

# LAB-SCALE ASSESSMENT OF GASEOUS EMISSIONS FROM LAYING-HEN MANURE STORAGE AS AFFECTED BY PHYSICAL AND ENVIRONMENTAL FACTORS

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**ABSTRACT.** Manure-belt (MB) and high-rise (HR) laying-hen houses are the two predominant housing types in the U.S. Compared with HR houses, MB houses have better indoor air quality and lower aerial emissions as a result of frequent (every 1 to 4 d) manure removal from the hen houses into separate manure storage. However, emissions from on-farm manure storage are integral parts of the whole-farm emissions and need to be quantified. This series of lab-scale studies assesses emission rates (ER) of ammonia (NH<sub>3</sub>) and greenhouse gases (CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O) from stored laying-hen manure as affected by the following physical and environmental factors: air exchange rate (10 or 20 air changes per hour, or ACH), manure stacking configuration expressed as surface area to stack volume ratio (SVR at 2.5, 5, 10, or 20 m<sup>-1</sup>), air temperature (constant at 25 °C or diurnal cyclic from 21 °C to 32 °C), manure moisture content (MC, 50% or 77%), and periodic addition of new manure to the existing stack. Results of the studies showed the following: (1) air exchange rate of 10 or 20 ACH had no apparent effects on the gaseous emissions; (2) SVR significantly affected emissions, with larger SVR leading to higher NH<sub>3</sub> and CO<sub>2</sub> ERs but lower CH<sub>4</sub> ER on per kg manure basis; (3) emissions were positively related to air temperature; and (4) laying-hen manure with 77% MC had higher emissions than that with 50% MC. At the storage condition of 25 °C air temperature, 20 ACH, every 2 d addition of 120 kg (5 cm thick layer) manure at 75% MC (equivalent to 2 d manure production of 682 laying hens) to the flat base area of 2.8 m<sup>2</sup>, the daily gaseous ERs per hen were 0.06 to 0.22 g NH<sub>3</sub>, 1.6 to 4.8 g CO<sub>2</sub>, and 7.4 to 32 mg CH<sub>4</sub> (0.18 to 0.8 g CO<sub>2</sub>e). N<sub>2</sub>O concentrations from the stored manure were below the detection limit (0.03 ppm) of the measurement instrument; hence, N<sub>2</sub>O emission was omitted from the presentation.

**Keywords.** Ammonia, Greenhouse gases, Laying hen, Manure storage, Poultry.

Microbial decomposition of poultry manure leads to gaseous emissions, with the predominant gas being ammonia (NH<sub>3</sub>) that results from breakdown of uric acid in the feces. NH<sub>3</sub> emission to the atmosphere can cause eutrophication and acidification, and it may also serve as a precursor to fine particulate matter (PM<sub>2.5</sub>) (NRC, 2003). Battye et al. (1994) reported that NH<sub>3</sub> emissions from animal feeding operations represent the largest portion (over 70%) of the national NH<sub>3</sub> emissions inventory in the U.S. According to the most recent estimates (USEPA, 2004), NH<sub>3</sub> emissions from laying hens contribute 30.5% of the poultry emissions inventory and 8.3% of animal agriculture emissions.

Poultry manure may also emit various levels of greenhouse gases (GHGs, i.e., CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), hydrogen sulfide (H<sub>2</sub>S), and volatile organic compounds (VOCs),

depending upon the nutritional (diet composition), chemical (e.g., pH), and physical (e.g., moisture content of the manure, climate) conditions. Nitrous oxide (N<sub>2</sub>O) is emitted from manure to the atmosphere via microbial processes of nitrification and denitrification, and it contributes to both tropospheric warming and stratospheric ozone depletion. N<sub>2</sub>O is globally distributed because of its long atmospheric residence time (~100 years), and it has a global warming potential (GWP) 298 times that of CO<sub>2</sub> within a 100-year horizon (IPCC, 2007). Methane (CH<sub>4</sub>) and CO<sub>2</sub> are formed by microbial degradation of organic matter under anaerobic conditions (Steed and Hashimoto, 1994). CH<sub>4</sub> is a greenhouse gas and contributes to global warming, with a GWP 25 times that of CO<sub>2</sub> for a 100-year horizon (IPCC, 2007). The agricultural sector has been reported to be the largest source of total global CH<sub>4</sub> emission, with livestock production being a major component within this sector (van Aardenne et al., 2001). Breakdown of urea and uric acid and aerobic microbial degradation processes also generate CO<sub>2</sub> (Møller et al., 2004). Agriculture has been identified by the U.S. EPA as contributing 6.2% of the total U.S. GHG emissions (CO<sub>2</sub> equivalent) in 2008. The inventory of U.S. GHG emissions and sinks (USEPA, 2009) identifies animal manure management contributing 14.5% of agricultural GHG emissions. Therefore, animal manure management accounts for 0.9% of the total national GHG emissions in the U.S.

