Ammonia Concentrations and Emission Rates at a Commercial Poultry Manure Composting Facility

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ABSTRACT. Composting facilities are essential parts of most manure-belt (MB) poultry houses in the U.S., but their NH₃ concentrations and emission are not well understood. This may affect farm operation safety and limit the development of NH₃ mitigation and management strategies. The study aimed to quantify NH₃ concentrations and hen-specific emission rates (ER) at a commercial poultry manure composting facility and to understand their diurnal and seasonal

variations. Two large tunnel-ventilated composting buildings with twelve 122-cm exhaust fans were chosen as the study site, which received manure from four on-site manure-belt layer barns. The inlet and exhaust NH_3 concentrations at the compost building were monitored quasi-continuously for one month per season for two years. Ammonia ERs were calculated based on the NH_3 concentrations and building ventilation rates. The average daily mean $\pm$ SD of the NH_3 concentrations in spring, summer, fall, and winter were 114 ± 20 , 144 ± 35 , 115 ± 13 , and 141 ± 25 ppmv, respectively. Seasonal and diurnal variations existed in both NH_3 concentrations and ERs. The daytime NH_3 ER was significantly higher than that of night time. These results showed that NH_3 emissions from composting facilities are considerably high, and thus mitigation strategies are needed to further reduce NH_3 from the whole MB layer facility system.

KEYWORDS. Poultry, manure, layer hens, composting, ammonia emissions

1 Introduction

Ammonia (NH_3) is a major pollutant gas emitted from poultry facilities as a result of the microbial degradation of uric acid present in poultry manure. The United States Environmental Protection Agency (USEPA) National Emission Inventory estimated that animal production and other agricultural activities released about 2,418,595 tons of NH_3 to the atmosphere in 2002, which comprised 80.9% of the total anthropogenic NH_3 emissions in the U.S. (USEPA, 2004). Ammonia is a significant environmental and public concern as it attacks both the respiratory and cardiovascular systems of humans (Frank et al., 2012; Wing and Wolf, 2000). It can cause ecosystem acidity and fine $\text{PM}_{2.5}$ (particulate matter with diameter less than $2.5\text{ }\mu\text{m}$) formation in the presence of NO_x or SO_x , which generates haze that reduces visibility (NRC, 2003).

The majority of egg layer houses in the U.S. are two types: high-rise (HR) and manure-belt (MB) houses. In HR houses, manure is normally stored in deep pits under the cages of hens for 6–12 months before it is removed. In MB houses, manure is typically removed from the layer houses every 1–3 days using conveyor belts and transferred to manure storages or compost buildings. The MB houses have significantly less NH_3 emissions from the houses themselves in comparison with conventional HR houses due to early manure removal. Based on recent studies, the average daily mean NH_3 emission rate from HR houses can range from $0.59\text{--}1.57\text{ g d}^{-1}\text{ hen}^{-1}$, while from MB buildings with 1–4 days of manure removal, $0.05\text{--}0.48\text{ g d}^{-1}\text{ hen}^{-1}$ (Wang-Li et al., 2013; Lin et al., 2012; Liang et al., 2005; Keener et al., 2002). Little research has been done to quantify NH_3 emission from on-site external facilities that treat and/or store manure from MB houses. These facilities are an integral process component of MB egg layer production and can emit

1 significant amounts of NH_3 . Liang et al. (2005) observed an NH_3 emission rate of $0.10 \text{ g d}^{-1} \text{ hen}^{-1}$
2 from the external storage shed for manure from MB houses, giving an overall NH_3 emission rate
3 of $0.15\text{--}0.19 \text{ g d}^{-1} \text{ hen}^{-1}$ for the entire poultry facility. Between 2009 and 2013, all newly built
4 poultry facilities utilized the manure belt systems, and by 2013 about 45% of the poultry
5 facilities in the U.S. use the MB system (Lippi, 2013). It is therefore important to understand
6 NH_3 concentrations and emissions at poultry manure composting facilities for effective
7 mitigation of NH_3 emissions to improve farm and neighbourhood safety.

8
9 Composting is an attractive waste treatment technology, as it produces organic fertiliser that are
10 more stable and can be stored or applied to soil with little or no odour, pathogens, weed seeds, or
11 fly larvae (Pitaway, 2002; Hao et al., 2001). Composting involves the growth of aerobic
12 microorganisms present in the poultry manure. Adequate air and moisture would allow these
13 microorganisms to feed on the poultry manure and break them down into nutrients. There are a
14 couple of methods used to manage manure from MB houses: one is through static manure piles
15 and then the other one is windrow composting. For the static manure storage, manure is piled in
16 a shed with little aeration until it is used by nearby crop farmers for fertiliser. This type is not
17 labour-and energy-intensive but may result in slow composting and may potentially lead to odour
18 problems on the end-products. For windrow composting, manure is placed in long windrows that
19 are turned every week or two-week cycle using bucket loaders or commercial turning machines.
20 This may be energy-intensive, but can speed up the compost process resulting in a more finished
21 by-product. Typically, compost storages for this type of composting are equipped with
22 ventilation system that provides adequate aeration during composting and helps prevent the
23 build-up of toxic and flammable decomposition gases inside the composting facility.

