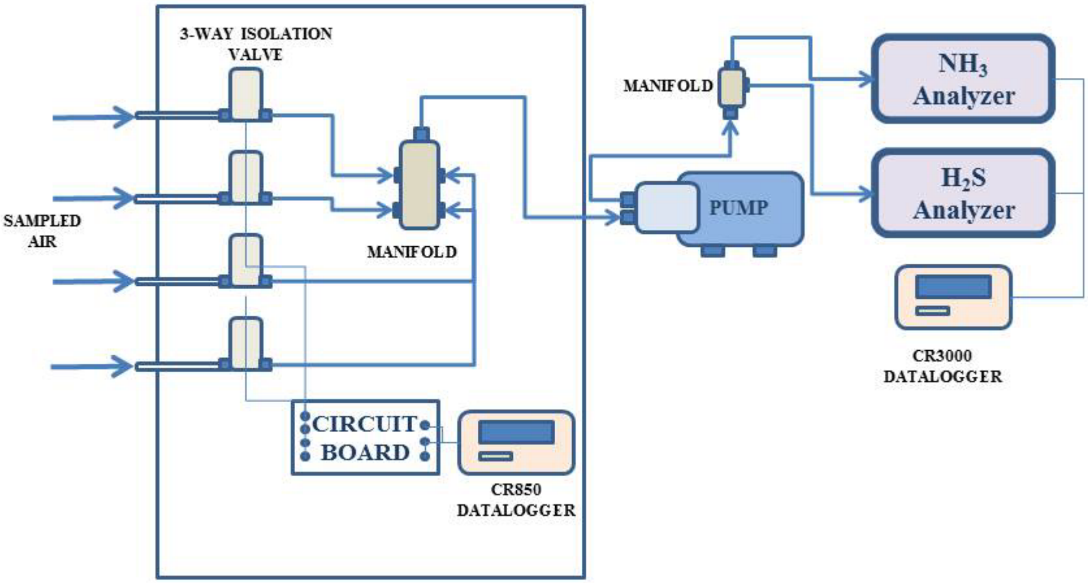


Figure 6. Schematic of the gas sampling system for NH_3 and H_2S.

speed, and direction were obtained from this site. For the calculation of emission rates of gases, atmospheric pressure data were obtained from a weather station at Corsicana Airport in Texas (station no. 483491051). Since the sea-level atmospheric pressure was reported at the station, it was adjusted for location and temperature using the exponential model of pressure presented in equation 1 (NOAA-NASA, 1976).

$$P(h) = P(0)\cdot e^{-\left(\frac{M\cdot g}{R\cdot T}\cdot h\right)} \qquad (1)$$

where
P(h) = atmospheric pressure at elevation h (Pa)
P(0) = pressure at sea level (Pa)
M = mean molecular weight of the atmosphere = 0.02897 kg/mole
h = station elevation (m)
g = gravitational acceleration, 9.80665 m/s^2
R = Universal gas constant for air = 8.31432 N-m/(mol-K)
T = air temperature at location (K)

DATA ANALYSIS

The amount of dust collected on the filters was the difference between the weights of the loaded filter and its clean weight before sampling. TSP concentration was the mass of dust collected divided by the total volume of the sampled air. The total volume of the sampled air was the product of the sampling flow rate and the sampling duration. Filters were conditioned for 24 hours prior to and after sampling and an analytical balance with a 10 µg resolution was used to determine the mass of dust collected.

The emission rates of TSP, NH_3, and H_2S were calculated by multiplying the mass concentrations of these parameters by the building ventilation rates corrected to standard conditions (20°C, 101325 Pa). Equation 2 was used to calculate the ventilation rates at standard conditions. The measured volumetric concentrations of NH_3 and H_2S were converted into mass concentrations at standard conditions using equation 3 (Zhang, 2005). For NH_3 and H_2S data analysis, the pre-equilibrium concentrations (first 3 min of a 15-min sampling period) measured when the sampling location was switched were not used in the analysis. The concentrations of PM_{10} were estimated following the procedure reported in Lacey et al. (2003). Lacey et al. (2003) reported that PM_{10} emissions from tunnel ventilated broiler facilities can be estimated using Equation 4, where PM_{10} is the emission rate per bird (gram/day/bird) and Wt is the average bird weight (g).

