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Ammonia emissions from manure belt laying hen houses and manure storage

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Ammonia emissions from manure belt laying hen houses and

manure storage

by

Hong Li

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering
(Agricultural Structures and Environmental Systems Engineering)

Program of Study Committee:
Hongwei Xin, Major Professor
Robert Burns
Steven Hoff
Brian Kerr
Dan Nettleton

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2006

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Graduate College
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This is to certify that the doctoral dissertation of
Hong Li

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program
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ACKNOWLEDGEMENTS
Chapter 1

General Introduction

Air quality associated with animal feeding operations (AFOs) remains a pressing issue for the animal industry, regulatory agencies and academic communities. Aerial ammonia (NH₃) has received increasing attention as a potential air pollutant. Domestic animal production has been identified as the largest source of atmospheric NH₃ in the United States. Accurate quantification of NH₃ emissions from AFOs is needed to develop improved emission inventories and emission factors for AFOs as well as to determine if certain regulatory reporting requirements of emissions are needed. A concern for the US poultry industry as well as for regulatory agencies is to ensure that reasonable estimates of emission source contributions to US air emissions are used. Currently, data are lacking for such estimates. The mass of NH₃ emitted from a facility is the product of source concentration of the gas and air exchange rate through the source following proper unit conversion and correction for temperature and barometric pressure effects. It is a challenge to reliably quantify pollutant concentration and airflow in AFOs on a continuous and prolonged basis. The harsh nature of the sample air, high humidity and high pollutant concentration is beyond the operational limits of many analytical instruments. The determination of ventilation rate through the animal housing, based on manufacture supplied fan performance curves, is difficult due to the large number of fans involved, inherent variation among them, and deviation of the fans working condition from those under which the fans performance curves were developed.
Frequent removal of laying hen manure from the houses, via manure belt, greatly improves indoor air quality (i.e., lowering \( \text{NH}_3 \) and dust levels) and reduces house-level air emissions (Grood Koerkamp et al., 1995; Liang et al., 2005). Layer houses with manure belt have been shown to emit less than 10% of \( \text{NH}_3 \) released from the high-rise houses (Liang et al., 2005). Hence, use of a belt system is likely to increase for future layer housing in the United States. Although a belt system is effective in achieving excellent indoor air quality and thus meeting animal welfare guidelines, the need to quantity and control emissions from manure storage remains. Hen manure is regularly removed from the houses to manure storage or holding facilities and information on the rate of \( \text{NH}_3 \) emission from stored laying hen manure is meager. Ammonia volatilization rate from solid poultry manure is affected by the nitrogen content, moisture content, stacking configuration, pH, temperature, and oxygen availability, all of which contribute to the microbial activities and ammonia transfer inside from the manure pile.

Ammonia emission from manure storage can be controlled using physical, chemical, and biological methods. Numerous additives have been investigated to reduce \( \text{NH}_3 \) volatilization from livestock manure. Natural zeolite is a cation-exchange medium that has high affinity and selectivity for \( \text{NH}_4^+ \) ions due to its crystalline, hydrated properties resulted from its infinite, 3-dimentional structures (Mumpton and Fishman, 1977). It has been widely used as amendment to poultry litter (Nakaue and Koelliker, 1981; Maurice et al., 1998). Manure pH plays an important role in ammonia volatilization. Ammonia emission tends to increase with increasing pH. The \( \text{NH}_3 \) emission can be inhibited by acidulants, which can lower manure pH and reduce conversion of ammonium to ammonia. The acidulants also inhibit the activities of bacteria and enzymes that are involved in the formation of ammonia, reducing
ammonia production. Commercialized Al\(^+\)Clear (aluminum sulfate), Ferix-3 (ferric sulfate), and PLT (sodium hydrogen sulfate) are acidulants that produce hydrogen ions (H\(^+\)) when they dissolve, and the hydrogen ions produced by this reaction will attach to ammonia to form ammonium. However, information on the efficacy of three acidulants on ammonia emission mitigation with laying hen manure is meager. The efficacy of Zeolite, liquid or dry granular Al\(^+\)Clear, Ferix-3, or PLT on reduction of ammonia emission from layer manure storage was thus evaluated in this study.

In response to the above concerns on ammonia emissions from laying hen operations, ammonia emission rates for manure-belt house were measured and presented; manure storages were simulated, and the ammonia emission from manure storage as affected by environmental factors was evaluated in this study.

**OBJECTIVES**

The overall goal of this study was to quantify ammonia emissions from manure-belt (MB) laying hen houses and manure storage as affected by environmental and management condition and management practices.

The specific objectives of the study were:

1. Quantify ammonia emission from MB layer houses with daily manure removal, and to compare the results with those currently available in the literature.

2. Quantify ammonia emission from laying hen manure storage as affected by manure stack surface area to volume ratio (SVR), air exchange rate, manure moisture content, storage temperature, and storage time.

3. Evaluate four commercially available additives (Zeolite, Al\(^+\)Clear, Ferix-3, and PLT) on reduction of ammonia emission from stored laying hen manure.
4. Compare ventilation rate of the MB layer house as determined either through indirect CO₂-balance or direct measurement of the fan capacity plus runtime.

MEASUREMENT METHODS

MEASURING AMMONIA EMISSION RATE

The NH₃ emission rates from animal feeding operations could be determined by the following two major approaches:

- Direct or air extraction measurement through summation of NH₃ emissions through all outlets.
- Indirect or mass balance measurement through feed and manure nitrogen balance.

Using the direct method, the amount of NH₃ emitted from a livestock building is the sum of the net NH₃ mass flows through all outlets. Emission is defined as the product of the ventilation flow rate and the concentration of the NH₃, both of which must be measured reliably and accurately at the same time. The emission rate of NH₃ could be estimated using the following relation:

\[ E = (C₀ - Cᵢ) V \]

where

- \( E \) = emission rate of NH₃ (mg hr⁻¹)
- \( V \) = ventilation rate of the building (m³ hr⁻¹)
- \( C₀ \) = concentration of NH₃ at the exhaust air (mg m⁻³)
- \( Cᵢ \) = background concentration of NH₃ (mg m⁻³)
For the nitrogen balance approach, calculation of the ammonia emission for the housed animals is based on the difference between nitrogen excretion by the animal and the amount of nitrogen in the manure at the end of the period of housing. This method is also available for determining the emission from manure storage. In practice, this method has limitations because it is usually very difficult to measure production output, feed consumption, feed composition and animal weight accurately.

MEANS TO MEASURE AERIAL AMMONIA CONCENTRATIONS

Many techniques and measurement methods are available that provide either simple or sophisticated analysis for NH₃ concentration in air (Phillips et al., 2001; Arogo et al., 2002; Xin et al., 2002). The following analyzing methods are discussed.

Detector Tubes

These devices provide a simple and convenient way of measuring atmospheric NH₃. The NH₃ tube has a specified range of 0.25 to 200 ppm with a standard deviation of ±10 to 15% concentrations (Parbst et al., 2000). They consist of a scaled glass vial containing a chemical absorbed onto inert support granules. The chemical reacts with the substance being measured in air drawn through them. Tubes exist for both short- (10 sec-15 min) and long- (2-8 hrs) term exposures. However, these devices are only semi-quantitative in nature and are primarily designed to assess human exposure at relatively high concentrations.

Acid Scrubbers

Ammonia concentration in air can be measured by introducing the air through a large excess of strong acid solutions and absorption is quantitative. The volume of air passed through the acid must be measured. Typically, non-volatile acids (sulfuric acid, hydrochloric acid, phosphoric acid, or boric acid) are used to prevent loss of acid when ambient air at a known
flow rate is bubbled through the solutions. The ammonia captured in the acid can be assayed by colorimetry. The method is simple, cheap, reliable, and suitable for low concentration of ammonia in air, although only the average concentration over the long sampling time in hours may be possible. The main drawbacks of the method are that acid scrubbers cannot discriminate between NH$_3$ and NH$_4^+$, or N-containing volatile organic compounds that may become entrained in the acid solution and the high labor input and the fact that it is basically non-continuous (Schilke-Gartley and Sims, 1992; Sommer and Hutchings, 1995).

**Electrochemical Cells**

An electrochemical cell has two or three electrodes in an electrolyte that consists of a combination of electrochemically active reagents. Ammonia contained in a flowing air stream diffuses through a permeable membrane into the electrolyte solution, where an electrochemical reaction takes place. The resulting electrochemical reaction produces an electric potential that can be measured as a voltage or current. The transport rate of ammonia into the electrolyte is approximately a linear function of the ammonia concentration in air (Phillips et al. 2001). These types of sensors are frequently used as toxic gas monitors in alarm systems, as they react quickly to sudden rise in concentration. Normal measuring ranges for ammonia electrochemical cells are approximately 5 ppm or greater (Phillips et al. 2001). A change in sensor sensitivity will take place during the long-term exposure to ammonia-laden air (Xin et al., 2002).

**Chemiluminescence Analyzers**

A chemiluminescence analyzer uses the reaction of nitric oxide (NO) with ozone (O$_3$) as its basic principle, namely,

\[ \text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 + \text{hv} \]
where \( hv \) is a photon.

A chemiluminescence detector can be used to measure ammonia concentration. An air sample is drawn into the analyzer and ammonia is first oxidized to NO. When the nitric oxide is further oxidized within the instrument, nitrogen dioxide is produced, in an excited state. The nitrogen dioxide molecules return to a lower energy state by releasing photons. This electromagnetic radiation has a wavelength around 1200 nm. The prior oxidation of ammonia to nitric oxide can be achieved using a stainless steel catalytic converter in the form of a long tube of 5 mm, at a temperature of 750 °C (Phillips et al., 1998; Aneja et al., 2001). The stream of nitric oxide in air then passes into the analyzer through a molybdenum converter, which converts background nitrogen dioxide to nitric oxide. Use of this analyzer requires measurement of the background concentration of ammonia, nitric oxide and nitrogen dioxide sensitivity is from 1 ppb with sampling rates of 0.1 Hz.

**Photoacoustic Analyzer**

The photoacoustic analyzer uses a measurement system based on the photoacoustic infrared detection method, and is capable of measuring almost any gas that absorbs infrared light. Light from an infrared light source is reflected off a mirror, passed through a mechanical chopper, which pulsates it, and then through the optical filters (Figure 1). The gas being monitored, causing the temperature of the gas to increase selectively absorbs the light transmitted by the optical filter. Because the light pulsating, the gas temperature increases and decreases, causing an equivalent increase and decrease in the pressure of the gas (an acoustic signal) in the closed cell. Two microphones mounted in the cell wall measure this acoustic signal, which is directly proportional to the concentration of the monitored gas present in the
cell. The response time of this type analyzer is down to 1 minute. The full scale of NH₃ measurement is adjustable up to 2000 ppm.

In this study, electrochemical NH₃ (PAC III, Dreager Safety Inc) sensors in portable monitoring units (PMU) were used to measure NH₃ concentration of the exhaust air from the layer houses and a photoacoustic multi-gas analyzer (INNOVA 1314, INNOVA AirTech Instruments, Denmark) was used to measure the NH₃ concentration from the stacked layer manure due to high NH₃ concentrations from the manure storage that are beyond the measurement range of most analyzers.

**MONITORING VENTILATION RATE**

Many of the approaches to measuring ammonia emission rates require the monitoring of ventilation rates of buildings. Two major techniques for such ventilation rate monitoring exist. The first, more general kind, based on using a tracer, allows an indirect measurement of overall ventilation rate, is applicable to both mechanically and naturally ventilated buildings, as well as to airflows across slurry and manure storages. The second kind relies on directly measuring the airflow rates through all openings in a building and then summating these to obtain the total ventilation rate. The second kind is basically simpler, readily applicable to mechanically ventilated buildings.

**Indirect measurement of overall ventilation rate**

The basic principle of tracer techniques for direct measurement of overall ventilation rate is to release a tracer at a known rate, monitor its concentration at downwind points and hence deduce the airflow necessary to reconcile the known rate of release with these measured concentrations. In the case of a livestock building, it is necessary to assume good air mixing
inside. In practice, this may well not be the case, especially in naturally ventilated buildings, and errors in the ammonia emission rate may result (Demmers et al., 1998).

The ideal characteristics of a released tracer include low, and stable background level, no hazard, acceptability, ease of measurement, stability, and low price. There are many potential releasable tracers. Radioactive tracers were among the earliest used. The drawbacks of radioactive tracers are the cost and time-consuming carbon monoxide (Demmers et al., 1998) and Helium have been used in livestock facilities and elsewhere. Another reliable tracer is SF6 (sulphur hexafluoride), which has been used to some extent with livestock buildings.

Carbon dioxide balance method was used in this study for measuring the ventilation rate. The ventilation rate is based on the indoor and outdoor carbon dioxide concentration and can be calculated by:

\[ \text{CO}_2 = V (C_o - C_i) \times 10^{-6} \]  

where

\( \text{CO}_2 \) is the carbon dioxide production (m\(^3\) hr\(^{-1}\)), \( C_o \) is the outdoor carbon dioxide concentration (ppm), \( C_i \) is the indoor carbon dioxide concentration (ppm), and \( V \) is ventilation rate (m\(^3\) hr\(^{-1}\)).

**Direct ventilation rate measurement by summation of airflows through individual openings**

A wide range of instruments, such as hot wire anemometers and fan wheel anemometers, can be used to monitor the airflow through openings. Full size fan wheel anemometers (measuring fan), which are sited in the ventilation ducts, are frequently used for the continuous monitoring of the ventilation rate of mechanically ventilated livestock.
buildings. Measuring fans are robust and offer direct measurement of volumetric ventilation rate through the duct at a relatively low cost. Hot wire anemometers are another option, giving a point measurement of air velocity, which may or may not be that accurate for measuring airflow. Recently, a more sophisticated tool, known as the Fan Assessment Numeration System (FANS), was developed and is increasingly used to improve in-situ measurement certainty of fan airflow capacity (Simmons et al., 1998; Gates et al., 2004). Even with the FANS, challenges still exist in that certain types of confinement housing (e.g., cross-ventilated laying hen houses) have a large number of ventilation fans (e.g., 40-70 per house), making it a formidable task to calibrate all the fans. Furthermore, the in-situ fan curves may vary over the course of monitoring due to outside wind speed/direction or conditions of the fan itself.

Measuring ventilation rate by the summation of airflows through individual opening, where it is feasible, has an inherent advantage over measuring a gross ventilation rate. The more detailed picture of the ventilation may simplify the task of planning how to abate ammonia emission from a livestock building.

**LAYER HOUSES WITH MANURE BELT AND PORTABLE MONITORING UNIT (PMU)**

Two manure-belt laying hen houses owned by a cooperative egg producer located in north central Iowa were used for the study. The layer houses had an east-west orientation and a dimension of 18 m (61 ft) wide by 159 m (522 ft) long. The houses used a quasi-tunnel ventilation system that consisted of 13, 1.2 m (48") diameter exhaust fans and two 0.9 m (36") diameter exhaust fans in each end-wall and two rows of continuous slot ceiling inlets (4.5 m or 15 ft interior from each sidewall) controlled by static pressure set at 17 Pa (0.07” H₂O) (figure 2). Exhaust fans at each end were grouped in pairs that were controlled, in eight stages,
according to the mean house temperature near the middle of the house. The exhaust fan numbers and ventilation stages for layer house 1 (MB-1) and house 2 (MB-2) are shown on Table 1 and 2. One of the 0.9 m fans at each end operated continuously. The battery cages were arranged in eight cage rows with three tiers per cage row. Bird feces fell directly onto the belt underneath the cages and were removed from the house each morning at 0500 hr. There was an 18 m (61 ft) open space between adjacent buildings. At the onset of the monitoring study in 2003, there were 100,000 Hy-Line W-36 hens in each house. The bird ages were 37 wk in house 1 and 96 wk in houses 2 on January 1, 2003. A replacement flock of 100,000 W-36 hens at 20 weeks of age was introduced into the house 1 in July 2003. Photoperiod remained 16L:8D during the monitoring period for the first flock; but it started at 12L:12D and was increased by 30 minutes per week until it reached 16L:8D for the replacement flock. Ad-lib feed and water were provided, and standard commercial egg industry diets were used.