1
2 The composting processes may therefore still result in substantial air emissions, which may not
3 only reduce the agronomic value of the compost, but also potentially harm the environment with
4 the release of gases like NH_3 , nitrous oxide (N_2O), and methane (CH_4). Among these gases, NH_3
5 has the highest economic impact because its loss reduces the fertiliser value of the compost.
6 Studies are therefore needed to quantify the NH_3 emitted from layer manure composting
7 facilities. This will enable further development of innovative technologies for the abatement and
8 recovery of NH_3 emissions from poultry facilities, which can help protect the environment and
9 conserve nitrogen from manure compost in today's high fertiliser cost environment.

10
11 Important factors that affect NH_3 emissions during manure composting include temperature,
12 moisture content, pH, initial nitrogen content of the manure substrate, aeration, the compost
13 storage ventilation rates, and the type of composting process. According to Pagans et al. (2006),
14 NH_3 emissions increased exponentially during the thermophilic first stage ($>45^\circ\text{C}$) and linearly
15 within the mesophilic final stage ($25\text{--}40^\circ\text{C}$) of composting. High pH (>7) and aeration rate
16 increases NH_3 emission, while high C/N ratio decreases it (Matsuda et al., 2002). Hellebrand and
17 Kalk (2001) reported that aeration rate and C/N ratio have effects on the type of nitrogen
18 transformations. High aeration rate and low carbon content result in nitrite accumulation and
19 incomplete ammonium oxidation, which lead to high NH_3 emissions.

20
21 Ammonia emissions from composting processes have been measured in several laboratory
22 studies. Matsusada et al. (2002) showed that NH_3 emissions from composting animal manure
23 varied from 323 to 2840 mg kg^{-1} for swine, 41 to 458 mg kg^{-1} for dairy, and 15 to 2740 mg kg^{-1}

for poultry manure for aeration rates ranging from 0.2 to 1.4 L min⁻¹ kg⁻¹ and C/N ratios from 13 to 43 for swine, 19 to 42 for dairy, and 19 to 56 for poultry, respectively. Hao et al. (2001) documented that about 42% of the total nitrogen was lost during the composting of straw bedded manure from cattle feedlot manure. Most of the NH₃ emissions occur within the initial three weeks of the composting period while the peak of N₂O emissions occur in the middle of the composting period (Hellebrand and Kalk, 2001). Keener and Zhao (2008) estimated NH₃ emissions from a poultry composting facility using a mass-balance approach and concluded that the NH₃ emission rates from MB houses and the composting facility during March and July 2000 were about 0.42 and 0.45 g d⁻¹ hen⁻¹, respectively. These estimated values obtained from the mass balance approach did not compare well with measured values of 1.45 and 0.75 g d⁻¹ hen⁻¹ (Kenner and Zhao, 2008).

Existing literature shows that the significant variations in NH₃ emissions from composting facilities were due to the differences in types and management practices of composting facilities, active management of ventilation rates in compost storages, and technologies and methodologies utilized for NH₃ emission measurement or estimation. Long-term field measurements using reliable monitoring technology are necessary to accurately characterize NH₃ emissions from commercial composting facilities. The objectives of this study were to: (1) quantify the NH₃ concentrations and hen-specific NH₃ emission rates (ERs) at a commercial layer manure composting facility, (2) evaluate the diurnal and seasonal variations of NH₃ concentration and ER, and (3) estimate the annual NH₃ ER from composting houses and compare it with other sources of NH₃ in agriculture.