$$Q_s = Q_A x \left(\frac{P_A}{P_S}\right) x \left(\frac{T_S}{T_A}\right) \qquad (2)$$

$$C_m = \left(C_{vo} - C_{vi}\right)\times\frac{M}{24.1} \qquad (3)$$

$$PM_{10} = 2.44\, x 10^{-5}\, x\ Wt \qquad (4)$$

where
C_m = gas mass concentration at standard conditions (mg/m^3)
C_{vo} = gas volumetric concentrations at the exhausts (ppm)
C_{vi} = gas volumetric concentrations at the inlet (ppm)
M = gas molecular weight (17.03 g/mol for NH_3, 34.08 g/mol for H_2S)
Q_S = buildings ventilation rate at standard conditions (m^3/h)
Q_A = buildings ventilation rate at actual conditions (m^3/h)
P_S = standard atmospheric pressure (101325 Pa)
P_A = actual atmospheric pressure (Pa)
T_S = standard temperature (293.15°K)
T_A = actual temperature(°K)

A randomized block design with day treated as block was used in the analysis of data. Specifically, the proc glm procedure of the analysis of variance (ANOVA) was used to determine if there were statistically significant differences between the means of the environmental conditions, NH_3, H_2S, and TSP concentrations and emission rates in the control and treatment houses, and to determine the effect of the BioCurtain™ and EPI system on emissions abatement.

RESULTS AND DISCUSSION

ENVIRONMENTAL CONDITIONS

Table 1 provides the environmental conditions (ventilation rate, temperature, and relative humidity) in the control and treatment poultry houses. The mean temperature and relative humidity between the two houses did not vary significantly ($p>0.05$). The temperature in September ranged from 23.2°C to 32.8°C and from 14.1°C to 21.7°C in December. The fluctuation in relative humidity in December (from 24.1% to 88.4%) was higher than that in September (from 55.8% to 99.1%). In September, the average temperature and relative humidity outdoors during the two days of sampling were almost the same while in December, the average temperature was lower and the relative humidity was higher on the second day than on the first day of sampling. The daily average ventilation rates between the control and treatment buildings did not differ by more than 28%.

The wind roses in September and December (fig. 7). In September, the mean wind direction was almost South (170° from North) and the dominant wind velocity was from 0.5 to 2.1 m/s (frequency of 55%). During the two sampling days in December, the mean direction of the wind was SSE (146° from North) and the prevailing wind velocity was also from 0.5 to 2.1 m/s (frequency of 58.3%).