Portable monitoring units (PMUs) as described by Xin et al. (2002) were used to continuously collect CO₂ concentration of incoming and exhaust air (Figure 3). One PMU was mounted on each end wall of the house. A programmable on/off timer was used to operate a 3-way solenoid valve that in turn controlled the switching between incoming fresh air and exhaust air. The incoming air was sampled from the attic space and the exhaust air was a composite sample from four aisle locations at each end about 5 m (15 ft) from the exhaust fans. Due to the operational characteristics of the electro-chemical ammonia sensors used in the PMU, 8-minute sampling of the exhaust air followed by a 22-minute purging with incoming air was used throughout the measurement episodes. Carbon dioxide concentration was monitored with an infrared CO₂ transmitter (0-7,000 ± 20 ppm, Model GMT222, Vaisala Inc., Woburn, MA). The output of the transmitter (4-20 mA) was recorded with a 4-channel battery-operated
data logger (4-20 mA ± 0.1%, Onset Computer Corporation, Bourne, MA). Temperature and RH at each end, about 5 m from the exhaust fans, and in the middle of the house were recorded with portable temperature/RH loggers (0-50°C ± 3%, HOBO Pro RH/Temp, Onset Computer Corporation). Outside temperature and RH were also measured with the same type of temperature/RH loggers.

**MANURE STORAGE MEASUREMENT SYSTEM**

An open-circuit and positive pressure measurement system was used to measure the emission for stored manure stacks. This system consisted of the following major components: four individually controlled environmental chambers (1.5 m\( \times \) 1.8 L\( \times \) 1.8 H each) (figure 4); an air handler with capacity of 850 m\(^3\)/hr (Model Climate-Lab-AA, Parameter Generation & Control or PGC, Black Mountain, NC); a dew point hygrometer (Model 2001, EG&G Moisture and Humidity Systems, Burlinton, MA); a advanced photoacoustic multi-gas analyzer (1314, INNOVA, Denmark); a barometric pressure sensor (Model CD105, Campbell Scientific Inc, Logan UT); four thermoelectric air mass flowmeters, one per chamber (Model LS-4F, Teledyn Hastings-Ravidist, Hampton, VA); a Teflon diaphragm pump (Catalog L-79200-30, Cole-Parmer Instruments Co.); and a PC-based environmental control and data acquisition system. The fresh air was heated to the desired temperature of the chamber by two 1500 W electric heater/fan units (Model 3VU37, Grainger) located in the plenum space of the air inlet and the porous ceiling of the chamber. An air distribution duct was located along the perimeter of the chamber near the manure stack surface to enhance uniform mixing of the outgoing air. Electric heating cords (Cat No.H-03122-24, Cole Parmer Instrument Co.) in conjunction with a variable power controller (Model 2604-00, Cole Parmer Instrument Co.) were used to prevent moisture condensation inside the air sampling line (1/4 inch OD and 1/8 ID FEP tubing). Soil
moisture probes (Model EC-20, Decagon Devices, Inc.) were used to measure manure moisture content. The moisture probes were calibrated individually. Air samples from four chambers and the supply air were controlled by the control and data acquisition system operated solenoid valves. Air sampling was performed at a 20-min interval, with the first 15-min used for purging and stabilization and the last 5-min used for data collection. The data acquisition system took measurements every two seconds and stored the one-min average. The INNOVA 1314 analyzer was checked weekly with certified grade calibration gases (Matheson Gas Products, Inc., Chicago, IL). If the reading of the analyzer were out of ±2% span gas range, it would be calibrated. The four air flowmeters were recalibrated by the factory at least annually. CR10 programs were used to run the control and data acquisition system. They performed: sequential and independent sampling and measurement results of fresh air or air from individual chambers; continuous measurement of air flow rate though each chamber; continuous measurement of fresh air and chamber air temperature, RH, dew point temperature, barometric pressure, manure temperature and manure moisture content and turning the space heaters on and off as needed to maintain the predetermined chamber temperatures.

**SCOPE OF RESEARCH**

This study’s major components included: (1) conducting field measurements of ammonia emission from layer houses with manure belt, (2) conducting large scale laboratory measurements of NH₃ emission of stacked layer manure and evaluating the effects of manure handling practices and corresponding environmental factors on NH₃ emission, (3) evaluating efficiency of manure additives at various dosage on NH₃ emission from hen manure, (4) comparing two ventilation rate measuring methods (direct vs. indirect and quantifying the CO₂ balance method applied to MB layer houses with manure belts.
DISSEMINATION ORGANIZATION

This dissertation is comprised of four papers, corresponding to the four research objectives. The first paper entitled “Ammonia Emission from manure-belt in laying hen houses in Iowa” has been published as one component of the article “Ammonia Emissions from U.S. Laying Houses in Iowa and Pennsylvania” published in the Transactions of the American Society of Agricultural Engineers (ASAE) 48(5):1927-1941. The second paper entitled “Ammonia Emission from Laying Hen Manure Storage as Affected by Environmental Conditions” will be submitted to the Transactions of the ASAE. The third paper entitled “Effects of Topical Application of Zeolite, Al’Clear, Ferix-3, or PLT to poultry manure on ammonia emissions” will be submitted Journal of Applied Poultry Research. The fourth paper entitled “Comparison of Direct vs. Indirect Ventilation Rate Determination for Manure Belt Laying Hen Houses” has been published in the Transactions of the ASAE 48(1): 367-372. The chapters that follow will describe each of the studies.

REFERENCES


Table 1. Exhaust fan number and ventilation stages for layer house 1 (MB_1)

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</table>

East

|      | 1     | 1                   | 73                  | 2               |
|      | 2     | 1,3,4               | 74                  | 2               |
|      | 3     | 1,2,3,4,15          | 75                  | 2               |
|      | 4     | 1,2,3,4,5,14,15     | 75                  | 2               |
|      | 5     | 1,2,3,4,5,6,13,14,15 | 74             | 2               |
|      | 6     | 1,2,3,4,5,6,7,12,13,14,15 | 75             | 2               |
|      | 7     | 1,2,3,4,5,6,7,8,11,12,13,14,15 | 76             | 2               |
|      | 8     | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15 | 76             | 2               |

West

|      | 1     | 1                   | 72                  | 2               |
|      | 2     | 1,3,4               | 73                  | 2               |
|      | 3     | 1,2,3,4,15          | 74                  | 2               |
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|      | 7     | 1,2,3,4,5,6,7,8,11,12,13,14,15 | 75             | 1               |
|      | 8     | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15 | 75             | 2               |

Table 2. Exhaust fan number and ventilation stages for layer house 2 (MB_2)

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East

|      | 1     | 1                   | 72                  | 2               |
|      | 2     | 1,3,4               | 73                  | 2               |
|      | 3     | 1,2,3,4,15          | 74                  | 2               |
|      | 4     | 1,2,3,4,5,14,15     | 74                  | 2               |
|      | 5     | 1,2,3,4,5,6,13,14,15 | 74             | 1               |
|      | 6     | 1,2,3,4,5,6,7,12,13,14,15 | 74             | 2               |
|      | 7     | 1,2,3,4,5,6,7,8,11,12,13,14,15 | 75             | 1               |
|      | 8     | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15 | 75             | 2               |

West
Figure 1. Schematic of a photoacoustic gas monitor
Figure 2. Picture and schematic layout of the manure-belt layer house showing the end and cross-section of the house and the sampling locations (O HOBO T/RH logger, □ Gas sampling port, □ PMU)
Figure 3. Portable Monitoring Unit (PMU) (top) and Fan motor logger (bottom)
Figure 4. Picture and schematic of the four environmentally controlled emission chambers.
CHAPTER 2

AMMONIA EMISSION FROM MANURE-BELT LAYING HEN HOUSES IN IOWA

ABSTRACT

Ammonia (NH₃) emission rates (ER) of two commercial manure-belt (MB) layer houses in Iowa were monitored for a full year. Hen manure was removed daily from the MB houses. Ammonia and carbon dioxide (CO₂) concentrations of incoming and exhaust air streams were measured using custom-designed portable monitoring units (PMUs) that shared similar performance to EPA-approved measurement apparatus. Ventilation rates of the houses were determined by calibrated CO₂ mass balance using the latest metabolic rate data for modern laying hens. The data were collected bi-weekly throughout the year, with each collection episode lasting two consecutive days. A total of 108 independent house-day measurements or 5,184 semi-hourly emission data points were involved for the layer houses. Ammonia ER showed considerable diurnal variation, with the peak occurring during manure removal. Data from the 12-month monitoring revealed the NH₃ ER (mean ±standard error) of 0.054 ±0.0035 g NH₃ d⁻¹ hen⁻¹ (varying from 0.002 to 0.195 g NH₃ d⁻¹ hen⁻¹) for the belt layer houses with manure removed daily. Seasonal variations in NH₃ ER were less noticeable, with the mean ER of 0.042, 0.060, 0.054, and 0.057 g NH₃ d⁻¹ hen⁻¹ for the spring, summer, fall and winter season, respectively. Results of the study contribute to the U.S. national inventory on NH₃ emissions from animal feeding operations.

Keywords: Ammonia emissions, Manure belt, Poultry, Layer, CO₂ balance.
INTRODUCTION

Aerial ammonia (NH$_3$) is the predominant pollutant gas in poultry production facilities, resulting from microbial decomposition of uric acid in bird feces. According to the U.S. Environmental Protection Agency's emission inventory (USEPA, 2002, 2004), livestock operations and fertilizer application constituted about 85% of the total national NH$_3$ emissions in 1998, while publicly owned treatment works, mobile sources, and combustion sources made up the remaining 15%. Ammonia emission is environmentally important because of its contribution to acidification of soil and water and increased nitrogen deposition in ecosystems. Excessive NH$_3$ in animal housing can also adversely affect bird performance and welfare. Moreover, NH$_3$ is considered a source of secondary particulate matter (Baek and Aneja, 2004) that is regulated under the U.S. National Ambient Air Quality Standard. The potential for additional federal air quality regulations for animal feeding operations necessitates better inventory and mitigation of NH$_3$ emissions. Limited research information is available concerning NH$_3$ emissions from U.S. animal feeding operations (Maghirang and Manbeck, 1993; Patni and Jackson, 1996; Keener et al., 2002; Burns et al., 2003). In comparison, more data for European livestock production facilities have been reported (Wathes et al., 1997; Groot Koerkamp et al., 1998; Hinz and Linke, 1998; Nicholson et al., 2004). However, applicability of the European emission data to U.S. conditions remains to be examined or validated due to differences in housing style, manure management practices, climate, etc. Data on NH$_3$ emission rates are particularly lacking for modern U.S. laying hen houses.

Manure management in laying hen facilities can greatly influence NH$_3$ emission. High-rise (HR) and manure-belt (MB) houses are the two most common housing styles of the egg industry in the U.S. In the case of HR houses, solid manure is stored in the lower level of the
building for about a year before removal. In comparison, manure in MB houses drops onto a belt beneath cages and is frequently removed from the house, say, two to seven times a week. However, data are lacking that link NH$_3$ emission to the HR and MB houses under commercial production settings.

The objective of this study was to measure NH$_3$ emission rate (ER) from representative U.S. MB layer houses. The data reported here represent 108 house-day or 5,184 semi-hourly observations for two MB houses over one-year period. The study was part of a multi-state project that aimed to collect baseline NH$_3$ emission data from representative U.S. layer houses and to evaluate the efficacy of certain management practices.

MATERIALS AND METHODS

Housing Characteristics and Management Practices

This field monitoring study involved two commercial manure-belt (MB) layer houses in central Iowa. The 99% annualized heating season dry-bulb temperatures for central Iowa are -22°C with a corresponding 1% cooling season dry-bulb and coincident wet-bulb temperatures of 31°C/23°C (ASHRAE, 2001). Hen manure in the MB houses was removed daily between 5:00 and 6:00 am. Details of the housing characteristics and management schemes of the layer houses are presented in Table 1. Photoperiod was 16L:8D throughout the monitoring period except during molting or new flocks. Weekly bird performance data, including feed and water consumption, egg production, mortality, bird age, and body weight, were collected from the cooperating producers.

Instrumentation and Measurement Protocols

Portable monitoring units (PMUs) were used in the field study, as described by Xin et al. (2002, 2003) and Gates et al. (2005). The PMU used two electrochemical (EC) NH$_3$ sensors
(0 to 200 ±3 ppm; PAC III H, Dräger Safety, Inc., Pittsburgh, Pa.) and an infrared CO₂ sensor (0 to 5,000 or 0 to 7,000 ±[20 + 2% of reading] ppm; Vaisala, Inc., Woburn, Mass.). To avoid measurement errors caused by EC sensor saturation from continuous exposure to NH₃-laden air, measurement cycles consisting of 24 min purging with fresh outside air and 6 min sampling of the exhaust air stream (as determined by trial and error) were used. This purging-sampling cycle resulted in 30 min measurement intervals of both NH₃ and CO₂ concentrations of the inlet and exhaust air streams.

Before and after each field-monitoring episode, the NH₃ sensors were checked and recalibrated, as needed, with zero and span gases. Before each trip to the MB houses, NH₃ span gas of 18 ppm (N₂ balance, ±2% accuracy, IA) (Matheson Tri-Gas Inc., La Porte, Texas) was used to calibrate the NH₃ sensors. The NH₃ loggers were programmed to collect data at 30 s. Ammonia measurements from redundant sensors in a PMU were averaged. Use of redundant sensors enabled the collection of the NH₃ concentrations with minimal interruptions or loss of data.

The CO₂ sensors were calibrated every three months with zero, 2,000 ppm, and 4,000 ppm CO₂ calibration gases (N₂ balance, ±2% accuracy, Matheson Tri-Gas Inc., La Porte, Texas). Concurrent measurements of inside and outside air temperature (±0.2°C resolution) and relative humidity (RH, ±3% resolution) were made with portable, programmable data loggers (HOBO Pro RH/Temp, Onset Computer Corporation, Bourne, Mass.).

Each data collection period consisted of 48 h or longer continuous measurements, and was performed bi-weekly. Two PMU units were installed in each house at locations described below. The length of the sample tubing varied from 5 to 20 m, while the length of the purging
tubing varied from 7 to 15 m. Data reported in this article covered the period from early January to late December 2003.

One PMU was installed at each exhaust end of the quasi-tunnel ventilation houses. Composite samples from four sampling ports at each end were introduced into the respective PMU. Air temperature and RH were monitored at three locations along the length of the houses (Fig. 1).

**Determination of Ventilation Rate**

Ventilation rates of the houses were determined using CO$_2$ balance method as governed by indirect animal calorimetry relation. The potential of using CO$_2$ concentration in the exhaust air from animal facilities to estimate ventilation rate has long been recognized and explored (Feddes et al., 1984; Ouwerkerk and Pedersen, 1994; Pedersen et al., 1998). Li et al. (2004) estimated building ventilation rate (Q, m$^3$ h$^{-1}$ kg$^{-1}$) of MB layer houses based on CO$_2$ production of the birds only, namely:

$$Q = \frac{CO_2_{bird}}{[CO_2]_e - [CO_2]_i} \times 3,600 \quad \text{[1]}$$

where $[CO_2]_e$ and $[CO_2]_i$ are exhaust and incoming air CO$_2$ concentrations (ppm), respectively, and CO$_2$ bird is the specific CO$_2$ production rate of the hens (mL s$^{-1}$ kg$^{-1}$) derived from recently updated total heat production rates (THP), and respiratory quotient (RQ) for W-36 laying hens of different ages under light and dark conditions (Chepete and Xin, 2004; Chepete et al., 2004).
Determination of Emission Rate

The NH₃ emission rate (ER) reported herein was the mass of NH₃ emitted from the layer houses to the atmosphere per unit time. The ER (g h⁻¹ hen⁻¹) was calculated using the semi-hourly concentration readings, of the form:

\[
ER = Q \times M \times (\frac{[NH₃]_i - [NH₃]_e)}{V_m \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}}} \times 10^{-6} \times \frac{w_m}{V_m} \times \frac{T_{std}}{T_a}\]

where

\(Q\) = building ventilation rate at field temperature and barometric pressure (m³ h⁻¹ kg⁻¹)

\(M\) = average body weight of the hen (kg)

\([NH₃]_i\) = NH₃ concentration of building inlet air (ppm)

\([NH₃]_e\) = NH₃ concentration of building exhaust air (ppm)

\(w_m\) = molar weight of NH₃, 17.031 g mole⁻¹

\(V_m\) = molar volume of NH₃ at standard temperature (0°C) and pressure (101.325 kPa) (STP), 0.022414 m³ mole⁻¹

\(T_{std}\) = standard temperature, 273.15 K

\(T_a\) = absolute house temperature, (°C + 273.15) K

\(P_{std}\) = standard barometric pressure, 101.325 kPa

\(P_a\) = atmospheric barometric pressure, 98 kpa based on site elevation.