2 Materials and Methods

2.1 The Composting Facility

A commercial poultry manure composting facility in Ohio was monitored in this study. It consists of two mechanically-ventilated hoop structures covered with plastics that received poultry manure from four adjacent manure-belt layer houses containing a total of 0.83 million Hyline laying hens (Figure 1). Manure from one layer house was removed once every day and about one-fifth of the total manure was transported using a manure belt and dropped to the beginnings of six composting windrows in building 1 or 2 according to the capacity availability of the windrows. No external carbon sources were further added into the manure for composting. Also, the MB houses did not use any drying mechanisms besides the natural evaporation of moisture from manure on the belt before it was transferred to the compost buildings. The two compost buildings have the same length of 108 m but differ in width, 64 m wide for building 1 and 32 m wide for building 2. Therefore, building 2 is half the size of building 1. The compost buildings were tunnel ventilated, which means that exhaust fans are located at one end of the building with air inlets or openings located at the opposite end. As a result, air is drawn through the openings toward the compost piles then exhausted toward the atmosphere. There were a total of 12 fans in the composting facility: eight fans from Building 1 and four fans from Building 2 where the measurement and instrumentation were set up. The exhaust fans were continuously operated with constant airflow rates all year round.

A total of three Salmeter composters (SALMET®, SALMET International GmbH, Dietzenbach,

Germany) that turned the manure into a dry product suitable for fertiliser applications were used. Two composters were used for building 1 with six windrows and one for building 2 with three windrows. The composters turned the windrows row by row every day from 8:00 am to 5:00 pm. Two rows of compost windrows were turned each day. The poultry manure was moved forward 5.48 m (18 ft) every three days toward the compost storage areas (Figure 1) and exited the composting lanes after 54 days or until the compost was picked up for use by nearby crop farmers.

Insert Figure 1

2.2 Measurement Plan and Instrumentation

The NH_3 concentrations at the air inlet and exhaust ends of building 2 (Figure 2) were measured continuously for about a month during each of the four seasons: spring, summer, fall, and winter for two years (year 1 and year 2). Table 1 summarizes the actual dates of the measurement periods and the numbers of valid measurement days.

Insert Figure 2

Insert Table 1

The air samples were drawn using a Teflon gas sampling line and a gas sampling probe located at the inlet of one of the four 122-cm axial exhaust fans (Figure 3). Ammonia concentration was measured using a photo-acoustic NH_3 analyser (MSA Chillgard RT, MSA Inc., Pittsburg, PA),

1 which had an accuracy of ± 1 ppmv. It drew air samples at a flow rate of 0.75 L min^{-1} and
2 equilibrated to 90% of a concentration step change in 70 s. Particulate filters were installed at
3 both ends of the Teflon sampling line to prevent contamination of the NH_3 sensor. To withstand
4 the highly corrosive environment and varied ambient weather conditions, the NH_3 analyser was
5 housed in a NEMA 4 enclosure, which was ventilated using fans with automatic control to
6 achieve a workable environment for the analyser. The sampling lines were also heated using heat
7 tapes and insulated to prevent condensation inside the sampling tubes. Data acquisition (U12
8 data logger, Onset Computer Corp, Pocasset, MA) was installed on the analogue signal output of
9 the NH_3 analyser to quasi-continuously record NH_3 concentration at 2-min intervals. Before and
10 after each measurement period, the NH_3 sensor was zero calibrated using nitrogen gas and span
11 calibrated using a certified 1000 ppmv NH_3 calibration gas with accuracy of $\pm 5\%$.

12
13 Temperature and relative humidity were continuously measured at the two NH_3 sampling
14 locations using a HOBO RH/temp sensor connected to a data logger (U23 Temperature/RH data
15 logger, Onset Computer Corp, Pocasset, MA) that obtained data every 2 mins. New HOBO
16 Temp/RH sensors were used during year 1 test period, but during year 2 test period, they were
17 calibrated using a laboratory instrument (EdgeTech RH Calibrator, Hudson, MA).

18
19 For the ambient temperature and relative humidity, the hourly weather data was obtained from
20 the Delaware station through Ohio Agricultural Research and Development Center (OARDC,
21 n.d.) weather system over the year 1 and year 2 test periods. Table 1 also summarizes the
22 ambient weather conditions reported as daily averages for each season of year 1 and year 2 test
23 periods. The average daily ambient temperature observed from the entire test periods ranged

1 from -5.2 to 31.6 with a mean $\pm$ standard deviation of 14.6 ± 9.5 °C. The average daily means of
2 ambient relative humidity during individual test periods ranged from 22.4 to 98.6% with an
3 overall mean of 74.7 ± 18.6 %.

4
5 Insert Figure 3

6 7 2.3 Determination of Manure and Compost Characteristics

8
9 Samples of manure and compost were sent to Service Testing and Research (STAR) Lab through
10 the OARDC for the analysis of pH, total solid content, moisture content, volatile solids, and total
11 nitrogen. Fresh manure samples coming from the poultry houses on the conveyor belt before the
12 composting building were obtained for analysis. About 50 grams of samples were collected for
13 both fresh manure and compost. The compost samples were obtained from random piles for each
14 season when the compost was ready for pick up. The exact dates when the compost was obtained
15 were: 6 Jun 07, 08 Aug 07, 10 Oct 07, and 11 Jan 08. About six 5-g samples were drawn for each
16 analysis. This analysis was only done during year 1 test period. No manure and compost samples
17 were obtained during the year 2 test period.