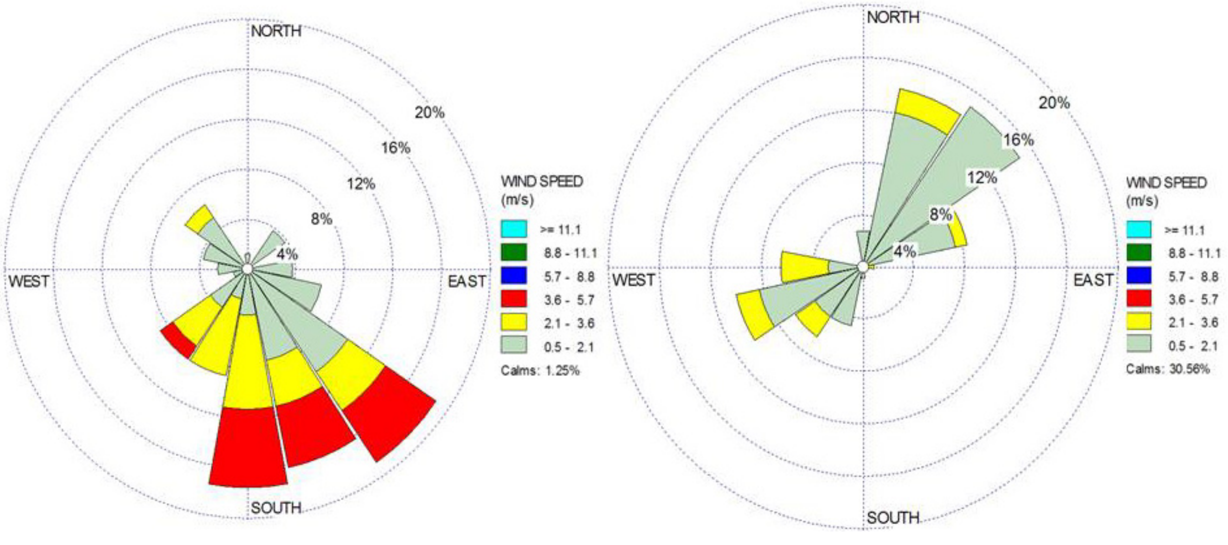
EFFECT OF THE BIOCURTAIN™

The average concentrations of NH_3 in the treatment and control houses measured in September when only the BioCurtain™ was in operation are shown in table 2. The average NH_3 concentration upstream of the exhaust fans in the treatment house was only slightly higher by 4.3% (6.3 vs. 6.0 ppm). Downstream of the exhaust fans, the average NH_3 concentration in the treatment house was significantly lower by about 25% (6.4 vs. 8.0 ppm) ($p<0.05$). The H_2S concentrations in September were below the lower detectable level (1 ppb) of the analyzer based on the manufacturer's specifications. Despite the NH_3 concentration being significantly lower at the treatment house than in the control house, there was no reduction in the NH_3 concentrations going into and leaving the BioCurtain™ (6.3 vs. 6.4 ppm). In terms of the emission rate, the incoming and exhaust NH_3 concentrations were not significantly different at the 5% level (1414 vs. 1428 g/h).

In December, the NH_3 and H_2S concentrations between the treatment and control houses upstream of the exhaust fans were about the same (table 3). Downstream of the exhaust fans, the concentrations of both NH_3 and H_2S were lower in the treatment house than in the control house by about 13 and 8%, respectively, although these differences were not significantly different ($p>0.05$). It should be noted though that the downstream concentrations in the control house is potentially influenced by the exhaust from the adjacent building. There was a slight reduction in the NH_3 and H_2S concentrations going into and leaving the BioCurtain™ in the treatment house. However, in terms of the emission rate, the NH_3 and H_2S decreased by about 9% (1040 vs. 943 g/h for NH_3 and 9.2 vs. 8.4 g/h for H_2S).

Table 1. Environmental conditions inside and outside the control and treatment poultry houses.

	Temperature (°C)							
	Control House				Treatment House			
Sampling Day	Avg.	SD	Min	Max	Avg.	SD	Min	Max
23-Sep-10	27.3	1.0	23.2	29.5	27.3	1.1	23.6	32.8
24-Sep-10	27.0	1.2	23.2	28.7	26.8	1.2	23.2	28.7
7-Dec-10	17.7	1.0	14.1	21.3	17.6	1.2	14.5	21.7
8-Dec-10	17.5	0.8	14.1	20.6	17.0	1.2	14.1	20.6
	Relative Humidity (%)							
	Control House				Treatment House			
Sampling Day	Avg.	SD	Min	Max	Avg.	SD	Min	Max
23-Sep-10	81	7	66	96	78	7	56	94
24-Sep-10	88	7	74	99	86	7	73	99
7-Dec-10	52	18	24	87	51	18	24	87
8-Dec-10	70	8	39	88	66	8	43	85
	Ventilation Rate (m^3/h)							
	Control House				Treatment House			
Sampling Day	Ave	SD	Min	Max	Avg.	SD	Min	Max
23-Sep-10	317,812	78,119	126,834	364,589	326,897	2,478	317,955	336,914
24-Sep-10	332,671	61,519	126,834	443,168	305,754	53,179	163,105	331,961
7-Dec-10	91,516	34,120	47,165	138,571	117,069	23,990	79,260	166,033
8-Dec-10	98,123	42,351	22,784	190,509	85,918	22,176	48,669	129,523
	Outside Conditions							
	Temperature (°C)				Relative Humidity (%)			
Sampling Day	Avg.	SD	Min	Max	Avg.	SD	Min	Max
23-Sep-10	29.7	3.0	23.0	33.3	59.8	16.3	65.8	96.3
24-Sep-10	28.7	3.5	21.9	32.5	68.2	17.1	48.7	98.0
7-Dec-10	10.9	3.6	1.3	14.3	33.2	10.5	23.8	65.0
8-Dec-10	6.4	2.2	2.5	9.8	74.9	14.8	53.6	96.7