During the PMU development, a comparison of NH₃ concentration recordings between PMU and a chemiluminescence NH₃ analyzer was conducted at a laying hen monitoring site. The results showed that the maximum value of the sampling cycle with the PMU yielded similar measurement as with the NH₃ analyzer (Xin et al., 2003). The readings of the PMU were further validated with the same type of NH₃ monitors held in the exhaust air stream where
the PMU sample was drawn. Background NH$_3$ of the intake air was checked periodically during different seasons and it was proven to be negligible as compared with the exhaust concentrations. Hence, NH$_3$ concentration of the exhaust air ([NH$_3$]$_e$) without subtraction of that from the intake air ([NH$_3$]$_i$) was used in the calculation of emission rates for this study.

RESULTS AND DISCUSSION

Environmental Conditions

Outside daily mean temperature during the one-year measurement ranged from -17.5°C to 27.9°C with a mean of 9.4°C. Outside RH ranged from 42% to 95% with a mean of 71%. Daily mean house temperatures relative to outside temperatures are shown in Figure 2. Inside temperature began to increase with outside temperature when outside temperature exceeded about 8°C to 10°C.

Gas concentrations

Carbon dioxide concentrations of the inlet (purging) air ranged from 350 to 500 ppm. The difference in CO$_2$ concentration between inlet and exhaust air streams varied from 210 to 4,300 ppm during the measurement period, with the maximum difference occurring on 21 January 2003 and the minimum difference on 20 August 2003. Daily mean NH$_3$ concentrations of the exhaust air varied from 0.01 to 8.24 ppm with a mean 2.8 ppm (Fig. 3). The NH$_3$ concentrations were inversely related to outside temperature and building ventilation rates (Fig. 4).

Ammonia Emission Rates

The MB houses had a least mean square daily ER of 0.054 (±0.0035) during the monitoring period (Fig. 5). The ER translates to an annual NH$_3$ emission factor of 20 (±1) g NH$_3$ year$^{-1}$ hen$^{-1}$. 
In a concurrent study, as reported by Liang et al. (2005), MB houses with semi-weekly manure removal had an ER of 0.094 g d\(^{-1}\) hen\(^{-1}\) or (34 g NH\(_3\) year\(^{-1}\) hen\(^{-1}\)), i.e. 74% higher than ER of MB houses with daily manure removal. Kroodsma et al. (1988) reported an NH\(_3\) emission factor of 34 g year\(^{-1}\) hen\(^{-1}\) for battery systems with manure removed twice a week (without drying) and 31 g year\(^{-1}\) hen\(^{-1}\) with manure drying on belts and removed once a week. Groot Koerkamp et al. (1998) reported NH\(_3\) ER values of 14 (Germany), 39 (The Netherlands), and 52 (Denmark) g NH\(_3\) d\(^{-1}\) AU\(^{-1}\) (AU = animal unit, 500 kg live weight) for manure-belt laying hen houses. A recent study of NH\(_3\) emission from broiler and layer manure management systems by Nicholson et al. (2004) reported 3.3 g NH\(_3\)-N h\(^{-1}\) AU\(^{-1}\) (96 g NH\(_3\) d\(^{-1}\) AU\(^{-1}\)) from weekly belt-scraping layer houses, 1.3 g NH\(_3\)-N h\(^{-1}\) AU\(^{-1}\) (38 g NH\(_3\) d\(^{-1}\) AU\(^{-1}\)) from daily belt-scraping layer houses in England. In comparison, the current study revealed an NH\(_3\) ER of 17.5 g NH\(_3\) d\(^{-1}\) AU\(^{-1}\) for the MB houses with daily manure removal. Similar trends of reduced building NH\(_3\) ER versus more frequent belt scraping were noted by both Groot Koerkamp et al. (1998) and Nicholson et al. (2004).

The HR houses had much higher ammonia ER than the MB houses. An ER of 0.87 g NH\(_3\) d\(^{-1}\) hen\(^{-1}\) NH\(_3\) ERs for HR houses in Iowa and Pennsylvania were reported by Liang et al. (2005). The Netherlands (Anon., 1990, as cited by Groot Koerkamp, 1994) reported an emission factor of 386 g NH\(_3\) year\(^{-1}\) hen\(^{-1}\) for deep-pit and channel layer houses. According to Groot Koerkamp (1994), both deep-pit and channel houses used the building’s lower level (referred to as “basement”) as the manure storage area, with the difference being whether manure was allowed to spread over the entire basement (deep-pit, much like the HR houses in the current study) or restricted within the channels (formed by two walls) underneath each cage row. Maximum manure storage time was one year for the deep-pit houses and four months for
the channel houses. These types of houses in the Netherlands typically employ active aeration in the manure storage level in an effort to dry the manure (E. N. J. Ouwerkerk, personal communication, 2004). Wathes et al. (1997) reported an NH$_3$ ER of 192 g NH$_3$ d$^{-1}$ AU$^{-1}$ in winter and 290 g NH$_3$ d$^{-1}$ AU$^{-1}$ in summer for four deep-pit layer houses in England.

**Variations in Ammonia Emission Rates**

The seasonal NH$_3$ emission rates ranged were 0.057, 0.042, 0.060 and 0.054 g NH$_3$ d$^{-1}$ hen$^{-1}$, respectively, for winter, spring, summer and fall (Table 2 and Fig. 6). There was no significant difference in ER among the seasons (P=0.125).

Manure belt operation and manure removal, usually occurring around 5 a.m. each day, resulted in a temporarily higher NH$_3$ emission (Fig. 7). It can be noted that after an initial burst of volatilization during manure removal, ER dropped sharply and then slowly increased throughout the day, presumably as manure accumulated on the belt. This pattern was most noticeable during cold weather when the building had relatively constant and low ventilation rates.

**CONCLUSION**

Ammonia emission rates (ER) from representative manure-belt (MB) layer houses in Iowa were measured for a full year. Ammonia ER showed considerable diurnal variation, but not as much in seasonal variation. Data from the 12-month monitoring revealed the NH$_3$ ER (mean ±standard error) of 0.054 ±0.0035 g NH$_3$ d$^{-1}$ hen$^{-1}$ for the MB houses with manure removed daily. Results of the study contribute to the U.S. national inventory on NH$_3$ emissions from animal feeding operations.
ACKNOWLEDGEMENTS

Financial support for this study was provided by the USDA Initiative for Future Agriculture and Food System (IFAFS) Program, the Iowa Egg Council, and the Center for Advanced Technology Development of Iowa State University.

REFERENCES


Table 1. Characteristics and management data of the commercial manure-belt layer houses monitored in this study.

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Diet</th>
<th>Width x Length (m)</th>
<th>Hen Breed</th>
<th>Manure Removal Frequency</th>
<th>Vent. System</th>
<th>No. of Vent. Fans</th>
<th>No. and Type of Inlets</th>
<th>No. of Birds at Start</th>
<th>No. of Cage Rows</th>
<th>No. of Cage Tiers</th>
<th>Measurement Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB-1 and 2</td>
<td>Standard</td>
<td>18 x 159</td>
<td>W-36</td>
<td>Daily</td>
<td>Quasi Tunnel</td>
<td>26 (1.2 m)</td>
<td>2 rows of CSCI</td>
<td>104,860</td>
<td>8</td>
<td>3</td>
<td>31 Dec. 2002 to 8 Jan. 2004</td>
</tr>
</tbody>
</table>

*MB = manure belt

*CSCI = continuous slot ceiling inlet

Table 2. Seasonal emission rates of ammonia (mean and standard error) from manure-belt layer houses in Iowa.

| Time Period[a] | Outside Temp., °C | ER, g hen\(^{-1}\) d\(^{-1}\) | ±
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>-4.65</td>
<td>0.057</td>
<td>±0.0038</td>
</tr>
<tr>
<td>Spring</td>
<td>12.22</td>
<td>0.042</td>
<td>±0.0030</td>
</tr>
<tr>
<td>Summer</td>
<td>21.56</td>
<td>0.060</td>
<td>±0.0085</td>
</tr>
<tr>
<td>Fall</td>
<td>3.56</td>
<td>0.054</td>
<td>±0.0034</td>
</tr>
<tr>
<td>Overall</td>
<td>9.01</td>
<td>0.054</td>
<td>±0.0048</td>
</tr>
</tbody>
</table>

*a Winter=December 31 2002 to March 12 2003 and December 2 to 31 2003, Spring=March 18 to May 31 2003, Summer=June 13 to September 17 2003, Fall= September 31 to November 12 2003
Figure 1. Schematic layout of the manure-belt layer house showing the end wall, cross-section, and floor plan of the house and the sampling locations.
Figure 2. Daily mean air temperature vs. daily mean outside temperature
Gas Concentrations

Figure 3. Daily mean ammonia concentrations in exhaust air of manure-belt layer houses
Figure 4. Daily mean ammonia concentrations in exhaust air of manure-belt layer houses vs. daily mean ventilation rate and outside temperature
Figure 5. Daily mean ammonia emission rate of manure-belt layer houses and outside temperature. ER_MB-1: emission rate of manure-belt house 1; ER_MB-2: emission rate of manure-belt house 1.
Figure 6. Daily ammonia emission rates of manure-belt houses vs. ventilation rate (top) and outside temperature (bottom)
Figure 7. An example of diurnal variations of ammonia emission rate (ER) of a manure-belt house.
CHAPTER 3

AMMONIA EMISSION FROM LAYING HEN MANURE STORAGE AS AFFECTED BY ENVIRONMENTAL CONDITIONS

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H. Li, H. Xin

ABSTRACT

Frequent removal of manure from laying hen houses greatly improves indoor air quality and reduces air emissions at the house level. Low ammonia (NH$_3$) emission is critical for meeting certain regulatory limits of emissions from animal feeding operations. While manure removal from the houses, via manure-belt system, is effective in improving indoor air quality and reducing house-level emissions, the need to quantify and control emissions from manure storage remains. Many factors affect NH$_3$ volatilization of stored poultry manure, such as moisture content (MC), pH, and storage temperature. In this study, the effects of five manure stack surface area to volume ratios (SVR) (1.2, 2.5, 5, 10, or 20) and two air exchange rates (10 or 20 ACH) on NH$_3$ emission from laying hen manure stacks were evaluated during a 40-d ventilated storage period under a constant air temperature of 25°C. The effects of two MC levels (50% and 77%) and diurnal cyclic temperature (21 °C to 32 °C) were also evaluated with 20 ACH and an SVR of 20. The study was carried out using environmentally controlled chambers. The results revealed that air change rates of 10 or 20 ACH had no significant effect on total NH$_3$ emission from the storage. The rising ambient temperature enhances NH$_3$
emission of the manure stack at the rate of 6% per degree Celsius rise. The NH$_3$ emission rate (ER) from manure stack at 50% MC is 59% of the NH$_3$ ER from manure stack at 77% MC. The total NH$_3$ emissions during the 40-day storage at 25°C were 2.17, 3.51, 6.45, 9.70 and 12.4 g kg$^{-1}$ fresh manure, respectively, for SVR of 1.2, 2.5, 5, 10 and 20. A regression model was developed to predict the NH$_3$ emissions from manure stacks with the five SVRs and the associated storage time.

**Keywords:** Ammonia emission, Poultry, Laying hen, manure storage

**INTRODUCTION**

Ammonia (NH$_3$) is the predominant pollutant gas emitted from large confined animal production facilities, resulting from the microbial decomposition of urea and uric acid present in animal excreta, which takes place varying from just a few hours for urea to some days for uric acid. Commercial laying hen operation is an example of high-density animal production. Frequent removal of laying hen manure from the houses, via manure belt, greatly improves indoor air quality (i.e., lowering NH$_3$ and dust levels) and reduces house-level air emissions. Recent field monitoring of NH$_3$ emissions from laying hen houses showed that manure-belt layer houses with daily or semi-weekly manure removal emit less than 10% of the NH$_3$ as compared to high-rise layer houses where manure is stored in the houses for approximately one year (Liang et al. 2005). However, NH$_3$ emissions from manure storage of belt houses remain to be quantified and controlled as part of the overall production system. Estimating NH$_3$ emission from manure storages also presents considerable difficulties since storages are mostly open with large and varying surface area. Thus, there is no physical border to the emission source from which measurements or samples can be taken. The NH$_3$ emission from animal manure is largely dependent upon the environmental conditions of temperature, air velocity,
and handling practices (Sommer, S.G. et al., 1991; Phillips, V.R. et al., 2000). Ammonia volatilization rate from stored manure is affected by the nitrogen content, moisture content and pH of the manure, and oxygen availability (Ni, 1999; Liang et al., 2004).

To reduce NH$_3$ losses from manure storage and to increase the predictability of nitrogen losses in the manure, the effects of environmental conditions of manure storage, characteristics of manure, and manure handling practices on NH$_3$ emission must be quantified. Consequently, it is important to identify the most significant parameters and establish general relationships between these parameters and the NH$_3$ emission. Many studies have been conducted to quantify the NH$_3$ emissions affected by wind speed, pH, temperature, and nitrogen content from liquid manure storage (Elzing, et al., 1997; Arogo, et al., 1999). Carr (1990) reported a model to determine the ammonia concentration from broiler litter as a function of pH, ambient temperature, relative humidity (RH), and litter moisture content. The rate of NH$_3$ loss increased with increasing storage temperature (Pratt et al., 2002). However, data are lacking for the NH$_3$ emissions from layer manure storage under various environmental conditions.

Treating manure in storage shed to reduce NH$_3$ emission may be more readily implemented than inside the layer houses because of potential bird health concerns and detrimental effects of the treatment on the housing equipment. Increasing the manure stack height will limit available surface area of a manure pile and could reduce the NH$_3$ emission. Ventilation has been used to improve air quality and may increase NH$_3$ emission due to high NH$_3$ concentration gradient between manure surface and the surrounding air. Therefore, decreasing the air exchange rate of the manure storage may reduce NH$_3$ emission because of lower pressure gradient in NH$_3$ between the manure pile and the surrounding air. Drying can be
used to reduce NH$_3$ emission from stored manure. Drying poultry manure to more than 40% dry matter content reduced NH$_3$ emission from manure on belt (Groot Koerkamp, et al., 1995).

This paper reports the effects of physical condition of manure, manure stacks, and ambient temperature on NH$_3$ emission from stored laying hen manure. Specific objectives of this study were: 1) to determine the effect of two different air exchange rates and five manure stack surface area to volume ratios (SVR) on NH$_3$ emission from manure stacks; and 2) to evaluate the effects of ambient temperature and moisture content of hen manure on NH$_3$ emission from the manure stacks.

**MATERIALS AND METHODS**

**Experimental Setup**

*Air emission chambers*

Laying hen manure used in this study was acquired from an Iowa commercial layer farm where manure-belt system was used for daily manure removal. The laying hens (100,000 per house) were fed standard ration and watered though nipple drinkers. On the starting day of each trial, manure removed from a layer house of similar bird age was trucked from the farm to our emission measurement laboratory. Four environmentally controlled chambers were used to store the laying hen manure (Fig. 1). Each chamber had the dimension of 1.5 m wide × 1.8 m deep × 2.4 m high and operated as a positive pressure system. Four height adjustable stands were used to achieve the same head space in the four chambers with different depths of manure. A plastic film liner was used in each chamber to prevent the moisture loss from the manure stack to the floor/stand. An air handler unit (850 m$^3$ hr$^{-1}$ capacity) was used to supply fresh air to each chamber whose airflow was adjusted with an inlet baffle. The plenum of each chamber had two electric heaters (Model 3VU37, Cole-Parmer Instruments Co.) to heat the
incoming air to achieve the desired air temperature near the manure level. In addition, the following environmental variables were continuously measured: 1) dry-bulb air temperature and RH in the center of each chamber and 30 cm above the manure surface, 2) manure stack temperature measured with type T thermocouples (0.2 °C resolution), 3) manure moisture content measured with calibrated soil moisture content probes (Model EC-20, Decagon Devices, Inc., Pullman, WA) and 4) airflow rate through each chamber with thermoelectric air mass flow meters (HFM-200B, Hastings Instruments, Hampton, Virginia) placed in the supply air stream.

**Ammonia sampling**

A multi-gas photoacoustic monitor (INNOVA 1314, Innova AirTech Instruments, Denmark) was used to measure the NH₃ concentration in the sample air. Incoming (1) and exhaust (4) air samples were taken and analyzed sequentially at 20 min intervals with the first 15 min for purging/stabilization and the remaining 5 min for measurement. Therefore, each measurement cycle took 100 min. The control and data acquisition programs were used to log the signal output from all the sensors and the gas analyzer. The data acquisition programs took measurements every two seconds and stored the data at one minute interval.