18 19 2.4 Determination of Ventilation Rates

20
21 A portable fan tester called Fans Assessment Numeration System (FANS) (Gates et al., 2004)
22 was used to determine the actual fan ventilation rates. The FANS was calibrated at the University
23 of Illinois Bioenvironmental and Structural Systems (BESS) Laboratory (Ford, 2006). The

measured airflow rate was expressed in terms of standard dry air conditions (20°C and 1 atm) and calculated using Equations 1 and 2 (ASHRAE, 2009):

$$Q_{\text{dry}} = Q_{\text{moist}} \times (1 - W) \quad (1)$$

$$Q = Q_{\text{dry}} \times \left(\frac{20 + 273.15}{T} \right) \quad (2)$$

where Q is the standard airflow rate ($\text{m}^3 \text{ hr}^{-1}$), Q_{dry} is the dry airflow rate ($\text{m}^3 \text{ hr}^{-1}$), Q_{moist} is the actual moist airflow rate obtained from the FANS measurements ($\text{m}^3 \text{ hr}^{-1}$), T is the dry-bulb temperature (K), and W is the humidity ratio.

The ventilation rates of the two exhaust fans at building 2 were measured and averaged to represent the mean air flow rate of individual exhaust fan of the composting buildings. Although the FANS can also quantify the static pressure drop, a digital manometer (Alnor, TSI Inc., Shoreview, MN) was still used to confirm differential static pressure measurements inside building 2 and the exhaust fans where the rates were measured. The total ventilation rate of the entire composting facility (building 1 and building 2) was then estimated as the average ventilation rate per fan multiplied to the total number of fans (12 fans) in the facility.

Gas sampling was done in building 2 due to ease in location and its accessibility to the main power supply. The two exhaust fans closer to the side walls and the main entrance door were practically chosen to minimise the length of gas tubes and heat tapes needed for sampling. It was assumed that the tunnel ventilation system would result in negligible spatial and temporal variations of air inside the facility and thus the gas sampling locations would not significantly

1 impact measurement readings.

2 3 2.5 Hen-Specific Emission Rate Calculation

4
5 The hen-specific NH₃ ER was calculated in terms of the total NH₃ release rate from the compost
6 facility exhaust fans normalized by the number of laying hens inside the four poultry houses that
7 generated manure towards the composting buildings. Equation 3 shows the calculation of NH₃
8 ER:

$$9 \quad ER = Q_{\text{total}} \times (C_{\text{NH}_3,0} - C_{\text{NH}_3,i}) \times 24/N \quad (3)$$

10
11 where ER is the hen-specific NH₃ emission rate of the entire compost facility (g d⁻¹ hen⁻¹), Q_{total}
12 is the total ventilation rate using the standard dry air conditions (m³ hr⁻¹), C_{NH₃,0} is the NH₃
13 concentration at the exhaust fan (mg m⁻³), C_{NH₃,i} is the NH₃ concentration at the building inlet
14 (mg m⁻³), and N is the total number of hens inside the egg layer barns.

15 16 2.6 Data Processing and Analysis

17
18 The data were processed using MS Excel, which was used to calculate daily, seasonal, and
19 annual averages of NH₃ concentration, NH₃ ER, and indoor environmental conditions for year 1
20 and year 2. The daily means refer to the average hourly means of the 2-min data observed over
21 the 24-h period. The seasonal means were the average daily means observed in each season,
22 while the annual means were the average seasonal means over the four seasons. The overall

seasonal means and the overall annual mean were also reported as the average seasonal and annual means from year 1 and year 2. The daily means were treated independently in the analysis, although strong correlation between days may exist. Instruments tend to malfunction due to harsh environmental conditions in the farm. Invalid readings caused by dust loads on the filter, condensation, and moisture were removed from the overall data analysed.

The processed data were analysed using JMP[®] 9.0 (SAS Institute Inc., Cary, NC). An analysis of variance (ANOVA) was conducted to evaluate the significant effects of weather conditions such as temperature, relative humidity and seasonal effects on NH₃ concentrations and NH₃ ERs. The significant differences in the seasonal means of temperature, relative humidity, NH₃ concentrations, and NH₃ ERs each year were analysed using Tukey-Kramer Honest Significant Difference (HSD) test. A level of significance of 0.05 was used in the analysis.