(a) (b)

Figure 7. The wind rose during (a) September and (b) December sampling periods. Resultant vectors indicate the mean direction the wind blew from and the magnitude of the resultant vector is represented by the frequency count. WRPLOT View version 6.5.1 of Lakes Environmental was used to generate the plots.

A comparison of the concentrations of TSP between the treatment and control houses is presented in table 4. The average concentrations of TSP in the treatment and control houses were about the same in both September (993 vs. 975 μg/m^3) and December (3640 vs. 3620 μg/m^3). Significant differences were detected between the TSP emission rates going into the BioCurtain™ and leaving the BioCurtain™ in both September and December sampling periods. The BioCurtain™ resulted in a 34.4% reduction of TSP emission in September (325 vs. 213 g/h) and 43% reduction in December (396 vs. 227 g/h).

EFFECT OF THE EPI SYSTEM

The concentrations of NH_3 and H_2S when both the BioCurtain™ and the EPI system were in operation are presented in table 2. There were no significant differences between the concentrations of NH_3 and H_2S in the treatment and control houses in both September (5.8 vs. 5.5 ppm for NH_3; 17.9 vs. 17.7 ppb for H_2S) and December (16.5 vs. 16.9 ppm for NH_3; 49.2 vs. 49.9 ppb for H_2S). The NH_3 and H_2S concentrations downstream of the exhaust fans of the treatment house in September were significantly lower than that of the control house (6.1 vs. 7.6 ppm for NH_3 and 17.6 vs. 19.8 ppb for H_2S) while they were not significantly different in December ($p>0.05$).

The effect of the EPI on the concentrations and emission rates was determined by comparing the means between day one (when only the BioCurtain™ was in operation) and day two of sampling (when both the BioCurtain™ and EPI were in operation). In September, the NH_3 concentrations downstream of the BioCurtain™ dropped by about 5% from day one to day two. However, this minimal drop cannot be attributed to the EPI system since there was also an accompanying 8% reduction in NH_3 concentrations inside the treatment building during the same time period. In December, the NH_3 concentrations downstream of the BioCurtain™ and in the building significantly increased by about 65% and 35%, respectively. In September, the EPI significantly reduced the emission rate of NH_3 by 17% (from

Table 2. Comparison of NH_3 and H_2S concentrations and house emission rates measured in September when only the BioCurtain™ was in operation and when both the BioCurtain™ and EPI were active.

	September			
	BioCurtain			
	NH_3 (ppm)		NH_3 (g/h)	
Location[a]	Avg.	SD	Avg.	SD
Trt_In	6.3	0.5	1413.5	104.3
Trt_Out	6.4	0.6	1427.8	137.4
Ctrl_In	6.0	0.5	1263.0	426.6
Ctr_Out	8.0	0.8	1775.8	443.0

	BioCurtain and EPI							
	NH_3 (ppm)		H_2S (ppb)		NH_3 (g/h)		H_2S (g/h)	
Location	Ave	SD	Ave	SD	Ave	SD	Ave	SD
Trt_In	5.8	0.4	17.9	2.0	1178.9	243.9	7.1	1.6
Trt_Out	6.1	0.3	17.6	1.3	1236.4	249.1	7.2	1.5
Ctrl_In	5.5	0.3	17.7	1.2	1317.2	59.5	8.4	0.7
Ctr_Out	7.6	0.5	19.8	2.2	1688.2	198.7	8.4	0.9

[a] Trt = treatment, Ctrl = control, In = upstream of the exhaust fans, Out = downstream of the exhaust fans.