**Experimental Regimens**

*Experiment 1: two SVR and two ventilation rate*

Manure stacks were 43 cm deep in two of the four chambers and 81 cm deep in the other two. The 43 cm stacks had a manure volume of 1.20 m³ and a surface area to volume ratio (SVR) of 2.3, whereas the 81 cm stacks had a manure volume of 2.26 m³ and SVR of 1.23. One chamber of each manure height was ventilated at 10 air changes per hour (ACH) (35 m³ hr⁻¹), whereas the other companion chamber of manure height was ventilated at 20 ACH
(70 m$^3$ hr$^{-1}$) (Table 1). The experimental regimens were designated as H43AC10, H43AC20, H81AC10, and H81AC20. Assignment of the manure stacks to the emission chambers was randomized. All chambers were maintained at the same air temperature of 25°C with a concomitant dew-point temperature of 10-24°C. Based on a preliminary test, the NH$_3$ emission rate tended to be stable after 40-d ventilated storage. Therefore, emission from each chamber or regimen was measured continuously for 40 d, and was replicated twice. The total weight of fresh manure for replicate 1 and 2 were 6,540 and 6,490 kg, respectively.

**Experiment 2: surface to volume ratio effect**

Manure stacks were 5, 10, 20 or 40 cm high in the four chambers and the corresponding manure volumes were 0.142, 0.283, 0.566 or 1.13 m$^3$. The corresponding surface area to volume ratios (SVR) for the four depths were 20, 10, 5 or 2.5. All four chambers were ventilated at 20 ACH (70 m$^3$ hr$^{-1}$) (Table 1). The experimental regimens were designated as SVR20, SVR10, SVR5, and SVR2.5. Assignment of the manure stacks to the emission chambers was randomized. All chambers were maintained at the same air temperature of 25°C with a concomitant dew-point temperature of 10-24°C. Emission from each chamber or regimen was measured continuously for 40 days, and was replicated twice. The total weight of fresh manure for replicate 1 and 2 was 2,100 kg. Loading of manure into the four chambers was done at the same time to maximize homogeneity of manure among the chambers.

**Experiment 3: Ambient temperature and moisture content effects**

The test conditions for this experiment are also listed in Table 1. Laying hen manure with two levels of initial moisture content – lower or higher moisture content (LMC, HMC), both using standard diet, were used. The LMC manure (50% MC) was acquired from a commercial layer facility where manure was pre-dried before transported to the storage. The
HMC (77% MC) manure was from the daily removed fresh manure. Four manure stacks with 5 cm height (SVR of 20) were used: two LMC manure stacks were randomly assigned to two chambers and two HMC manure stacks were assigned to the other two. All four chambers had the same diurnal cyclic air temperature of 21 to 32 °C with a mean of 26.7 °C, and an air change rate of 20 ACH. The cyclic temperature followed a sinusoidal shape with the highest temperature (32°C) occurring at 12 pm and the lowest temperature (21°C) at 6 am. The LMC and HMC trials were conducted twice, yielding four replicates per treatment. Emissions from each chamber were measured continuously for 3 weeks. The weight of LMC and HMC manure were 95 kg and 110 kg (as-is), respectively. The equivalent fresh manure (at 75% MC) weights of the LMC and HMC regimes were 190 and 101 kg fresh manure based on the dry matter.

**Experiment 4: Manure addition effect**

Four chambers were used to measure NH$_3$ ER of 5 cm deep fresh manure from day 0. Then, every two days, another 5-cm high manure layer was added on the top the existing manure stack in each chamber. A total of seven layers of manure were added into each chamber and over the 20-d experimental period. All four chambers were ventilated at 20 ACH and with the same air temperature of 25°C. The weight of each layer of fresh manure in each chamber was 120 kg, which was equivalent to the daily manure production of 1364 laying hens. This calculation was based on the laying hen manure production data from ASAE Standards (D384.2, 2005). Loading of manure into the four chambers was done at the same time to maximize homogeneity of manure among the chambers and it took about 1 hour. Emission data during the 1-hr manure loading and the subsequent 3 hrs were excluded from the analysis to ensure sufficient time for the system to reach steady state following opening of the chambers.
Manure Analyses

Nutrient and physical properties of the manure were analyzed by a certified commercial analytical lab at the beginning and the end of the trial. Moisture content was determined by drying wet samples in an electric oven at 135 °C for 2 hours (AOAC 930.95, 1990). Total nitrogen (Total N) was measured by using improved Kjeldahl method (AOAC 955.04, 1990). Total ammoniacal nitrogen (ammonia plus ammonium, TAN) was measured by cadmium reduction method (AOAC 922.03, 1990) and pH was measured by electrode (MAES, 1998).

Intermediate sampling of the manure nutrients was not performed to avoid disturbing the manure stacks. Manure samples were taken from each stack at five locations (four quadrants and the center) and two layers (the top 5 cm layer from the surface and the lower layer). At the end of monitoring, a relatively rigid and dry top layer of 5-8 cm in depth was found for the manure stacks. This layer was quite distinctive from the remaining wetter stack. Therefore, manure samples from the surface layer and subsurface were taken and analyzed separately.

After mixing all the samples from each layer, one composite sample was sent to the commercial lab for analysis.

Calculation of NH₃ Emission

Ammonia emission rate (ER₁NH₃, mg/hr-kg) was calculated using the following equation:

$$ ER_{NH_3} = \left([NH_3]_e - [NH_3]_i\right) \times 10^{-6} \times \frac{Q}{M} \times \frac{17.03 \text{ g/mol}}{0.0224 \text{ m}^3 / \text{ mol}} \times 1000 \text{ mg/g} \quad [1] $$

where

$[NH_3]_e, [NH_3]_i$ =NH₃ concentrations at exhaust and inlet air, respectively, ppm

Q = ventilation rate, m³ hr⁻¹ chamber⁻¹ at STP
M = amount of manure placed in the chamber, kg

RESULTS AND DISCUSSIONS

Properties of the Manure Stacks

The composition of the manure at the onset and end of the 40-day trial period are shown in Tables 2 and 3. The dry matter (DM) content of the fresh manure was about 23%. For the “dried” manure, the dry matter was 50%. The proportion of TAN form in fresh manure was about 48% of the total N, varying from 16 to 19 g kg\(^{-1}\) fresh manure. The differences in the compositions among the fresh manure probably stemmed from difference in bird age, thus dietary composition, and inherent variability in manure samples.

Tables 2 and 3 show the compositions of the manure at the end of the 40-day ventilated storage. The DM content of the stacks increased (47.7-68.4%) for the top layer but decreased (22.5-23.8%) for the remaining bottom layer when the manure stacks was deeper than 10 cm. However, TAN (both wet and dry base) in the top layer was lower than that in the bottom layer. The proportion of TAN in the top and bottom layer was about 30% and 77% of the total N, respectively. No significant differences in the manure properties (P>0.10) were found among the four treatments in the Experiment 1 after the 40-day ventilated storage. In Experiment 2, the surface composition of the SVR20 manure stack (5cm) was different from other manure stacks and the bottom layer composition of the SVR10 manure stack was different from that of the other two manure stacks, SVR5 and SVR2.5 (P<0.001).

A relationship between pH and degradation of uric acid, major nitrogen resource in poultry manure, had been reported such that a sharp increase in pH was associated with decrease in the uric acid content of poultry manure (Burnett et al., 1969). In the aerobic processes, the degradation of uric acid is faster compared with anaerobic processes. The high
pH in the stored manure resulted in the majority of nitrogen loss as NH$_3$ (Elliot et al., 1982). Manure pH (8.0 to 8.5) of the surface layer was higher than that of the pH (7.8 to 8.0) of subsurface because of the more aerobic process in the surface manure and more anaerobic processes in the subsurface.

Although only the nutrient and physical properties of the manure stacks at the onset and end of the storage period were available, some inferences could be made. First, the surface layer of the manure stack seemed to be the main contributor to the NH$_3$ loss due to larger size of air pores resulting in lower mass transfer resistance. Second, anaerobic condition presumably existed under the surface due to the high moisture content. Finally, in the subsurface manure, the large proportion of the total N existed as TAN (77%) after 40-day storage when manure was deeper than 10 cm and NH$_3$ would be more easily retained in the subsurface because of high resistance to the nutrient diffusion.

**Measured Ammonia Concentrations**

The NH$_3$ concentration in the chambers rapidly reached maximum after about 2 days: about 400 ppm for the stacks with 10 ACH and about 200 ppm for the stacks with 20 ACH. Then, the NH$_3$ concentration began to decrease exponentially. The NH$_3$ concentration of stacks with 10 ACH remained about twice that of stacks with 20 ACH.

**Effects of the Air Exchange Rates at Two SVRs**

Figure 2 depicts the daily NH$_3$ emission rates (ER) during the 40-d trial. The ER profiles of the four regimens followed similar patterns to the measured concentrations. This result was expected as ventilation rate for each chamber was held essentially constant. Ammonia is mainly a product of degradation of uric acid and undigested proteins from the
surface layer manure. The exponential decrease of the uric acid content and a corresponding release of NH$_3$ from layer excreta over three weeks were reported.

Ammonia ER on per chamber basis did not show significant differences among the four regimens during the 40-d of ventilated storage (Fig. 2). However, on per kg manure basis, i.e., g NH$_3$ day$^{-1}$kg$^{-1}$ fresh manure, NH$_3$ ER of the shallower stacks (43 cm) was higher during the first 5 wks. Then the difference in NH$_3$ ERs tended to decrease. In addition, cumulative NH$_3$ emissions from each chamber ranged from 3.62 kg to 4.77 kg (SD = 0.38 kg), showing no significant difference (P = 0.52). The cumulative NH$_3$ emissions are shown in Figure 3. There were no significant effects of air change rate (P = 0.94) or SVR (P = 0.25) when evaluated on the basis of kg NH$_3$ per chamber. However, the effect of SVR was highly significant (P = 0.008) when based on the ER unit of g/kg manure. For the stacks with 43 cm depth, 40-d NH$_3$ emission was 3.6 g kg$^{-1}$ manure and the NH$_3$-N loss was about 16% of the total N in the fresh manure. For the 81 cm stacks, the 40-d NH$_3$ emission was 2.2 g kg$^{-1}$ and the NH$_3$-N loss was 9.9% of the total N in fresh manure (Table 4).

From the standpoint of mass transfer theory, increasing partial NH$_3$ pressure in the boundary air by reducing air exchange rate should reduce the partial pressure gradient and thus NH$_3$ emission. However, this effect was not seen in our experiment. Several factors might have contributed to this outcome. If the manure stack surface had a constant NH$_3$ concentration, NH$_3$ emission rate would increase with increase of ACH due to lower partial NH$_3$ pressure. Otherwise, NH$_3$ emission rate would decrease when NH$_3$ concentration in the surface decreased due to lower diffusion rate of NH$_3$ in the top layer even if ACH is increased. The NH$_3$ ER under 10 ACH was similar to ER under 20 ACH during the first 28-day period and tended to be lower afterwards. On the 40$^{th}$ day of storage, the NH$_3$ ER under 20 ACH and 10
ACH were 1.72 and 1.41 mg hr\(^{-1}\)kg\(^{-1}\) fresh manure for the 83 cm stacks, respectively; and 2.52 and 1.81 mg hr\(^{-1}\)kg\(^{-1}\) fresh manure for the 43 cm manure stacks, respectively. The result implies that the air change rate did influence NH\(_3\) emission after four weeks of storage, with the lower ventilation rate leading to reduced NH\(_3\) emission. However, in the 40-day trial period, the effect of ACH on NH\(_3\) emission during the last 12-day period could have been masked due to the large weight of data from the first four weeks during which no significant effect was observed.

Due to the same emitting surface area, the stacks had very similar cumulative NH\(_3\) of 1.5 to 1.7 kg m\(^{-2}\) surface area with 41 and 83 cm depth, respectively (P=0.23). It implied that reducing the surface area of manure exposed to air is more effective than reducing the ventilation rate for lowering NH\(_3\) emission from the manure storage. Compared with the test result (0.054 g NH\(_3\) d\(^{-1}\) kg\(^{-1}\) manure) reported by Pratt (2002), NH\(_3\) emission rate in this study were greater for the same storage period. The possible reasons could be different stacking configurations, manure properties, and environmental conditions.

**Effect of Surface to Volume Ratio (SVR)**

The ammonia ERs for the four treatments with different depths were shown in Figure 4 and the cumulative ammonia emission was shown in Figure 5. Ammonia ER and cumulative emission on per mass basis and per area basis showed significant differences among the four regimens during the 40-day ventilated storage (p<0.01). Generally, on per kg manure basis, i.e. g NH\(_3\) day\(^{-1}\)kg\(^{-1}\) fresh manure, the manure stacks with higher SVR value had higher ER during the 40-day storage. However, the NH\(_3\) ER of the 5 cm stack with 20 SVR showed its continual decline with storage time presumably because of limited nitrogen resource in the smaller manure stack. It suggests that the stack will reach its emission limit after certain time. On the
per surface area basis, the higher manure stacks had higher NH$_3$ ER because the subsurface manure provide adequate nutrient resource to sustain the emission from the surface manure, including moisture and TAN. In addition, cumulative NH$_3$ emissions from each chamber were 1.46, 2.42, 3.11 and 3.41 kg for SVR20, 10, 5 and 2.5, respectively, showing significant difference (P < 0.001). Total N and TAN content (dry-basis) decreased for the subsurface layer, as seen in Experiment 1, but increased in SVR5 and SVR2.5 regimens. It should be noted that the top and bottom layers were essentially the same for regimen SVR20 because the stack was only 5 cm thick. The dynamic moisture content of the manure stacks was depicted in Figure 6. Moisture was continuously lost from the surface layer due the convective water vapor transfer and evaporation. Carr et al. (1990) concluded that ammonia loss from stored manure was only reduced when the moisture content was below 30%. The ammonia emission rate decreased following the decrement of manure moisture content in the surface layer. High moisture content of the manure surface layers may stimulate the ammonia volatilization due to high NH$_3$ diffusivity in the “wet” manure.

To quantify the relationship between the cumulative ammonia emission and the stack SVR and storage time at the constant air temperature of 25°C, an empirical model was developed from the experimental data. The relationship has the following form,

\[
Q_{NH_3} = \frac{a \times ST \times SVR}{b + c \times ST \times SVR + SVR}
\]

where

- $Q_{NH_3}$ = cumulative ammonia emission during the specified storage time, g NH$_3$ kg$^{-1}$ fresh manure
- ST = storage time of the manure, day
- SVR = storage volume ratio
- $a$, $b$, and $c$ are empirical constants

Carr et al. (1990) concluded that ammonia loss from stored manure was only reduced when the moisture content was below 30%. The ammonia emission rate decreased following the decrement of manure moisture content in the surface layer. High moisture content of the manure surface layers may stimulate the ammonia volatilization due to high NH$_3$ diffusivity in the “wet” manure.
SVR = surface-to-volume ratio of the manure stack, m$^{-1}$
a, b, c are regression coefficients, $a = 1.57 \times 10^8$, $b = 3.60 \times 10^9$, $c = 7.60 \times 10^6$

The degree of fitness between the predicated and measured cumulative ammonia emissions is shown in Figure 7. Figure 7 shows paired comparisons of cumulative NH$_3$ emission between the measured and predicted values from the regression model at daily time intervals. The number of observations associated with each of the time intervals was 100. The corresponding regression line revealed good regression coefficient ($R^2$) of 0.9954. The empirical model represents the data well.