3 Results and Discussion

3.1 Manure and Compost Characteristics

The characteristics of both manure and compost obtained for a day in each season of year 1 are summarized in Table 2. The average pH values of both manure and compost were within neutral to basic range, which ranged from 6.9-8.3 and 8.0-8.6, respectively. The manure moisture content of the manure was highest during summer, averaging to about 71±4%, followed by that during winter averaging to about 59±10%. The moisture content of the compost ranged from 28-41%, which was more evident during summer and winter. The % solids in manure averaged

between 29 and 50%, and in compost, 28 and 41% on a wet basis. The volatile solids out of the total solids were about 62-67% in manure and 56-61% in compost. The nitrogen content was only about 5-6% in manure and 4-6% in the compost.

Insert Table 2

3.2 Seasonal Variations in Ammonia Concentrations and Emission Rates

Table 3 summarizes the seasonal means of NH_3 concentrations, ERs, and indoor environmental conditions observed in year 1 and year 2 test periods, the overall seasonal means, and the overall annual means. From the calculated daily averages, the season mean NH_3 concentrations in spring, summer, fall, and winter were 117 ± 25 , 152 ± 42 , 116 ± 24 , and 157 ± 66 ppmv, respectively. This corresponds to NH_3 ERs of 0.61 ± 0.13 , 0.82 ± 0.22 , 0.66 ± 0.13 , and 0.99 ± 0.40 g d⁻¹ hen⁻¹ in spring, summer, fall, and winter, respectively. The indoor temperature observed were 12.2 ± 7.7 , 26.3 ± 2.7 , 18.5 ± 4.4 , and 4.8 ± 5.5 °C, while the relative humidity values were 69.8 ± 13.5 , 87.5 ± 7.4 , 91.8 ± 7.3 , and 97.5 ± 7.6 % in spring, summer, fall, and winter, respectively.

Insert Table 3

Figure 4 also plots the daily averages of NH_3 concentrations, ERs, indoor temperatures and relative humidity for four seasons in year 1 and year 2. Based on the entire data collected, the daily NH_3 concentrations varied from 59 to 278 ppmv with an overall mean of 134 ± 47 ppmv. An ANOVA showed a significant effect of season on the NH_3 concentrations [$F(3, 142) = 9.66$, $p <$

0.0001]. Higher NH_3 concentrations were observed in harsher seasons (winter and summer) than in milder seasons (spring and fall). Post-hoc Tukey test showed that the daily mean NH_3 concentrations in winter and summer were not significantly different from each other ($p < 0.05$) when higher concentrations were observed. The NH_3 concentrations observed in the milder conditions of spring and fall seasons were also not significantly different ($p < 0.05$).

The daily NH_3 ERs ranged from 0.32 to 1.61 $\text{g d}^{-1} \text{ hen}^{-1}$ with an overall mean of $0.77 \pm 0.28 \text{ g d}^{-1} \text{ hen}^{-1}$. As expected, the NH_3 ERs positively correlated with NH_3 concentrations because the airflow was constant throughout the test periods. High NH_3 ERs were observed in winter and summer due to high NH_3 concentrations observed during this season. This may be attributed also to lower temperature in winter and greater humidity in summer that may have reduced the drying of the compost material, resulting in more ammonia emissions.

The indoor temperatures of the facility varied from -5.2 to 31.6°C with a mean of $14.7 \pm 9.4^\circ\text{C}$. As expected, an ANOVA revealed that season had a significant effect on temperature [$F(3, 142) = 93.78, p < 0.0001$]. Post-hoc Tukey test that the temperature from all season were different from one another. Additionally, the indoor relative humidity varied from 39.95 to 100%, with an average of $86.6 \pm 13.0\%$. The compost building always had high relative humidity, with the maximum observed in winter, as the manure from the layer houses arrived with more moisture content in cool weather. This in effect, also caused the increase in NH_3 concentrations and ERs during highly humid days. An ANOVA over the entire data set showed that temperature did not have a significant effect on NH_3 ER [$F(3, 142) = 9.66, p < 0.0001$]. However, the NH_3 ER only showed a slight linear correlation with indoor air temperature at lower temperature range during

winter ($r = 0.51$, $n = 40$, $p = 0.0007$) as shown in Figure 5. Relatively high moisture content of the compost during winter may also have additional effect on NH_3 ER.