Osada et al. (1998) reported CH<sub>4</sub> and N<sub>2</sub>O emissions from fattening pigs on slatted floors in Denmark. GHG emissions

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from swine farrowing house in China (Dong et al., 2007), from swine hoop structures (Singh et al., 2003), and from stored swine manure (Laguë et al., 2005) have also been reported. Burns et al. (2008) reported GHG, ammonia, and particulate matter emissions from broiler houses in the southeastern U.S. However, very limited information concerning GHG emissions from U.S. laying-hen production systems could be found in the literature.

Manure-belt (MB) and high-rise (HR) laying-hen houses are the two predominant housing types used by the U.S. egg industry. Recent monitoring of NH<sub>3</sub> emissions from commercial laying-hen houses showed that MB houses with daily or semi-weekly manure removal emit less than 10% of the NH<sub>3</sub> as compared with HR counterparts where manure is stored in the house for one year (Liang et al., 2005). However, NH<sub>3</sub> emissions from manure storage of MB houses remain to be quantified and controlled as part of the overall production system. Estimating NH<sub>3</sub> emissions from manure storage also faces considerable challenges because storage facilities are mostly open (i.e., naturally ventilated) with large and varying surface areas. Gaseous emissions from animal manure are largely dependent upon environmental conditions, such as air temperature, air velocity, and handling practices (Elzing et al., 1997; Arogo et al., 1999; Sommer et al., 1991; Phillips et al., 2000). NH<sub>3</sub> volatilization 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). Most of the studies reported in the literature focus on liquid manure; and data are lacking for NH<sub>3</sub> and GHG emissions from laying-hen manure storage under various environmental conditions. This data shortage for laying-hen manure storage is partially attributed to the fact that HR housing has traditionally been the norm for the egg industry, and recently the trend has been MB housing with separate manure storage.

The objective of this study was to assess NH<sub>3</sub> and GHG emissions from stored laying-hen manure as affected by air exchange rate, manure stacking configuration, manure moisture content (MC), ambient temperature, and periodic addition of manure to the existing stack.

## MATERIALS AND METHODS

### EXPERIMENTAL SETUP

#### Laying-Hen Manure and Air Emission Chambers

Laying-hen manure used in this study was procured from two MB housing egg farms in Iowa: one had manure naturally dried on belts and manure removed daily; the other had manure actively dried (with a drying air duct) on the belts and manure removed every three days. The laying hens were fed industry-standard laying-hen diets and watered through nipple drinkers (Li et al., 2005). On the starting day of each trial, manure removed from MB layer houses of similar bird age was transported by truck from the farm to our emission measurement laboratory.

Four environmentally controlled chambers and the associated measurement system were used to store the laying-hen manure and continually quantify the gaseous emissions (fig. 1). The chambers each had dimensions of 1.5 m width × 1.8 m depth × 2.4 m height and a positive-pressure ventilation system (fig. 2). Height-adjustable stands were used to achieve the same head space (3.5 m<sup>3</sup>) in all four emission chambers regardless of height of manure stack. A plastic film liner was used to prevent moisture loss from the manure stack to the floor. An air handler unit (850 m<sup>3</sup> h<sup>-1</sup> capacity, Parameter Generation and Control, Black Mountain, N.C.) was used to supply fresh air (dew-point temperature of 8.4°C to 12.1°C) to each chamber, whose airflow was adjusted with an inlet baffle. The plenum of each chamber had two electric heaters (1.5 kW capacity, model 3VU37, Cole-Parmer Instruments Co., Vernon Hills, Ill.) used to heat the incoming fresh air to the desired air temperature near the manure level. The following environmental variables were continuously measured: (1) dry-bulb air temperature and RH (model HMP35, Vaisala, Inc., Woburn, Mass.) in the center of each chamber and 30 cm above the manure surface; (2) manure stack temperature measured with type T (copper-constantan) thermocouples (0.2°C resolution); (3) manure MC measured with calibrated soil moisture content probes (model EC-20, Decagon Devices, Inc., Pullman, Wash.) (Mendes et al.,