**Effects of Moisture Content and Ambient Temperature**

In Experiment 3, the chamber air temperature was controlled to simulate diurnal temperature variation during production. The set points of air temperature were 21 and 32 °C at 6:00h and 18:00h, respectively. Hourly NH$_3$ emission rate (ER) was derived from two different moisture content manure stacks and the ER was expressed as emitted NH$_3$ per day per kg fresh manure. Figure 8 shows that the NH$_3$ ERs of LMC (50%) and HMC (77%) manure stacks were following the air temperature at a constant ventilation rate of 20 ACH. The ERs from LMC and HMC increased with temperature during the 3-week storage time. The peak ER appeared on the second day because of low initial manure temperature, which affects the NH$_3$ dissociation rate and mass transfer from manure surface to surrounding air. After reaching the peak, the ER decreased with the time. A regression model was derived using the SAS statistical package (SAS Institute) to relate ER to air temperature and manure moisture content:

$$\ln(ER_{NH_3}) = 1.53 + 0.53 \times MC - 0.085 \times ST + 0.059 \times T_o \quad [3]$$

where
With a natural log transformation of ER, Ln(ER) showed linearity with the moisture content, temperature and storage time. Figure 9 shows paired comparisons of cumulative NH$_3$ emission between the measured and predicted values from the regression model at daily time intervals. Under the situation, temperature changes significantly affected the NH$_3$ emission. In the range of 21 to 32 °C, the ER would increase 6% per 1°C increment. For the HMC (77%) manure stack, the highest ER (1.1 g day$^{-1}$kg$^{-1}$ fresh manure) was twice the lowest ER (0.55 g day$^{-1}$kg$^{-1}$ fresh manure) during the second temperature cycle. For the LMC (50%) manure stack, the highest and lowest ERs were 0.9 and 0.55 g day$^{-1}$kg$^{-1}$ fresh manure during the same period. The effect of the temperature was a combined effect on degradation and volatilization process. The high temperature stimulates the dissociation of NH$_3$ on the manure surface and decomposition rate of uric acid and organic nitrogen. The gas phase NH$_3$ above the manure surface increased and more NH$_3$ was emitted into the surrounding air. Pratt et al. (2002) reported a linear trend of nitrogen loss from stored poultry manure with the air temperature from 12.3 to 24.4 °C.

The NH$_3$ ER of HMC (77%) was 1.7 times that of the LMC (50%). After 21-day storage, the cumulative NH$_3$ emission of LMC manure was 5.80 g kg$^{-1}$ fresh manure (25.2 g kg$^{-1}$ DM) which is 38% of the cumulative NH$_3$ emission of HMC manure, 9.10 g kg$^{-1}$ fresh manure (39.4 g kg$^{-1}$ DM) (Table 4). Compared with the cumulative NH$_3$ emission in
Experiment 2 for the first 21 days, the cumulative NH$_3$ emission of SVR20 (initial MC of 78%) stack was 9.95 g kg$^{-1}$ fresh manure (35.53 g kg$^{-1}$ DM) at a constant air temperature of 25°C.

**Ammonia Emission with Manure Additions**

In Experiment 4, hen manure was added to each chamber every two days. This resulted in a total of seven layers of manure added per chamber during 20-day storage. Figure 11 shows the dynamic NH$_3$ ERs based on the surface area of the manure stacks. The NH$_3$ ER dropped sharply after new manure layers were placed in. Then, the NH$_3$ ER increased to the maximum in two days. After the 14th day, the NH$_3$ ER slightly decreased. The daily NH$_3$ ERs in g d$^{-1}$ hen$^{-1}$ from the progressively growing manure stack are shown in Figure 12. After the manure addition, the first daily NH$_3$ ERs were significantly lower than the second daily ERs (P<0.001). After five manure layer additions, the peak NH$_3$ ER (0.11 g d$^{-1}$ hen$^{-1}$) on the second day tended to be stable.

**Ammonia Emission from Laying Hen Houses and Storage**

Ammonia emission from manure storage primarily depends on the manure handling practices. The manure surface exposed to the air should be limited to control the NH$_3$ emission. The following practices are suggested: 1) reduce the surface area of manure piles; 2) keep adding new manure on the old manure pile; 3) keep the temperature of manure storage low if possible. If the daily fresh manure from the belt houses was added to the same manure pile with the environment condition of high temperature (>30°C), high manure moisture content (75-77% MC) and large surface to volume ratio (SVR =20), the peak NH$_3$ ERs would be around 1.3 g d$^{-1}$ kg$^{-1}$ fresh manure, which is equivalent to 0.11 g d$^{-1}$ hen$^{-1}$. Liang et al. (2005) reported 0.87 g NH$_3$ d$^{-1}$ hen$^{-1}$ NH$_3$ ER for HR houses in Iowa and Pennsylvania and 0.054 g NH$_3$ d$^{-1}$ hen$^{-1}$ NH$_3$ ER for MB houses with daily manure removal from Iowa. When the NH$_3$...
ER for manure storages was counted, the total NH$_3$ ER from MB houses and manure storage would be $0.054 + 0.110 = 0.164$ g d$^{-1}$hen$^{-1}$. Hence the combined ammonia emissions from MB laying hen house and the manure storage are likely much less than that from the high-rise (HR) houses.

**CONCLUSIONS**

The key contribution factor to this outcome is speculated to be the much lower emitting surface area for the MB system. The effects of surface area to volume ratios were significant on the rate of NH$_3$ emission from stored laying hen manure from belt houses. For stacks with 43 cm depth (SVR = 2.3), the NH$_3$ emission was 3.6 g kg$^{-1}$ fresh manure and the nitrogen (N) loss as NH$_3$ was about 16% of the total N in fresh manure. For 81 cm stacks (SVR=1.2), the NH$_3$ emission was 2.2 g kg$^{-1}$ fresh manure and 9.9% of the total N was emitted as NH$_3$.

Air exchange rate (10 or 20 ACH) positively affected the NH$_3$ emission rate after the first four weeks of storage. However, air change rates of 10 or 20 ACH showed no effect on the cumulative NH$_3$ emission during the 40-day ventilated storage.

The effects of five manure stack surface area to volume ratios (1.2, 2.3, 5, 10 and 20) on NH$_3$ emission of laying hen manure stacks were evaluated during a 40-d ventilated storage period under a constant temperature 25°C. The corresponding NH$_3$ emissions of the five SVRs were 2.27, 3.51, 6.45, 9.70 and 12.4 g kg$^{-1}$ fresh manure, respectively. A regression model was developed to quantify the NH$_3$ emissions from manure stack with five SVRs.

The effects of two moisture contents (50% and 77%) and temperature (21 °C to 32 °C) were also evaluated with 20 ACH and SVR 20. The nitrogen loss as NH$_3$ ranged from 10% to 63% of the total N in fresh manure after 40-day storage. The effect of temperature is +6% per degree Celsius rise. The NH$_3$ emission rate from 50% MC manure stack is 59% of the NH$_3$ ER
from 77% MC manure stack. The NH3 ER from manure-belt houses and manure storage is much smaller than that from high-rise houses.

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Table 1. Experimental conditions and regimens to evaluate the effects of surface to volume ratio (SVR), air exchange rate, moisture content and air temperature on NH$_3$ emissions from layer manure storage (assignment of the regiments to chambers was randomized)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Experiment 1</th>
<th></th>
<th>Experiment 2</th>
<th></th>
<th>Experiment 3</th>
<th></th>
<th>Experiment 4</th>
<th></th>
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</thead>
<tbody>
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<td></td>
<td>H43AC10$^1$</td>
<td>H43AC20$^2$</td>
<td>H81AC10$^3$</td>
<td>H81AC20$^4$</td>
<td>SVR20</td>
<td>SVR10</td>
<td>SVR5</td>
<td>SVR2.5</td>
</tr>
<tr>
<td>Manure stack depth, cm</td>
<td>43</td>
<td>43</td>
<td>81</td>
<td>81</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
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<tr>
<td>Manure volume, m$^3$</td>
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<td>1.2</td>
<td>2.26</td>
<td>2.26</td>
<td>0.14</td>
<td>0.28</td>
<td>0.57</td>
<td>1.14</td>
</tr>
<tr>
<td>Surface to volume ratio</td>
<td>2.3</td>
<td>2.3</td>
<td>1.23</td>
<td>1.23</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>Air changes per hour</td>
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<td>10</td>
<td>20</td>
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<tr>
<td>MC</td>
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<td>71%</td>
<td>71%</td>
<td>71%</td>
<td>72%</td>
<td>72%</td>
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</tr>
</tbody>
</table>

$^1$ H43AC10: 43 cm height stack with 10 ACH; $^2$ H43AC20: 43 cm height stack with 20 ACH

$^3$ H81AC10: 81 cm height stack with 10 ACH; $^4$ H81AC20: 81 cm height stack with 20 ACH
Table 2. Mean and standard deviation (in brackets) of initial and post (40-day) storage composition of laying hen manure stacked at one of the two surface to volume ratios and ventilated at either 10 or 20 air changes per hour (ACH) (Top layer refers to the top 5 cm of the stack and bottom layer to sub layer of stack) – Experiment 1 (n=2)

<table>
<thead>
<tr>
<th>Stack Layer</th>
<th>Manure Properties</th>
<th>Fresh</th>
<th>After 40-day Ventilated Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>H43AC10 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H43AC20 2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>H81AC10 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H81AC20 4</td>
</tr>
<tr>
<td>Top</td>
<td>Dry matter (%)</td>
<td>28.9(2.1)</td>
<td>50.4(2.6)</td>
</tr>
<tr>
<td></td>
<td>Total N, g kg⁻¹ (as-is)</td>
<td>18.5(0.42)</td>
<td>18.2(1.1)</td>
</tr>
<tr>
<td></td>
<td>Total N, g kg⁻¹ (dry base)</td>
<td>64(3.3)</td>
<td>36.1(0.3)</td>
</tr>
<tr>
<td></td>
<td>TAN, g kg⁻¹ (as-is)</td>
<td>7.8(2.5)</td>
<td>5.9(0.78)</td>
</tr>
<tr>
<td></td>
<td>TAN, g kg⁻¹ (dry base)</td>
<td>27(10.7)</td>
<td>11.8(2.2)</td>
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<tr>
<td></td>
<td>pH</td>
<td>7.5(0.07)</td>
<td>8.1(0.14)</td>
</tr>
<tr>
<td>Bottom</td>
<td>Dry matter (%)</td>
<td>28.9(2.1)</td>
<td>23.8(0.21)</td>
</tr>
<tr>
<td></td>
<td>Total N, g kg⁻¹ (as-is)</td>
<td>18.5(0.4)</td>
<td>17.1(1.2)</td>
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<td>Total N, g kg⁻¹ (dry base)</td>
<td>64(3.3)</td>
<td>71.9(4.5)</td>
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<td>TAN, g kg⁻¹ (as-is)</td>
<td>7.8(2.5)</td>
<td>13(1.1)</td>
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<tr>
<td></td>
<td>TAN, g kg⁻¹ (dry base)</td>
<td>27(10.7)</td>
<td>54.4(4.0)</td>
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<tr>
<td></td>
<td>pH</td>
<td>7.5(0.07)</td>
<td>7.8(0.07)</td>
</tr>
</tbody>
</table>

¹ H43AC10: 43 cm height stack with 10 ACH; ² H43AC20: 43 cm height stack with 20 ACH
³ H81AC10: 81 cm height stack with 10 ACH; ⁴ H81AC20: 81 cm height stack with 20 ACH
Table 3. Mean and standard deviation (in brackets) of initial and post (40-day) storage composition of laying hen manure stacked at a surface to volume ratio (SVR) of 20, 10, 5 or 2.5 and ventilated at 20 air changes per hour (ACH) (Top layer refers to the top 5 cm of the stack and bottom layer to sub layer of stack) – Experiment 2 (n=2)

<table>
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<tr>
<th>Stack Layer</th>
<th>Manure Properties</th>
<th>Fresh</th>
<th>After 40-day Ventilated Storage</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SVR20</td>
</tr>
<tr>
<td>Top</td>
<td>Dry matter (%)</td>
<td>28.1 (1.2)</td>
<td>68.4 (9.5)</td>
</tr>
<tr>
<td></td>
<td>Total N, g kg(^{-1}) (as-is)</td>
<td>16.2 (0.21)</td>
<td>19.9 (3.6)</td>
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<tr>
<td></td>
<td>Total N, g kg(^{-1}) (dry base)</td>
<td>57.7 (1.8)</td>
<td>28.9 (1.3)</td>
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<tr>
<td></td>
<td>TAN, g kg(^{-1}) (as-is)</td>
<td>8.8 (0.71)</td>
<td>4.6 (1.1)</td>
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<td>TAN, g kg(^{-1}) (dry base)</td>
<td>31.3 (1.1)</td>
<td>7.1 (2.5)</td>
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<td></td>
<td>pH</td>
<td>7.4 (0.28)</td>
<td>8.6 (0.00)</td>
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<tr>
<td>Bottom</td>
<td>Dry matter (%)</td>
<td>28.1 (1.2)</td>
<td>68.4 (9.5)</td>
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<tr>
<td></td>
<td>Total N, g kg(^{-1}) (as-is)</td>
<td>16.2 (0.21)</td>
<td>19.9 (3.6)</td>
</tr>
<tr>
<td></td>
<td>Total N, g kg(^{-1}) (dry base)</td>
<td>57.7 (1.8)</td>
<td>28.9 (1.3)</td>
</tr>
<tr>
<td></td>
<td>TAN, g kg(^{-1}) (as-is)</td>
<td>8.8 (0.71)</td>
<td>4.6 (1.1)</td>
</tr>
<tr>
<td></td>
<td>TAN, g kg(^{-1}) (dry base)</td>
<td>31.3 (1.1)</td>
<td>7.1 (2.5)</td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>7.4 (0.28)</td>
<td>8.6 (0.00)</td>
</tr>
</tbody>
</table>

* Thickness of the manure stacks (cm): SVR20=5 cm, SVR10=10 cm, SVR20=20 cm, SVR20=40 cm
Table 4. Ammonia cumulative emission of stored laying hen manure after 21 days and 40 days of storage

<table>
<thead>
<tr>
<th></th>
<th>H81AC10</th>
<th>H43AC10</th>
<th>H81AC20</th>
<th>H43AC20</th>
<th>SVR2.5</th>
<th>SVR5</th>
<th>SVR10</th>
<th>SVR20</th>
<th>LMC1</th>
<th>HMC2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Over 21 days</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH\textsubscript{3} Emission, g kg\textsuperscript{-1} fresh manure</td>
<td>1.42</td>
<td>2.22</td>
<td>1.40</td>
<td>2.19</td>
<td>2.02</td>
<td>3.54</td>
<td>5.93</td>
<td>9.95</td>
<td>5.80</td>
<td>9.10</td>
</tr>
<tr>
<td>NH\textsubscript{3}-N loss as % total N in fresh manure</td>
<td>6%</td>
<td>10%</td>
<td>6%</td>
<td>10%</td>
<td>10%</td>
<td>18%</td>
<td>30%</td>
<td>51%</td>
<td>30%</td>
<td>47%</td>
</tr>
<tr>
<td><strong>Over 40 days</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH\textsubscript{3} Emission, g kg\textsuperscript{-1} fresh manure</td>
<td>2.17</td>
<td>3.71</td>
<td>2.27</td>
<td>3.49</td>
<td>3.51</td>
<td>6.45</td>
<td>9.70</td>
<td>12.41</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>NH\textsubscript{3}-N loss as % total N in fresh manure</td>
<td>10%</td>
<td>17%</td>
<td>10%</td>
<td>16%</td>
<td>18%</td>
<td>33%</td>
<td>49%</td>
<td>63%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1 LMC: Manure stack with low moisture content (50% moisture content) with cyclic temperature 21 to 32 °C (mean of 26.5 °C). SVR = 20.

2 HMC: Manure stack with high moisture content (77% moisture content) with cyclic temperature 21 to 32 °C (mean of 26.5 °C). SVR = 20.

* SVR: Surface area to volume ratio; H xx AC yy - where xx indicated height of the manure stack in cm and yy indicates ventilation rate in air change per hour.