Insert Figure 4

Insert Figure 5

3.3 Diurnal Variations in Ammonia Concentrations and Emission Rates

Figures 6 and 7 show the diurnal variations of NH_3 concentrations and NH_3 ER observed in each season of year 1 and year 2. The variations in NH_3 concentrations correlated well with NH_3 ERs. Strong diurnal variations existed in all four seasons, but were more evident in summer and winter. In year 1, winter conditions were in a much colder range, and the increase in humidity levels caused NH_3 concentrations and NH_3 ERs to be extremely high (Figure 6a), which ranged from 231 to 319 ppmv and 56.7 to 80.4 $\text{mg hr}^{-1} \text{ hen}^{-1}$, respectively. Additionally, the NH_3 concentrations in year 1 for spring, summer, and fall seasons did not significantly differ from one another. They varied within the day from 81 to 223, 117 to 215, and 104 to 196 ppmv, respectively. The same trend was observed for NH_3 ERs, which varied daily from 17.9 to 47.1, 26.7 to 45.8, and 24.2 to 42.5 $\text{mg hr}^{-1} \text{ hen}^{-1}$. In year 2, the milder winter condition did not produce high values of NH_3 concentrations and NH_3 ERs during this season. The daily variations of hourly NH_3 concentrations and ERs of each season did not significantly differ from one another in year 2 (Figure 6b). Ammonia concentrations in year 2 varied from 80 to 198, 68 to 157, 88 to 164, and 99 to 171 ppmv in spring, summer, fall, and winter, respectively. The NH_3 ERs in year 2 varied daily from 17.1 to 42.1 kg, 15.8 to 34.2, 25.8 to 43.3, and 24.2 to 42.5 mg

1 $\text{hr}^{-1} \text{ hen}^{-1}$, for spring, summer, fall, and winter, respectively. The fluctuations in NH_3
2 concentrations and NH_3 ERs during the day were likely due to the compost turning operations.
3 Because a turning machine was used to turn three rows of the compost sequentially from 8:00
4 a.m. to 5:00 p.m. every day, at most three peaks of NH_3 ERs were observed.
5
6 The daytime averages (from 8:00 a.m. to 5:00 p.m.) of NH_3 concentrations and ERs were
7 significantly higher than those of night-time averages. The overall daytime averages of NH_3
8 concentrations in spring, summer, fall, and winter were 159 ± 3 , 154 ± 33 , 143 ± 30 , and 212 ± 94
9 ppmv, respectively. The overall night-time averages of NH_3 concentrations for each season were
10 98 ± 4 , 115 ± 22 , 109 ± 9 , and 180 ± 84 ppmv, respectively. The NH_3 concentrations during normal
11 work hours showed that the composting facility posed greater risks to the workers working inside
12 composting with potential respiratory exposure to NH_3 and other contaminants such as
13 particulate matter. The Occupational Safety and Health Administration (OSHA) set a permissible
14 exposure limit (PEL) of 50 ppmv for NH_3 as an 8-hour time-weighted average (TWA) (OSHA,
15 2012). The National Institute for Occupational Safety and Health (NIOSH) recommended
16 exposure limit (REL) is 25 ppmv TWA and 35 ppmv STEL (NIOSH, 1994). Such exposure may
17 lead to blindness, pulmonary edema, and eye, skin, and lung irritation to humans, but NH_3 levels
18 higher than 100 ppmv are proven to have more pronounced effects such as cardiovascular and
19 respiratory damages (Ryer-Powder, 1991; NIOSH, 1994). Exposure to NH_3 plus PM can also
20 have adverse effects on humans, which may lead to chronic bronchitis, hypersensitivity
21 pneumonitis, and permanent lung damage (Whyte, 1993). It is therefore recommended that
22 producers assure that workers are protected with appropriate respirators when they are entering
23 the composting facility or at the downwind location of the exhaust fans for an appreciable length

of time. New poultry workers should be educated about the air quality at composting facilities and the health effects of the exposure to NH_3 and other air contaminants on humans before they are on duty. Protective masks should also be properly sized and fit-tested for each individual worker.

Insert Figure 6

Insert Figure 7

3.4 Annual Ammonia Emission Rate and Emission Rates

Table 4 lists NH_3 ERs from previous publications in comparison with this study. Based on the average NH_3 ERs obtained from each one-month monitoring period, the overall average NH_3 ER of the composting facility over a total of 172 d was $0.72 \pm 0.13 \text{ g d}^{-1} \text{ hen}^{-1}$. Keener et al. (2002) also estimated NH_3 ER from the MB houses and the composting facilities at this site using mass-balance analysis as $0.10 - 0.48 \text{ g d}^{-1} \text{ hen}^{-1}$ and $0.50 - 0.70 \text{ g d}^{-1} \text{ hen}^{-1}$, respectively, with a total NH_3 ER of $0.6 - 1.18 \text{ g d}^{-1} \text{ hen}^{-1}$ from the entire MB layer facility system. The total NH_3 ER was comparable with that from high-rise houses (Lim et al., 2008; Liang et al., 2005; Lin et al., 2012). Although emissions from MB houses are lower than HR houses, the composting facility attached to the MB house has significant additional contributions to the whole-farm NH_3 emission. Based on this study, the daily NH_3 emission from the composting facilities was 596 kg d^{-1} , while the annual NH_3 emission was about 218 Mg (metric tons). Therefore, it may be beneficial to reduce NH_3 emissions and to study the economic benefit of recovering NH_3 lost from composting of layer manure.