Table 3. Comparison of NH_3 and H_2S concentrations and house emission rates measured in December when only the BioCurtain™ was in operation and when both the BioCurtain™ and EPI were active.

	December							
	BioCurtain							
	NH_3 (ppm)		H_2S (ppb)		NH_3 (g/h)		H_2S (g/h)	
Location[a]	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Trt_In	12.2	2.5	51.8	6.9	1040.3	242.6	9.2	1.8
Trt_Out	10.6	3.9	46.8	14.8	942.7	334.4	8.4	2.8
Ctrl_In	12.0	2.4	51.5	13.0	835.3	351.2	7.4	3.7
Ctr_Out	12.2	2.3	51.1	7.5	834.7	277.1	7.2	2.3

	BioCurtain and EPI							
	NH_3 (ppm)		H_2S (ppb)		NH_3 (g/h)		H_2S (g/h)	
Location	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Trt_In	16.5	3.5	49.2	30.8	1012.5	199.5	6.1	3.9
Trt_Out	17.5	2.4	45.2	31.3	1141.6	144.7	6.0	4.0
Ctrl_In	16.9	3.8	49.9	33.2	965.7	617.4	6.1	5.2
Ctr_Out	17.3	3.9	55.4	30.6	996.0	331.5	6.6	3.9

[a] Trt = treatment, Ctrl = control, In = upstream of the exhaust fans, Out = downstream of the exhaust fans.

1414 to 1179 g/h) ($p<0.05$). A non-significant ($p>0.05$) reduction of about 3% was obtained in December for NH_3 emission rates (from 1040 to 1013 g/h) while the EPI significantly reduced the H_2S emission rates (from 9.2 to 6.1 g/h) by 34%.

Significant differences were detected in TSP concentrations in the treatment house between day one (EPI was off) and day two (EPI was on). TSP concentrations were reduced by 39% in September (993 vs. 607 μg/m^3). Similar to the gases in September, the TSP concentrations in the treatment house were lower on day two than on day one. In December, no significant differences (3640 vs. 3610 μg/m^3) were detected in the TSP concentrations in the treatment house between day one and day two indicating that the EPI system had no significant impact ($p>0.05$). In terms of the TSP emission rates, the EPI resulted in 39% (325 vs. 199 g/h) and 33% reductions in September and December, respectively.

In September, there were 25,051 birds harvested from house 1 with an average weight of 4 kg. From house 2, 24,600 birds were gathered with an average weight of 3.9 kg. Applying equation 4 derived from Lacey et al. (2003), the average emission rates were 96.6 and 95.2 mg/day/bird for houses 1 and 2, respectively. Thus, considering the number of birds in each house, total PM_{10} emissions rates were of 101.9 g/h from house 1 and 97.7 g/h from house 2 were expected.

In September, PM_{10} emissions from the BioCurtain™ measured using FRM PM_{10} samplers house 1 on day one averaged 73.6 g/h, but emissions into the BioCurtain™ (calculated by multiplying the average ventilation rate by the average interior concentration) were only 39.1 g/h. The same phenomenon was observed on day two with an emission rate into the BioCurtain™ of 25.4 g/h and an emission rate out of the BioCurtain™ of 40.6 g/h. The_measured PM_{10} emission rates being lower than those estimated using the emission factor in Lacey (2003) can be attributed to the fresh litter used in September.

The increase in calculated emission rates may be explained by the wind-speeds encountered by the samplers at the outlet of the BioCurtain™. The PM_{10} samplers (which are only subjected to wind-speeds up to 24 km/h when undergoing certification for FRM status) were exposed to high wind velocities at the outlet of the BioCurtain™ as the full ventilation airflow of a bank of fans was forced through a small opening in which the samplers were placed. The high wind speeds may lead to artificially high penetration of particles through the sampler inlet and onto the filter. Because the magnitude of these phenomena is currently unknown, the concentrations of PM_{10} measured at the outlet of the BioCurtain™ using FRM samplers should be analyzed cautiously.