Air temperature for other regimes was constant at 25°C.
Figure 1. Schematic representation of emission measurement chambers and instrumentation
Figure 2. Daily ammonia emission rate (mean and standard error, n=2) from four laying hen manure stacks using two surface to volume ratios and air change rates (legend HxxACyy- where xx indicated height of the manure stack in cm and yy indicates ventilation rate in air change per hour). The emission rates are expressed in kg NH₃ per day per m² surface area (top) or g per day per kg of fresh manure weight (bottom).
Figure 3. Cumulative ammonia emissions of laying hen manure stacks under a 40-d storage using two surface to volume ratios and air exchange rates. The emissions are expressed in kg NH$_3$ per m$^2$ surface area (top) or g NH$_3$ per kg of initial manure weight (bottom).
Figure 4. Daily ammonia emission rates (mean and standard error, n=2) from four laying hen manure stacks using a surface to volume ratios (SRV) of 20, 10, 5 or 2.5 during a 40-d storage period. The emission rates are expressed in g NH₃ per day per m² surface area (top) or g NH₃ per day per kg of fresh manure weight (bottom).
Figure 5. Cumulative ammonia emissions from laying hen manure stacks using a surface to volume ratios (SRV) of 20, 10, 5, 2.5 or 1.23 during a 40-d storage period. The emissions are expressed in kg NH$_3$ per m$^2$ surface area (top) of g NH$_3$ per kg of fresh manure weight (bottom).
Figure 6. Dynamic moisture content and manure stacks temperature of laying hen manure stacks during a 40-d storage period in Experiment 1 (top) and Experiment 2 (bottom). For the top layer, moisture probes were placed horizontally at 2.5 cm below the surface of manure stacks; and for the bottom layer, they were placed horizontally at 2.5 cm above the bottom of manure stacks.
Figure 7. Relationship of cumulative NH$_3$ emission from measurement vs. from prediction model at constant air temperature of 25°C. The dash lines below and above the regression lines represent 95% confidence intervals of the observations.
Figure 8. Daily ammonia emissions from laying hen manure stacks using two moisture contents of LMC (50%) and HMC (77%) subjected to a sinusoidal diurnal temperature cycle of 21 to 32 °C. The emission is expressed in g NH₃ per day per kg fresh manure at 75% moisture content.

Figure 9. Relationship of measured Ln(ER) vs. predicted Ln(ER) from regression model. The dash lines below and above the regression lines represent 95% confidence intervals of the observations. ER: mg hr⁻¹ kg⁻¹ fresh manure.
Figure 10. Cumulative ammonia emissions (mean and standard error, n=4) from laying hen manure stacks using two moisture contents of LMC (50%) and HMC (77%) under a sinusoidal diurnal temperature cycle from 21 to 32 °C (mean of 26.5°C). The emission is expressed in g NH₃ per kg fresh manure at 75% moisture content.
Figure 11. Ammonia emissions rate (g hr\(^{-1}\) m\(^{-2}\) surface area) from layer manure storage at 25 °C air temperature. Fresh manure was added on days 2, 4, 6, 8, 10 and 12.

Figure 12. Daily ammonia emissions rate (g d\(^{-1}\) hen\(^{-1}\)) from layer manure storage at 25 °C air temperature. Fresh manure at 5-cm thickness was added on days 2, 4, 6, 8, 10, 12 and 14.
EFFECTS OF TOPICAL APPLICATION OF ZEOLITE, AL$^+$ CLEAR, FERIX-3 OR PLT TO POULTRY MANURE ON AMMONIA EMISSIONS

A paper to be submitted to Journal of Applied Poultry Research

H. Li, H. Xin, Y. Liang and R. T. Burns

ABSTRACT

Manure storage can be a significant source of ammonia emission that impacts the environment. Ammonia emission from manure storage can be controlled by using physical, chemical and/or biological methods. Five treatment agents, including zeolite, liquid Al$^+$ Clear (aluminum sulfate), granular Al$^+$ Clear (aluminum sulfate), and granular Ferix-3 (ferric sulfate), and PLT (sodium hydrogen sulfate) were topically applied to stored fresh layer manure. Each agent was tested at three application rates, i.e., low, medium and high. Manure was stored in 19-liter Teflon-lined vessels under a constant ambient temperature of 23 °C with a constant airflow of 3 liter per minute. The ammonia concentrations and emissions from the vessels were measured and ammonia emission reductions by the treatment regimens were evaluated as compared to the control. Reduction of ammonia emission as a result of topical application of the tested manure treatment agents, when compared to the control, over a 7-day manure storage period was as following: A) 68%, 81% or 96%, respectively, for zeolite applied at 2.5%, 5% or 10% of the manure weight; B) 63%, 89%, or 94%, respectively, for liquid Al$^+$ Clear applied at 1, 2, or 4 kg m$^{-2}$ of manure surface area; C) 81%, 93%, or 94%, respectively, for dry granular Al$^+$ Clear applied at 0.5, 1.0, or 1.5 kg m$^{-2}$; D) 82%, 86%, or 87%, respectively, for Ferix-3
applied at 0.5, 1.0, or 1.5 kg m\(^2\); and E) 74%, 90%, or 92%, respectively, for PLT applied at 0.5, 1.0, or 1.5 kg m\(^2\).

**Keywords:** laying hen, belt house, manure storage, ammonia emission, additives

**INTRODUCTION**

Ammonia (NH\(_3\)) volatilization from intensive livestock operation not only reduces fertilizer nitrogen (N) value when manure is applied to agricultural land, but also contributes to environmental pollution. Effective technologies that reduce ammonia loss during animal housing, manure storage and land application would have positive economic and environmental benefits.

Laying hen manure is typically either stock-piled in the lower level of high-rise houses or removed from belt cage layer houses to manure storage facilities once to seven times a week. Various mechanisms are involved in conserving N in poultry manure during storage, including immobilization of ammonium through addition of easily decomposable, N-poor materials, adsorption of ammonium (NH\(_4^+\)) and NH\(_3\) on suitable amendments, and pH regulation of the manure solution (Kirchmann and Witter, 1989).

Numerous additives have been investigated to reduce NH\(_3\) volatilization from livestock manure. McCroy and Hobbs (2001) published a comprehensive review of a wide range of additives, i.e., acidifying agents, absorbing agents, and bacterial additives, for reducing ammonia from livestock wastes. Natural zeolite is a cation-exchange medium that has high affinity and selectivity for NH\(_4^+\) ions due to its crystalline, hydrated properties resulted from its infinite, 3-dimentional structures (Mumpton and Fishman, 1977). It has been widely used as amendment to poultry litter (Maurice et al., 1998; Nakaue and Koelliker, 1981b), in anaerobic digesters treating cattle manure (Borja et al., 1996), during composting of pig slurry and
poultry manure (Bernal et al., 1993; Kithome et al., 1999), air scrubber packing material to improve poultry house environment (Koelliker et al., 1980), and as a filtration agent in deep-bedded cattle housing (Milan et al., 1999). Kithome et al. (1998) investigated the kinetics of \(\text{NH}_4^+\) adsorption and desorption by natural zeolite clinoptilolite \([\text{Na}_4\text{K}_4(\text{Al}_8\text{Si}_{140})\text{O}_{96}.24\text{H}_2\text{O}]\) for its ability to adsorb N in its \(\text{NH}_4^+\) form at various pH values and initial \(\text{NH}_4^+\) concentrations.

The volatilization of ammonia has been attributed to microbial decomposition of nitrogenous compounds, principally uric acid, in poultry manure. Manure pH plays an important role in ammonia volatilization. Ammonia concentration tends to increase with increasing pH. Ammonia release remains small when pH is below 7.0, but can be substantial when pH is above 8.0. Uric acid decomposition is most favored under alkaline (pH>7) conditions. Uricase, the enzyme that catalyzes uric acid breakdown, has maximum activity at a pH of 9 with uric acid decreasing linearly for more acid or alkaline pH values. The \(\text{NH}_3\) emission can be inhibited by acidulants, which can lower manure pH and reduce conversion of ammonium to ammonia. The acidulants also inhibit the activities of bacteria and enzymes that are involved in the formation of ammonia, reducing ammonia production. Liquid Al+Clear and dry granular Al’Clear (aluminum sulfate), Ferix-3 (ferric sulfate) and PLT (sodium hydrogen sulfate) are acidulants that produce hydrogen ions (H\(^+\)) when they dissolve, and the hydrogen ions produced by this reaction will attach to ammonia to form ammonium. Because of these reactions, the amount of ammonia emitted from the manure will be reduced, which will increase the nitrogen (N) content of the manure. Al’Clear and PLT had been applied to poultry litter control ammonia volatilization (Moore et al., 1995, 1996; Kithome et al., 1999; Lefcourt and Meisinger, 2001, Armstrong et al., 2003). Ferix-3 usually is used for industrial and
municipal water and wastewater treatment over a wide pH range. Uses include color removal, organics removal, phosphorous removal, bacteria reduction, arsenic removal, sludge conditioning, turbidity reduction, COD/BOD reduction, enhanced coagulation, and heavy metals removal. It performs very well in soil remediation applications. However, information on the three acidulants efficacies on ammonia mitigation with laying hen manure is meager.

The objective of the study was to evaluate/screen the efficacy of certain potential biodegradable treatment agents on reduction of ammonia emission from layer manure storage. The treatment agents included zeolite, Al'Clear (liquid and dry forms), Ferix-3, and PLT.

**MATERIALS AND METHODS**

**Air Emission Vessels**

Eight emission vessels were designed and built for the study (Fig. 1). The vessels were placed in an environment-controlled room with a constant temperature 23 °C at the Livestock Environment and Animal Physiology (LEAP) Lab II of Iowa State University. The vessels were made of 19-liter (5-gal) plastic containers. To prevent potential interference of the vessel material with ammonia emission measurement, each vessel was lined with Teflon FEP100 film (200A, DuPont Teflon ® Films, Wilmington, DE). Both air inlet and outlet were located in the air-tight lid. Teflon tubing (1/4" diameter) and manifold, along with PVC compression fittings, were used in constructing the emission vessel system.

The vessels were operated under positive pressure. A diaphragm pump (Model DOA-P104-AA, Gast Manufacturing, Inc., Benton Harbor, MI) was used to supply fresh air to the emission vessels. Flow rate of the fresh supply air was controlled and measured with an air mass flow controller (0 to 30 LPM, stainless steel wetted part, AAlborg Instruments and Control Inc., Orangeburg, N.Y.). The supply air was connected to a distribution manifold
where air was further divided via eight identical flowmeters (0.2 to 4 LPM, stainless steel valve, VFB-65-SSV, Dwyer Instruments, Inc., Michigan City, Indiana). A flow rate of 3 LPM was introduced into each vessel, resulting in an air exchange rate of 11 air changes per hour (ACH). Each vessel was equipped with a small stirring fan (12VDC, Radio Shack) located 6 cm below the lid for uniform mixing of the headspace. Gas exhausted from the vessels was connected to a common 5 cm PVC pipe that was routed to the building vent outlet. A photographic view of the experimental setup is shown in Figure 2.

Samples of the exhaust air from each of the eight vessels, the supply air, and the room air were sequentially taken at 6-min intervals, with the first 4 minutes for stabilization and the last 2 min for measurement. This yielded a measurement cycle of one hour for each vessel. The sequential sampling was achieved by controlled operation of eight solenoid valves (Type 6014, 24V, stainless steel valve body, Burkert Contromatic USA, Irvine, CA). A Teflon filter was placed in front of each solenoid valve. A photoacoustic infrared (IR) ammonia gas analyzer (Chillgard RT Refrigerant Monitor, MSA, Pittsburg, PA) was used to measure the NH$_3$ concentrations. The analyzer uses an internal pump to draw sample air at a flow rate of approximately 1.0 LPM. Manure temperature was measured with type T thermocouples (0.2 °C resolution). Air temperature and relative humidity of the room were monitored with a temp/RH data logger (HOBO Pro RH/Temp, Onset Computer Corporation, Bourne, MA). Analog outputs from the thermocouples, NH$_3$ analyzer, and the mass flow meter were logged at 20-s intervals into a measurement and control module (Model CR10, Campbell Scientific, Inc., Logan, UT).
**Laying Hen Manure and Mitigation Options Tested**

Hen manure that accumulated on belt for less than a day in a commercial manure-belt layer house was used in the evaluation of the treatment agents. Manure samples with an initial weight of 2.5 kg were used as the experimental units. The 2.5 kg sample was placed either in a 3.8-liter (1-gal) container (surface area of 0.02 m$^2$) that was further placed inside the 19-liter (5-gal) emission vessel or directly into the emission vessel (surface area of 0.05 m$^2$).

Five treatment additives at various application rates were tested, including natural zeolite, two forms (liquid and dry) of Al$^{3+}$Clear, Ferix-3, and PLT. The treatment agents were topically applied to the manure samples at 2.5%, 5% or 10% of the manure weight for zeolite; 1, 2, or 4 kg m$^{-2}$ of manure surface area for liquid Al$^{3+}$Clear; and 0.5, 1.0, or 1.5 kg m$^{-2}$ for dry granular Al$^{3+}$Clear, Ferix-3, and PLT. The application rates of Al$^{3+}$Clear, Ferix-3, and PLT referred to the application rates of alum on the broiler litter (Armstrong et al., 2003). Properties of the four chemicals tested are listed in Table 1.

Each treatment regime had 4 to 6 replications. The trials with the four chemical agents' treatment lasted 7 days. In the case of zeolite treatment, three trials were conducted. The first two trials examined the effects of single application at one of the afore-mentioned three rates on ammonia emissions over a 14-day storage period, where the third trial examined the effect of multiple applications (every two days, coinciding with manure loading) at the 5% application rate on ammonia emission during a 14-day test. Manure samples were taken from the top 2.5 cm and their physical and chemical properties were analyzed by a certified commercial analytical laboratory.
RESULTS AND DISCUSSION

Effect of Topical Application of Zeolite on NH₃ Emission from Hen Manure

Surface-applied zeolite on fresh manure substantially decreased NH₃ emission during 14-d storage period and the effect were generally proportional to the application rates. Daily NH₃ emissions of zeolite on manure in batch trials were illustrated in Figure 3. The adsorption of NH₃/NH₄⁺ took effect right after its application at Day 0 and resulted in largest ER reduction on Day 1. Ammonia emissions were reduced by 66, 91 and 96% at the end of Day 1, with application rates of 2.5, 5 and 10%, respectively. Daily ammonia emission of the Ctrl vessels became stabilized after day 3, whereas emissions of the Trt vessels continued to increase with the Trt2.5 being most obvious. Ammonia emissions of Trt5 and Trt10 were significantly lower than that of the Ctrl (P<0.01) throughout the 14-d trial period, whereas this was true for the Trt2.5 regimen during the first 7 d (P<0.01). Addition of two or more layers of manure did not seem to increase NH₃ emission on a per vessel basis (g d⁻¹ or g m⁻²d⁻¹), largely due to the same emitting surface area in the vessel. However, on a per unit manure mass basis, daily ER decreased progressively with the addition of manure (Fig. 4).

Table 2 summarizes the effects of single or multiple topical applications of zeolite at the three dosages on NH₃ emission reduction. Cumulative NH₃ ER reductions at the end of Day 7 and Day 14 were 68% and 20% for Trt2.5, 81% and 50% for Trt5, and 96% and 77% for Trt10. Fourteen-day daily average NH₃ ERs were 0.231, 0.185, 0.116 and 0.053 g d⁻¹ kg⁻¹ initial manure for control, Trt2.5, Trt5 and Trt10, respectively.

Kithome et al. (1999) reported that NH₃ loss was decreased by 44% when composting poultry manure over 56 days with a surface application of 38% zeolite. Bernal et al. (1993) also reported that more than 90% of N-loss was trapped by placing 12% (by weight) zeolite in
air stream over 13-day composting of pig slurry and chopped straw mixture. Zeolite additions at 2.5% and 6.25% into dairy slurry reduced NH$_3$ emissions by 22% and 47%, respectively, over 4-d storage period (Lefcourt and Meisinger, 2001).

**Effects of Al$^+$Clear, Ferix-3, and PLT Treatment on NH$_3$ Emission from Layer Manure**

Surface-applied liquid and granular Al$^+$Clear, Ferix-3, and PLT on fresh manure substantially decreased NH$_3$ emission during 7-d storage period. Daily NH$_3$ emissions from all treatment and control were illustrated in Figure 3. Ammonia emissions for each regimen, emission reduction by the treatment as compared to the control, and manure properties are summarized in Table 3. Reduction of ammonia emission as a result of topical application of the tested manure treatment agents, when compared to the control, over a 7-day manure storage period was as following: A) 63%, 89%, or 94%, respectively, for liquid Al$^+$Clear applied at 1, 2, or 4 kg m$^{-2}$ of manure surface area; B) 81%, 93%, or 94%, respectively, for powder Al$^+$Clear applied at 0.5, 1.0, or 1.5 kg m$^{-2}$; C) 82%, 86%, or 87%, respectively, for Ferix-3 applied at 0.5, 1.0, or 1.5 kg m$^{-2}$; and D) 74%, 90%, or 92%, respectively, for PLT applied at 0.5, 1.0, or 1.5 kg m$^{-2}$. Ammonia emission reduction from each of the three application rates (denoted as low, medium and high) was significantly lower than that of the control (P<0.001). After 7 days, the NH$_3$ emission reductions from all low application rates were lower than the higher application rates (P<0.001).