Insert Table 4

3.5 Sources of uncertainty

A major source of uncertainty for the reported values of NH_3 concentration and emission rates in this study is that the measurement of ventilation rates and NH_3 concentrations were obtained only from building 2. It was assumed that the composting operations were similar to both composting buildings, so that their air properties did not vary significantly. The measurements conducted in this study were also bound to uncertainties. The performance of the FANS measurement units vary for each fan model and therefore, the imprecision cannot be quantified. A study by Gates et al. (2004) showed that the FANS uncertainty can vary from $71\text{-}286\text{ m}^3\text{ hr}^{-1}$, which may impact our reported NH_3 emission factor by 0.008 to $0.04\text{ g hen}^{-1}\text{ day}^{-1}$. Other sources of uncertainty are the variations in the performance of the fans, variations in ventilation rates over time, differences in air densities, and variability in the number of hens within the test periods. The location of the gas sampling point in front of the fan can also add to the uncertainty on the measurement of NH_3 concentration.

4 Conclusions

The NH_3 concentration and hen-specific NH_3 ER from a composting building attached to manure-belt poultry houses were monitored continuously for about a month in each season of two different monitoring years (year 1 and year 2). The overall average daily mean NH_3

1 concentrations in spring, summer, fall, and winter were 114 ± 20 , 144 ± 35 , 115 ± 13 , and 141 ± 25
2 ppmv, respectively. These corresponded to overall daily NH_3 ER of 0.60 ± 0.09 , 0.77 ± 0.18 ,
3 0.65 ± 0.06 , and 0.88 ± 0.17 g d⁻¹ hen⁻¹ in spring, summer, fall, and winter, respectively. Seasonal
4 variations existed in both NH_3 concentrations and NH_3 ER.

5
6 There was a strong seasonal and diurnal variation of the temperature inside the compost facility,
7 which varied from -5.2 to 31.6 °C with a mean of 14.6 ± 9.5 °C. The compost building had high
8 relative humidity throughout the year, ranging from 39.95 to 100%, with an average of
9 $86.9\pm14.1\%$. The maximum humidity levels were most evident during the winter when manure
10 from layer houses was wetter.

11
12 Strong diurnal variations were observed in NH_3 concentrations and ERs existed for spring and
13 summer seasons. Fluctuations observed within a day were likely due to the composting turning
14 operations. The daytime NH_3 concentrations and NH_3 ERs were also significantly higher than
15 those at night-time. The daytime averages of NH_3 concentrations were 159 ± 3 , 154 ± 33 , 143 ± 30 ,
16 and 212 ± 94 ppmv, respectively. Safety precautions should be observed by poultry workers to
17 minimize their exposure to NH_3 and other air contaminants during normal working hours.
18 Properly sized and fit-tested respiratory masks with correct filters should be worn at all times
19 when going in the vicinity and inside the composting facility.

20
21 The estimated annual average emission factor of the composting facility was 0.72 ± 0.13 g d⁻¹ hen⁻¹
22 ¹ based on the seasonal average daily emission rates. The estimated total NH_3 ERs from the
23 composting facilities was 596 kg d⁻¹ and 218 Mg (metric tons) annually. This result showed that

the entire MB production facility, including both the MB poultry house and its composting facilities had a total NH₃ ERs comparable to those of high-rise poultry facilities. Thus, to further reduce NH₃ emissions from the whole MB layer facility operating with composting facilities, additional ammonia mitigation strategies are recommended.

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Figure 3. Schematic cross-section view of the sampling system.

Figure 4. Daily mean NH₃ emission rates, NH₃ concentrations, and indoor environment (temperature and relative humidity) at the composting facility observed in year 1 and year 2 test periods.

Figure 5. Correlations of temperature with NH_3 emission rates from measurements obtained from spring, summer, and fall versus that from winter of year 1 and year 2 test periods.

Figure 6. Daily diurnal variations of ammonia concentrations in different seasons for (a) year 1 and (b) year 2.

Figure 7. Daily diurnal variations of ammonia emission rates of the composting facility in

- 1 different seasons for (a) year 1 and (b) year 2.
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List of Tables

Table 1. Actual measurement period and number of valid measurement days in years 1 and 2.