ECONOMIC ANALYSIS

Fixed and variable costs of operating the automated EPI and the BioCurtain™ system for one 14 m wide and 152 m long broiler building, housing an average of 23,000 birds, are provided in table 5. It is estimated that each building houses five flocks of broiler chicken per year at a grow out rate of 63 days per flock. Useful working life of EPI and BioCurtain™ systems and repair and maintenance costs are assumed to be 10 years and 2% of the fixed cost, respectively. Two hours per week of labor cost for inspection of both systems per house is also included in the cost estimate.

Table 4. Comparison of concentrations and house emission rates of TSP measured in September and December when only the BioCurtain™ was in operation and when both the BioCurtain™ and EPI were active.

	September				December			
	BioCurtain		BioCurtain and EPI		BioCurtain		BioCurtain and EPI	
Location[a]	Concentration (μg/m^3)	ER (g/h)	Concentration (μg/m^3)	ER (g/h)	Concentration (μg/m^3)	ER (g/h)	Concentration (μg/m^3)	ER (g/h)
Trt_In	993	325	607	199	3640	396	3610	266
Trt_Out	-	213	-	134	-	227	-	138
Ctrl_In	975	-	450	-	3620	-	4170	-
Ctr_Out	-	-	-	-	-	-	-	-

[a] Trt = treatment, Ctrl = control; concentrations were measured upstream of the exhaust fans or inside the houses; for the emission rates: Trt_In was measured inside the BioCurtain™ and Trt_Out was measured at the exhaust side of the BioCurtain™ .

Table 5. Breakdown of the cost items used to estimate dust and odor mitigation cost.

Cost Items		Materials ($)	Labor ($)	Total Cost ($)
Fixed cost (for 10 years)	2 BioCurtain™ Systems	18,997	3,000	21,997
	EPI™ System	23,035	1,800	24,825
Fixed cost per year per barn spread over 10 years				4,682 yr^{-1}
Variable cost (based on 315 days per year operation)	Electricity			
	2 BioCurtain™ Systems	0.103 kW × 23 h/d × 315 d × $0.08/kWh		60 yr^{-1}
	EPI™ System	0.103 kW × 4 units × 23 h/d × 315 d × $0.08/kWh		239 yr^{-1}
	Labor	1 labor × 2h/wk × 45 wks × $10/h		900 yr^{-1}
	Repair and maintenance	2% of total fixed cost ($46,822) per year		936 yr^{-1}
				Variable cost = $2,135 yr^{-1}

For the EPI system, there are four power supply units that use a maximum of 103 W of power per unit. Therefore, total power usage for the system is estimated to be 412 W for 23 h a day of operation. The system is shutoff for cooling of power supply units for one hour during every 24 h of operation. It is assumed that the EPI system runs for 315 days per year. At $0.08 per kWh, the total cost of electricity is $239 per year per house. For the mini EPI systems in the two BioCurtain™ systems per house, they run on one power supply unit at 103 W. Assuming the same operation time for the mini EPI power supply unit as the main EPI system inside the house, at $0.08 per kWh, the total cost of electricity is $60 per year per house. The estimated number of broiler birds finished per house per year is 115,000. Therefore, the total cost (combined fixed and variable costs) of mitigation using the two technologies was estimated to be $0.06 per bird.

CONCLUSION

This study tested the effectiveness of a BioCurtain™ and Electrostatic Particle Ionization (EPI) system in reducing NH_3, H_2S, TSP, and PM_{10} emissions from a broiler building. Measurements were done in September and December 2010 in treatment and control buildings. Results of the study suggest that the BioCurtain™ and EPI system shows promise in reducing the NH_3, H_2S, and TSP emission rates. Reductions of as much as 8% for both NH_3 and H_2S, and 43% for the TSP emissions were achieved with the BioCurtain™ operating independently. The addition of the EPI decreased the emission rates by as much as 17%, 34%, and 39% for NH_3, H_2S, and TSP, respectively. Although the system shows promise and its application in a broiler facility is technically feasible, further tests are needed to confirm the initial results and determine the economic feasibility of operating the system long term. Economic analysis showed that operating the automated EPI and BioCurtain™ system for one 14 m wide and 152 m long broiler building housing an average of 23,000 birds will cost $0.06 per bird.

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