Daily NH$_3$ ER of control vessels became stabilized after Day 3, while those of medium and high application treatment vessels stayed with very low NH$_3$ ERs (Fig. 5). Ammonia ERs (<0.01 g NH$_3$ kg$^{-1}$ initial manure) of medium and high application rate on every single day were not different (P>0.70) during the 7 days. Ammonia ERs of low application rate vessels
started to increase from the 3\textsuperscript{rd}, 5\textsuperscript{th}, 6\textsuperscript{th} and 7\textsuperscript{th} day for liquid Al\textsuperscript{+}Clear, dry granular Al\textsuperscript{+}Clear, Ferix-3, and PLT, respectively.

Results of the manure properties in Table 2 showed that manure samples receiving the higher application rates had lower pH, lower TAN, and higher total N in the top 2.5 cm manure after the 7-day storage period. The average TAN from the controls, low, medium and high application rate vessel were 11.3, 9.9, 8.2, and 6.9 g kg\(^{-1}\) (as-is), respectively. The average pH values from the controls, low, medium, and high application rate vessel were 7.6, 7.4, 7.1 and 6.6 respectively. The average total N from the controls, low, medium, and high application rate vessel were 18.5, 18.6, 21.6, and 22.9 g kg\(^{-1}\) (as-is), respectively. The more nitrogen was conserved in the manure with higher application rate.

CONCLUSIONS

Surface-applying fresh layer manure with zeolite, Al\textsuperscript{+}Clear, Ferix-3 and PLT is an effective means to reduce NH\textsubscript{3} emission during storage. Reduction of ammonia emission as a result of topical application of the tested manure treatment agents, when compared to the control, over a 7-day manure storage period was as following: A) 68%, 81% or 96%, respectively, for zeolite applied at 2.5%, 5% or 10% of the manure weight; B) 63%, 89%, or 94%, respectively, for liquid Al\textsuperscript{+}Clear applied at 1, 2, or 4 kg m\(^{-2}\) of manure surface area; C) 81%, 93%, or 94%, respectively, for dry granular Al\textsuperscript{+}Clear applied at 0.5, 1.0, or 1.5 kg m\(^{-2}\); D) 82%, 86%, or 87%, respectively, for Ferix-3 applied at 0.5, 1.0, or 1.5 kg m\(^{-2}\); and E) 74%, 90%, or 92%, respectively, for PLT applied at 0.5, 1.0, or 1.5 kg m\(^{-2}\).

ACKNOWLEDGMENTS

Financial support for the studies has been provided by the Iowa Egg Council, the U.S. Poultry and Egg Association, and the ISU College of Agriculture.
REFERENCE


### Table 1. Physical and chemical properties of Al'Clear, Ferix-3 and PLT

<table>
<thead>
<tr>
<th></th>
<th>Liquid Al'Clear</th>
<th>Dry Al'Clear</th>
<th>Ferix-3</th>
<th>PLT</th>
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</thead>
<tbody>
<tr>
<td><strong>Molecular formula</strong></td>
<td>Al₂(SO₄)₃·14H₂O</td>
<td>Al₂(SO₄)₃·14H₂O</td>
<td>Fe₂(SO₄)₃·9H₂O</td>
<td>NaHSO₄</td>
</tr>
<tr>
<td><strong>Molecular weight</strong></td>
<td>594</td>
<td>594</td>
<td>562</td>
<td>120</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>2.0 (approx)</td>
<td>3.5 (1% solution)</td>
<td>1.02 (10% solution)</td>
<td>&lt;1 (5% solution)</td>
</tr>
<tr>
<td><strong>Appearance</strong></td>
<td>Clear</td>
<td>White granules</td>
<td>Yellowish granules</td>
<td>Off-white granules</td>
</tr>
<tr>
<td><strong>Physical state</strong></td>
<td>48.5% in water</td>
<td>Dry solid</td>
<td>Dry solid</td>
<td>Dry solid</td>
</tr>
<tr>
<td><strong>Odor</strong></td>
<td>Odorless</td>
<td>Odorless</td>
<td>Slight</td>
<td>Odorless</td>
</tr>
</tbody>
</table>
Table 2. Effects of topical application of zeolite at various rates on reduction of ammonia emission from laying hen manure storage. The application rates, expressed in % of manure weight, were 0% (Ctrl), 2.5% (Trt2.5), 5% (Trt5), and 10% (Trt10), respectively.

<table>
<thead>
<tr>
<th></th>
<th>Single Application (in 1-gal emission vessels)</th>
<th>Four Layers (5-gal vessels)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ctrl</td>
<td>Trt2.5</td>
</tr>
<tr>
<td>Amount of manure, kg</td>
<td>2.5</td>
<td>2.5 kgx4 = 10</td>
</tr>
<tr>
<td>Surface area of manure, m² (ft²)</td>
<td>0.02 (0.22)</td>
<td>0.05 (0.54)</td>
</tr>
<tr>
<td>Application rate</td>
<td>kg m²</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>lb ft²</td>
<td>0</td>
</tr>
<tr>
<td>Number of zeolite application</td>
<td>Once - at the beginning</td>
<td>Four - once per layer</td>
</tr>
<tr>
<td>Trial/treatment duration, day</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Avg. daily ER per unit of manure weight or surface area over trial period</td>
<td>g kg⁻¹d⁻¹</td>
<td>0.231</td>
</tr>
<tr>
<td></td>
<td>g m⁻²d⁻¹</td>
<td>29.9</td>
</tr>
<tr>
<td>7-d cumulative emission, g kg⁻¹</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>7-d emission reduction rate</td>
<td>-</td>
<td>68%</td>
</tr>
<tr>
<td>Total cumulative emission, g kg⁻¹</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Total cumulative emission reduction</td>
<td>-</td>
<td>20%</td>
</tr>
<tr>
<td>8-d emission reduction rate</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*comparison tests lasted 14 days for vessel trials

*represents cumulative emission reduction over 7 days following the last-layer addition of hen manure

*represents cumulative emission reduction during first 8 days of manure additions

\[
\text{Emission Reduction Rate} = \frac{\text{CumuEmission}_{\text{treatment}}}{\text{CumuEmission}_{\text{control}}} \times 100\% 
\]
Table 3. Effects of topical application of liquid Al’Clear, dry granular Al’Clear, Ferix-3 and PLT at different rates on reduction of ammonia emission from laying hen manure storage

<table>
<thead>
<tr>
<th>Application rate</th>
<th>Liquid Al’Clear, kg m²</th>
<th>Dry Al’Clear, kg m²</th>
<th>Ferix-3, kg m²</th>
<th>PLT, kg m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ctrl 1 2 4</td>
<td>Ctrl 0.5 1.0 1.5</td>
<td>Ctrl 0.5 1.0 1.5</td>
<td>Ctrl 0.5 1.0 1.5</td>
</tr>
<tr>
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<td>2.5 2.5 2.5 2.5</td>
<td>2.5 2.5 2.5 2.5</td>
<td>2.5 2.5 2.5 2.5</td>
</tr>
<tr>
<td>Surface area, m²</td>
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<td>0.02 0.02 0.02 0.02</td>
</tr>
<tr>
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<td>kg m⁻²</td>
<td>kg m⁻²</td>
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<tr>
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<td>0 1.0 2.0 4.0</td>
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<td>0 0.5 1.0 1.5</td>
<td>0 0.5 1.0 1.5</td>
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<tr>
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<td>lb ft⁻²</td>
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</tr>
<tr>
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<td>0 0.20 0.41 0.82</td>
<td>0 0.10 0.20 0.31</td>
<td>0 0.10 0.20 0.31</td>
<td>0 0.10 0.20 0.31</td>
</tr>
<tr>
<td>Avg. daily ER over trial period</td>
<td>g kg⁻¹d⁻¹</td>
<td>g kg⁻²d⁻¹</td>
<td>g kg⁻¹</td>
<td>g m⁻²</td>
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<td>0.187 0.070 0.020 0.011</td>
<td>0.150 0.029 0.011 0.009</td>
<td>0.075 0.014 0.011 0.010</td>
<td>0.144 0.037 0.014 0.012</td>
</tr>
<tr>
<td>Cumulative emission</td>
<td>g kg⁻¹</td>
<td>1.31 0.49 0.14 0.08</td>
<td>1.05 0.20 0.08 0.07</td>
<td>0.52 0.10 0.07 0.07</td>
</tr>
<tr>
<td></td>
<td>g m⁻²</td>
<td>148 55.1 16.1 8.90</td>
<td>119 22.6 8.62 7.48</td>
<td>58.8 10.9 8.33 7.60</td>
</tr>
<tr>
<td>Reduction Rate *</td>
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<td>- 63% 89% 94% 94%</td>
<td>- 81% 93% 93% 93%</td>
<td>- 82% 86% 87% 87%</td>
</tr>
<tr>
<td>Dry content</td>
<td>28.1 29.9 31.1 30.8</td>
<td>27.1 27.9 27.1 30.8</td>
<td>28.3 34.1 31.9 33.9</td>
<td>27.0 29.0 30.5 32.3</td>
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<tr>
<td>Total N, g kg⁻¹ (as-is)</td>
<td>17.6 16.5 21.0 24.1</td>
<td>18.5 18.8 20.0 19.1</td>
<td>21.1 23.0 23.5 24.9</td>
<td>16.6 16.2 21.9 23.4</td>
</tr>
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<td>62.6 55.2 67.5 73.5</td>
<td>68.3 67.4 73.8 62.0</td>
<td>74.6 67.4 73.7 73.5</td>
<td>61.5 55.9 71.8 72.4</td>
</tr>
<tr>
<td>TAN, g kg⁻¹ (as-is)</td>
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<td>11.1 12.5 12.3 10.4</td>
<td>13.2 8.6 7.1 5.6</td>
<td>10.5 8.6 7.3 6.0</td>
</tr>
<tr>
<td>TAN, g kg⁻¹ (dry base)</td>
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<td>41.0 44.8 45.4 33.8</td>
<td>46.6 25.2 22.3 16.5</td>
<td>38.9 29.7 23.9 18.6</td>
</tr>
<tr>
<td>pH</td>
<td>7.6 7.53 7.01 6.42</td>
<td>7.68 7.65 7.65 6.82</td>
<td>7.37 7.7 6.92 6.55</td>
<td>7.6 7.3 6.8 6.7</td>
</tr>
</tbody>
</table>

* Comparison tests lasted 7 days for vessel trials

\[ Emission \text{ Reduction Rate} = \frac{Cumulative \text{ Emission}_{\text{Control}} - Cumulative \text{ Emission}_{\text{Treatment}}}{Cumulative \text{ Emission}_{\text{Control}}} \times 100\% \]

* Represents cumulative emission reduction during 7 days

* Values of emission reduction rate for each agent followed by the same superscript letters are not significantly different (P>0.05).
Figure 1. Schematic representation of the experimental setup for evaluating efficacy of treatment agents on ammonia emission reduction from laying hen manure (EV = emission vessel). (Courtesy of Xin, 2005)
Figure 2. Photographs of the laboratory setup for evaluating efficacy of air emission mitigation strategies. Pictured to the right is topical application of zeolite on laying hen manure at various dosages.
Figure 3. Daily ammonia emissions of ventilated laying hen manure storage with various rates of single surface application of zeolite (Ctrl: no zeolite; Trt2.5: 2.5% zeolite by weight; Trt5: zeolite 5% by weight; Trt10: 10% zeolite by weight).
Figure 4. Daily ammonia emissions of ventilated hen manure storage. Fresh manure was added and zeolite topically applied on days 0, 2, 4, and 6 (Ctrl – no zeolite; Trt – 5% zeolite by weight).
Figure 5. Daily ammonia emission rate (mean and standard error, n=6) of ventilated storage of laying hen manure with different rates of topical application of liquid Al\textsuperscript{3+}Clear.
Figure 5 (continued). Daily ammonia emission rate (mean and standard error, n=6) of ventilated storage of laying hen manure with different rates of topical application of dry granular Al\textsuperscript{3+}Clear.
Figure 5 (continued). Daily ammonia emission rate (mean and standard error, n=4) of ventilated storage of laying hen manure with different rates of topical application of Ferix-3.
Figure 5 (continued). Daily ammonia emission rate (mean and standard error, n=4) of ventilated storage of laying hen manure with different rates of topical application of PLT.
CHAPTER 5

COMPARISON OF DIRECT VS. INDIRECT VENTILATION RATE DETERMINATION FOR MANURE BELT LAYING HEN HOUSES

A paper published in the Transactions of the American Society of Agricultural Engineers\(^1\)

H. Li, H. Xin, Y. Liang, R. S. Gates, E. F. Wheeler, A. J. Heber\(^2\)

ABSTRACT

Direct measurement of building ventilation rate in livestock housing is a formidable task due to uncontrollable variations in fan and system performance that are caused by factors such as building static pressure, fan belt slippage, and dust accumulation on shutters and blades. Estimating building ventilation rate by an indirect method based on a CO\(_2\)-balance offers a potentially viable alternative to direct measurement. The validity of the CO\(_2\)-balance method depends on the validity of relationship between CO\(_2\) production and metabolic rate of the animals and the knowledge of CO\(_2\) generation by the housing environment. Metabolic rates of modern laying hens have recently been quantified in intensive large-scale laboratory

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measurements. However, performance of the indirect method remains to be evaluated under field conditions. This paper compares building ventilation rates obtained by direct measurement and by a CO₂ balance. The test was conducted at a commercial laying hen house that used a manure belt with daily manure removal. The results indicate that ventilation rates estimated by the indirect method were not significantly different (P>0.2) from those as determined by the direct measurement when the averaging or integration time interval was 2 h or longer. Careful application of the indirect method could greatly improve the affordability and versatility of endeavors toward quantifying air emissions from confined animal housing.

**Keywords:** Air emissions, Building ventilation rate, CO₂ balance, Laying hen

**INTRODUCTION**

Air quality associated with animal feeding operations (AFOs) or concentrated animal operations (CAFOs) remains a pressing issue for both animal industry and academic communities. The need to quantify air emissions from AFOs/CAFOs with relative ease and reasonable certainty continues to rise. Ventilation rate through an emission source is one of the two essential elements for quantifying emission rates, with the other element being concentration of the substance in question. Ventilation rate is generally more complex and less certain to obtain than concentrations.

Two primary techniques exist for determining building ventilation rate of animal confinement, direct vs. indirect measurement. The direct measurement, applicable to mechanically ventilated buildings, involves determination of airflow rate of the exhaust or supply fans at certain static pressure and number of fans in operation. Airflow rate of each fan may be estimated based on manufacture supplied fan performance curves. However such estimation is prone to considerable (e.g., 20-25%) error due to altered fan curves arising from
uncontrollable variables in the field, such as loose fan belts, partially open and dirty shutters, and dirty fan blades. Alternatively and preferably, a fan may be calibrated in situ to reflect the actual operating conditions in the field. In the past, velocity traverse of fan airflow stream involving limited (e.g., 16-25) measurement points has been used to accomplish this. Recently, a more sophisticated tool, known as the Fan Assessment Numeration System (FANS), was developed and is increasingly used to improve in situ measurement certainty of fan airflow capacity (Simmons et al., 1998; Gates et al., 2004; Wheeler et al., 2002). Even with the FANS, challenges still exist in that certain types of confinement housing (e.g., cross-ventilated laying hen houses) have a large number of ventilation fans (e.g., 40-70 per house), making it formidable to calibrate all the fans. Furthermore, the in-situ fan curves may vary over the course of monitoring due to outside wind speed/direction or conditions of the fan itself.

Indirect ventilation measurement techniques involve use of a tracer gas in the ventilated building or space and monitoring the decay rate of the gas concentration to indirectly determine the ventilation rates. The basic principle of tracer technique is to release a known amount of tracer, monitor its concentration at downwind points and use the decay rate of tracer gas concentration to calculate the air exchange rate. Its application is often limited because it requires uniform air–tracer mixing to ensure good results, which is difficult to achieve under commercial production settings. Based on the ideal characteristics of a released tracer, (including low and stable background level, non-hazard, acceptability, ease of measurement, stability, and low price), carbon monoxide, helium and sulphur hexafluoride (SF$_6$) have been used in livestock-related cases (Phillips, et al., 2000, 2001). In addition to releasable tracers, metabolic carbon dioxide (CO$_2$) is available in livestock buildings as a tracer (Feddes et al., 1984; Van Ouwerkerk and Pedersen, 1994). Naturally, the validity of CO$_2$ balance method
depends on the reliability of the metabolic data of the animals. Metabolic rates of modern pullets and laying hens (Hy-Line W-36 breed, most popular U.S. commercial strain) have recently been quantified in large-scale indirect calorimetry measurements (Chepete, et al., 2004; Chepete and Xin, 2004). However, accuracy of the indirect method remains to be evaluated under field production conditions where CO₂ contribution from manure decomposition may contribute to the CO₂ generation and thus to the determination of building ventilation rate.