A. Year 1				
Season	Dates	Valid Days	Temperature (°C)	Relative Humidity (%)
Spring	23 May 07 to 12 Jun 07	21	19.3±6.3	66.7±20.1
Summer	4 Aug 07 to 01 Sep 07	19	23.0±4.8	77.7±17.4
Fall	03 Oct 07 to 24 Oct 07	22	11.6±6.2	74.1±19.2
Winter	04 Jan 08 to 05 Feb 08	33	-0.4±7.7	76.9±15.8
B. Year 2				
Season	Dates	Valid Days	Temperature (°C)	Relative Humidity (%)
Spring	9 May 12 to 25 May 12	16	17.5±6.5	66.3±22.8
Summer	13 Jul 12 to 7 Aug 12	25	24.3±4.7	73.9±18.8
Fall	22 Sept 12 to 11 Oct 12	20	11.7±5.4	79.8±18.4
Winter	23 Dec 11 to 09 Jan 12	16	3.6±2.7	77.7±12.1

Table 2. Characteristics of (A) manure and (B) compost samples obtained from each season of year 1 test period only.

A. Manure					
Sampling event	pH	% Moisture	% Solids	% Volatile solids	% Total nitrogen
Spring	7.6±0.7	50±2	50±2	67±1	5±1
Summer	6.9±0.2	71±4	29±4	62±2	5±1
Fall	8.1±0.8	55±10	45±10	62±3	6±1
Winter	8.3±0.2	59±6	41±6	66±3	6±0
B. Compost					
Sampling event	pH	% Moisture	% Solids	% Volatile solids	% Total nitrogen
Spring	8.6±0	28±2	72±2	57±2	6±1
Summer	8.0±0.5	41±20	59±20	61±1	6±1
Fall	8.5±0.1	39±3	61±3	58±3	6±1
Winter	8.6±0.1	41±4	59±4	56±1	4±0

Table 3. Seasonal averages of NH₃ concentration, NH₃ emission rates, indoor temperature and relative humidity, including daily averages observed in each season for year 1 and year 2 test periods.

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Season	Year observed	NH ₃ concentration (ppmv)	NH ₃ emission rates (g d ⁻¹ hen ⁻¹)	Temperature (°C)	Relative humidity (%)
Spring	Year 1	128±11	0.66±0.06	6.7±3.7	72.2±11.9
	Year 2	102±31	0.54±0.16	19.0±5.7	66.6±15.2
	Average	117±25	0.61±0.13	12.2±7.7	69.8±13.5
Summer	Year 1	169±26	0.91±0.14	26.7±3.1	85.9±7.9
	Year 2	117±48	0.64±0.26	25.5±1.6	90.8±5.2
	Average	152±42	0.82±0.22	26.3±2.7	87.5±7.4
Fall	Year 1	123±22	0.70±0.12	20.0±4.7	87.0±6.5
	Year 2	108±24	0.63±0.13	16.9±3.4	97.2±2.8
	Average	116±24	0.66±0.13	18.5±4.4	91.8±7.3
Winter	Year 1	158±70	1.00±0.41	4.1±5.8	97.0±8.3
	Year 2	151±53	0.94±0.32	8.3±1.7	100.0±0.0
	Average	157±66	0.99±0.40	4.8±5.5	97.5±7.6
Annual Average		134±47	0.77±0.29	14.7±9.4	86.9±14.1

*Standard deviations reported are based on daily averages.

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Table 4. Summary of NH₃ emission rates from layer houses obtained from literature compared with the current study.

Type and location of poultry house	NH ₃ emission rates (g d ⁻¹ hen ⁻¹)	Reference
HR (Iowa)	0.90 ± 0.03	Liang et al. (2005)
HR (Pennsylvania)	0.83 ± 0.07	Liang et al. (2005)
HR (North Carolina)	0.59 ± 0.20	Wang-Li et al. (2012)
HR (California)	0.95 ± 0.67	Lin et al. (2012)
HR (Ohio)	1.05*	Lim et al. (2008)
HR (Indiana)	1.28*	Heber et al. (2005)
HR house (Indiana)	1.57*	Lim et al. (2004)
MB house (Iowa)	0.054 ± 0.005	Liang et al. (2005)
MB house (Pennsylvania)	0.094 ± 0.019	Liang et al. (2005)
MB house (Ohio)	0.24 ± 0.21	Sun et al. (2005)
MB houses (Ohio)	0.20*	Keener et al. (2002)
MB composting facility (Ohio)	0.50-0.70*	Keener et al. (2002)
MB composting facility (Ohio)	0.72 ± 0.13	This study

*Standard deviation from the study was not reported.

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