The objective of this paper was to compare building ventilation rate of a commercial laying hen house featuring manure belt and daily manure removal, as obtained from direct measurement based on \textit{in situ} fan performance and runtime vs. indirect determination based on a CO₂ balance.

\textbf{MATERIALS AND METHODS}

\textbf{Layer House and Management}

A manure-belt laying hen house owned by a cooperative egg producer located in north central Iowa was used for the study. The layer house had an east-west orientation and a dimension of 18 m (61 ft) wide by 159 m (522 ft) long. It used a quasi-tunnel ventilation system that consisted of 13, 1.2 m (48”) diameter exhaust fans and two 0.9 m (36”) diameter exhaust fans in each end-wall and two rows of continuous slot ceiling inlets (4.5 m or 15 ft interior from each sidewall) controlled by static pressure set at 17 Pa (0.07” H₂O) (Fig. 1).

Exhaust fans at each end were grouped in pairs that were controlled, in eight stages, according to the mean house temperature near the middle of the house. One of the 0.9 m fans at each end operated continuously. The battery cages were arranged in eight cage rows with three tiers per cage row. Bird feces fell directly onto the belt underneath the cages and were removed from the
house each morning. There was an 18 m (61 ft) open space between adjacent buildings. At the onset of the monitoring study in March 2003, there were 98,000 Hy-Line W-36 hens at 104 weeks of age. A replacement flock of 100,000 W-36 hens at 20 weeks of age was introduced into the house in July 2003. Photoperiod remained 16L:8D during the monitoring period for the first flock; but it started at 12L:12D and was increased by 30 minutes per week until it reached 16L:8D for the replacement flock. Ad-lib feed and water were provided, and standard commercial egg industry diets were used (table 1).

**Measurement Instruments and Data Acquisition**

Portable monitoring units (PMUs) as described by Xin et al. (2002) were used to continuously collect CO₂ concentration of incoming and exhaust air (Fig. 2). One PMU was mounted on each end wall of the house. A programmable on/off timer was used to operate a 3-way solenoid valve that in turn controlled the switching between incoming fresh air and exhaust air. The incoming air was sampled from the attic space and the exhaust air was a composite sample from four aisle locations at each end about 5 m (15 ft) from the exhaust fans (Fig. 1). Due to the operational characteristics of the electro-chemical ammonia sensors used in the PMU, 8-minute sampling of the exhaust air followed by a 22-minute purging with incoming air was used throughout the measurement episodes. Carbon dioxide concentration was monitored with an infrared CO₂ transmitter (0-7,000 ± 20 ppm, Model GMT222, Vaisala Inc., Woburn, MA). The output of the transmitter (4-20 mA) was recorded with a 4-channel battery-operated data logger (4-20 mA ± 0.1%, Onset Computer Corporation, Bourne, MA). Static pressures of the building were monitored at both ends (4-20 mA ± 1% for 0-125 Pa or 0-0.5” H₂O, Model 262, Stage Inc., Pittsburgh, PA) and recorded with the same 4-channel data loggers. Temperature and RH at each end, about 5 m from the exhaust fans, and in the middle
of the house were recorded with portable temperature/RH loggers (0-50°C ± 3%, HOBO Pro
RH/Temp, Onset Computer Corporation). Runtime of the 14 paired exhaust fans (except the
minimum ventilation fan) at each end was monitored with on/off motor loggers (HOBO on/off
motor, Onset Computer Corporation) that were attached to the power lines for individual fans.
Outside temperature and RH were also measured with the same type of temperature/RH
loggers.

The semi-hourly average or instantaneous readings of CO₂ concentrations, static
pressure, air temperature and fan runtime were calculated and analyzed. Data collection was
conducted bi-weekly during the 8-month monitoring period. Each collection episode consisted
of continuous measurements of 48 hours or longer.

**Direct Measurement of Building Ventilation Rate**

A FANS unit (Casey et al, 2004; Gates et al., 2004) was used to individually calibrate
the airflow of all the exhaust fans of the layer house. With a hydraulic lift cart and plywood
platform for easy height adjustment, the FANS unit was placed upstream against the exhaust
fan to be calibrated (Fig. 3). Space gaps between the fan/wall and the FANS were carefully
sealed with foam insulation and duct tape. Since the house normally operated at static pressure
of 15-25 Pa (0.06-0.10” H₂O), airflow rates of the exhaust fans were evaluated at the static
pressure levels of 0, 12.5, 25, and 40 Pa (0.0, 0.05, 0.10, 0.16” H₂O). The tested static pressure
was achieved by adjusting the inlet opening through the inlet controller. Once the static
pressure was stabilized, the FANS unit was run twice (up and down), with each run taking
about 3 minutes. If the difference between the two runs was less than 2%, the result was
considered acceptable and the average was taken as the data point. An inclined barometer (-
12.5 to 62.3 Pa or -0.05 to 0.25” H₂O) was also used to provide instantaneous static pressure
readings. To eliminate the effect of airflow reduction when a fan operates with its stage members vs. running alone, measurements of the individual fans were conducted under their actual combinations of operation with other exhaust fans. Individual fan performance curves were then developed for all the exhaust fans. Subsequently, airflow through each fan was calculated with the actual static pressure measured by the static pressure transducer. Summation of the individual airflows at a given time yielded the instant ventilation rate of the layer house. The ventilation fans were checked again near the end of the monitoring period and the results revealed little change in their performance. The ventilation fans were compressed-air cleaned weekly.

**Indirect Determination of Building Ventilation Rate by CO₂ Balance**

The CO₂-balance method is based on the principle of indirect animal calorimetry. Namely, metabolic heat production of non-ruminants is related to oxygen (O₂) consumption and CO₂ production of the animals, of the following form (Brouwer, 1965):

\[
\text{THP} = 16.18 \text{O}_2 + 5.02 \text{CO}_2 \quad [1]
\]

where

\[
\begin{align*}
\text{THP} & = \text{total heat production rate of the animal, W.kg}^{-1} \\
\text{O}_2 & = \text{oxygen consumption rate (mL.s}^{-1}.\text{kg}^{-1}) \\
\text{CO}_2 & = \text{carbon dioxide production rate (mL.s}^{-1}.\text{kg}^{-1})
\end{align*}
\]

The ratio of CO₂ production and O₂ consumption is defined as respiratory quotient of the animal, i.e.,

\[
\text{RQ} = \frac{\text{CO}_2}{\text{O}_2} \quad [2]
\]

The CO₂ production rate also can be related to building ventilation rate (V, m³.hr⁻¹.kg⁻¹) as follows.

\[ V = \frac{CO₂ \text{production} \times 10^6}{[CO₂]_e - [CO₂]_i} \]  \hspace{2cm} [4]

where

\([CO₂]_e\) and \([CO₂]_i\) = CO₂ concentration (ppm) of exhaust and incoming air, respectively.

The hourly THP and RQ of W36 laying hens during light and dark periods of the day, as reported by Chepete et al. (2004), were used to estimate CO₂ production of the hens using equation 3.

**RESULTS AND DISCUSSION**

**Ventilation Rate by Direct Measurement**

A total of 28 exhaust fans (twenty-four 1.2-m fans and four 0.9-m fans) were calibrated and their performance curves were established (the remaining two 1.2-m fans were out of order). Considerable variations existed in fan performance (Fig. 4). For instance, airflow rate at 0 Pa static pressure varied from 11,560 to 15,300 m³/hr (6,800 to 9000 cfm) for the four 0.9-m fans and from 23,460 to 28,050 m³/hr (13,800 to 16,500 cfm) for the twenty-four 1.2-m fans. At 40 Pa (0.16" H₂O) static pressure, airflow rate varied from 2,060 to 5,678 m³/hr (1,212 to 3,340 cfm) and from 0 to 18,734 m³/hr (0 to 11,020 cfm) for the 0.9-m and 1.2-m fans, respectively. Hence, use of a single fan performance curve would have introduced gross errors to the determination of airflow rate of the seemingly identical ventilation fans.
Depending on the brand and operating conditions of the ventilation fans, certain airflow reduction or penalty due to the presence of the FANS might occur (Gates et al., 2004) and should be accounted for in determining the actual airflow rate of the fan. The type of fans and their operation conditions for this commercial layer house would experience negligible penalty, according to the BESS Lab test results of the same type of fans (K. D. Casey, 2004; unpublished data). Hence, no penalty was applied to the ventilation rate as measured by the FANS unit.

**Ventilation Rate by Indirect, CO₂ Balance Method**

Van Ouwerkerk and Pedersen (1994) indicated that to ensure reliability of the CO₂-balance method, the difference in CO₂ concentrations between outlet and inlet air should exceed 200 ppm. This criterion was met by our data. Ideally, CO₂ concentration of inlet or fresh air is constant at about 350 ppm. In reality, CO₂ concentrations of the inlet (or purging) air ranged from 350 to 500 ppm presumably due to partial return of the exhaust air. The difference between inlet and outlet air CO₂ concentrations varied from 206 to 3089 ppm during the measurement period. The maximum difference took place in winter (December 31, 2003) corresponding to an indirectly determined ventilation rate of 0.43 m³/hr-bird (0.25 cfm/bird). The minimum difference occurred in summer (July 22, 2003) corresponding to an indirectly determined ventilation rate of 5.28 m³/hr-bird (3.11 cfm/bird). Figure 5 shows the relationship of ventilation rate to CO₂ concentration difference. It can be seen that changes or fluctuations in the CO₂ concentration difference affected the derived ventilation rate more at the higher ventilation levels than at the lower ventilation levels, as would be predicted from equation [4].
Directly vs. Indirectly determined Ventilation Rate

Figure 6 depicts the dynamic profile of semi-hourly ventilation rates for a data collection trip (April 15-17, 2003). The directly and indirectly determined ventilation rates showed similar patterns in following the outside temperature profile. However, differences of various degrees existed between the two methods. The differences presumably resulted from the dynamic nature of the environmental conditions and activity level of the hens, which would have led to deviation of the dynamic THP from the average values (for light or dark period) used in the calculation. The outside weather, especially wind conditions, also could have temporarily affected the performance of the exhaust fans or air distribution inside the building, which in turn would affect determination of both the direct and indirect ventilation rates.

Figure 7 shows paired comparisons of ventilation rates between the direct and indirect methods at semi-hourly, hourly, bi-hourly (2-hr) and daily average or integration time intervals. The number of observations associated with each of the time intervals were, respectively, 1318, 660, 330, and 28. The corresponding regression lines of indirect vs. direct ventilation rates revealed good regression coefficient ($R^2$) of 0.904, 0.916, 0.926 and 0.956, respectively. The corresponding p-values of the paired t-tests were 0.019, 0.1, 0.205 and 0.763, respectively. Hence, the results indicate that the CO$_2$-balance method based on bi-hourly or longer averaging/integrating time interval would yield ventilation rates not significantly different from those obtained by direct measurement ($P>0.2$). All regression equations had a slope of nearly unity, indicating that hen manure on the belt contributed little to the CO$_2$ production inside the house. This seems logical as the manure was removed from the house daily.
CONCLUSION

For commercial laying hen (W-36 breed) houses using a manure belt with daily manure removal, a CO₂ balance was successfully used to determine building ventilation rate, when the integrating time interval is 2 hours or greater. The technique relies based on updated metabolic rate of the birds. Daily removal of manure from the house made contribution of CO₂ emission from manure negligible compared to respiratory CO₂ production by the birds. This method provides a suitable and accurate alternative means of building ventilation rate determination that can be used in building emissions calculations.

ACKNOWLEDGEMENTS

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REFERENCES


Table 1. Dietary ingredients of feed used in the field study (%, unless otherwise noted)

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<tr>
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</table>
Figure 1. Schematic layout of the manure-belt layer house showing the end and cross-section of the house and the sampling locations (O HOBO T/RH logger, □ Gas sampling port, ⊙ PMU)
Figure 2. Schematic representation of the portable monitoring unit (PMU) used in the field measurement of CO$_2$ and NH$_3$ concentrations.
Figure 3. A snapshot of in-situ calibration of airflow rate of exhaust fans in the monitored layer house using the Fan Assessment Numeration System (FANS) unit.
Figure 4. Performance curves of the 0.9-m (36-inch) fans (up) and 1.2-m (48-inch) fans (down) in the monitored commercial layer house (1 cfm = 1.7 m$^3$/hr)
Figure 5. Profiles of semi-hourly CO₂ concentrations and CO₂-balance derived ventilation rate of the monitored layer house during April 15 – 17, 2003 (1 cfm = 1.7 m³/hr⁻¹)
Figure 6. Comparison of directly measured vs. CO₂-balance derived (semi-hourly) ventilation rate of the monitored layer house during April 15-17, 2003 (1 cfm = 1.7 m³.hr⁻¹).
Figure 7. Relationship of ventilation rates determined from direct measurement vs. from CO₂-balance derivation for the monitored layer house at different integration time intervals. The dash lines below and above the regression lines represent 95% confidence intervals of the observations (1 cfm = 1.7 m³.hr⁻¹).
CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

The major conclusions drawn from this research are following:

1. Ammonia emission rates (ER) from representative manure-belt (MB) layer houses in Iowa were measured for a full year. Ammonia ER showed considerable diurnal variation, but not as much in seasonal variation. Data from the 12-month monitoring revealed the NH$_3$ ER (mean ±standard error) of 0.054 ±0.0035 g NH$_3$ d$^{-1}$ hen$^{-1}$ (varying from 0.002 to 0.195 g NH$_3$ d$^{-1}$ hen$^{-1}$) for the MB houses with manure removed daily. Results of the study contribute to the U.S. national inventory on NH$_3$ emissions from animal feeding operations.

2. Ammonia emission from manure storage was affected by surface area to volume ratio (SVR), air temperature and manure moisture content along with the storage time. Specifically,

   - The NH$_3$ emissions corresponding to the five SVRs of 1.2, 2.5, 5, 10, and 20 tested during a 40-day storage were 2.27, 3.51, 6.45, 9.70 and 12.4 3.6 g kg$^{-1}$ fresh manure, respectively. A regression model was developed to describe the NH$_3$ emissions from manure stack with the five SVRs and storage time under constant air temperature 25°C.

   - Rising ambient temperature enhances NH$_3$ emission of the manure stack at the rate of 6% per degree Celsius rise for the temperature range of 21 to 32 °C. The NH$_3$ emission rate from 50% MC manure stack is 59% of the NH$_3$ ER from
77% MC manure stack. A regression model has been developed to relate NH$_3$ emission rate of the manure storage to ambient temperature and storage time for the two moisture contents (50% and 77%).

3. Reduction of ammonia emission as a result of topical application of zeolite, Al$^+$Clear (aluminum sulfate), Ferix-3 (ferric sulfate) and PLT (sodium hydrogen sulfate), when compared to the control, over a 7-day manure storage period was as following: A) 68%, 81% or 96%, respectively, for zeolite applied at 2.5%, 5% or 10% of the manure weight; B) 63%, 89%, or 94%, respectively, for liquid Al$^+$Clear applied at 1, 2, or 4 kg m$^{-2}$ of manure surface area; C) 81%, 93%, or 94%, respectively, for dry granular Al$^+$Clear applied at 0.5, 1.0, or 1.5 kg m$^{-2}$; D) 82%, 86%, or 87%, respectively, for Ferix-3 applied at 0.5, 1.0, or 1.5 kg m$^{-2}$; and E) 74%, 90%, or 92%, respectively, for PLT applied at 0.5, 1.0, or 1.5 kg m$^{-2}$.

4. Direct and indirect (CO$_2$ balance) ventilation rates measurement methods were compared under field conditions using a manure belt with daily manure removal. The results indicate that ventilation rates estimated by the indirect method were not significantly different (P>0.2) from those as determined by the direct measurement when the averaging or integration time interval was 2 hours or longer. Careful application of the indirect method could greatly improve the affordability and versatility of endeavors toward quantifying air emissions from confined animal housing.

The following are recommended for future studies:

- Conduct measurement of NH$_3$ emission from manure storage associated with MB operations under field conditions.
- Conduct field verification test of the emission mitigation options that were evaluated in this research.
• Conduct an economic analysis of the various mitigation options.

• Improve and validate models used to predict NH$_3$ emissions from manure storage.
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