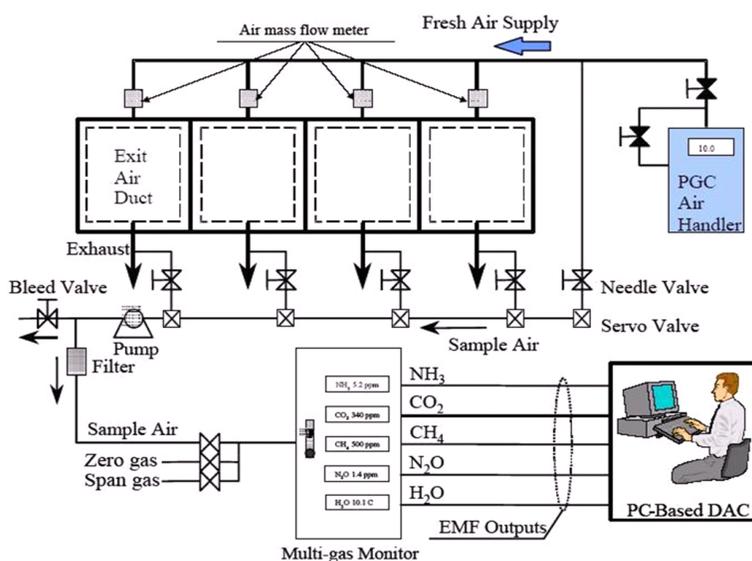
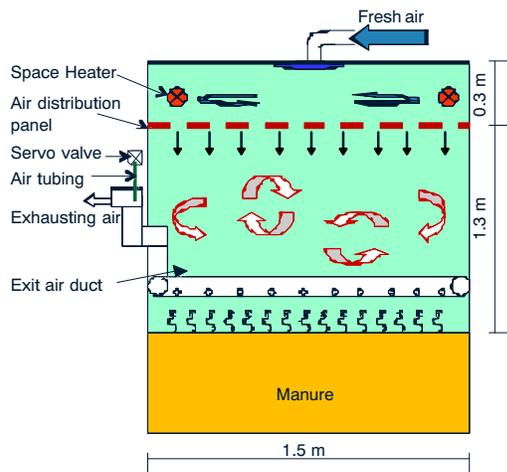


Figure 1. Schematic representation of environmentally controlled emission measurement chambers system.



**Figure 2. Vertical cross-section of the environmentally controlled emission measurement chamber.**

2008); and (4) airflow rate through each chamber with thermoelectric air mass flow meters (HFM-200B, Hastings Instruments, Hampton, Va.) placed in the supply air stream. The same environmental chambers have been used in numerous animal bioenergetics studies (Xin and Harmon, 1996; Xin et al., 1996, 1998, 1999; Harmon et al., 1997; Han and Xin, 2000; Chepete et al., 2004; Green and Xin, 2009a, 2009b).

#### **Air Sampling and Gaseous Analysis**

A multi-gas photoacoustic monitor (Innova 1314, Innova AirTech Instruments, Ballerup, Denmark) was used to measure the NH<sub>3</sub> (0-2000 ppm, 0.2 ppm detection limit), N<sub>2</sub>O (0-300 ppm, 0.03 ppm detection limit), CH<sub>4</sub> (0-4000 ppm, 0.4 ppm detection limit), and CO<sub>2</sub> (0-34000 ppm, 3.4 ppm detection limit) concentrations in the sample air. The common incoming air and four exhaust air samples were taken from the supply air pipe and exhaust air ducts through Teflon tubing (FEP, 3.2 mm ID × 6.4 mm OD) by an air pump with Teflon-coated wet parts (107CAB18, Gardner Denver Thomas, Sheboygan, Wisc.) and analyzed sequentially at 20 min intervals with the first 15 min for line purging and system stabilization and the remaining 5 min for measurement. Therefore, each measurement cycle took 100 min. A control and data acquisition system (CR10, AM416, and SDM-CD16, Campbell Scientific, Logan, Utah) was used to control five servo valves (model 8360, ASCO Valve, Inc., Florham Park, N.J.) and air temperatures and log the signal output from all the sensors, with the output

readings sampled at 2 s intervals and stored as 1 min averages.

#### **EXPERIMENTAL REGIMENS AND PROCEDURES**

Four experiments were designed and conducted to assess the effects of various physical and environmental factors on NH<sub>3</sub> and GHG emissions from the stored hen manure. The factors examined included air change rate expressed in air changes per hour (ACH), surface area to volume ratio (SVR, m<sup>-1</sup>), air temperature, manure moisture content (MC), and periodic (every 2 d) addition of manure, as may be encountered in commercial production settings with every 2 d manure removal and topical addition stockpiling. The conditions of the experiments are listed in table 1, and the procedures are described in more detail in the following sections. All manure stacks had a flat surface area of 1.5 m × 1.8 m (i.e., the horizontal dimension of each chamber).

#### **Experiment 1: Effects of Air Change Rates and Surface-to-Volume Ratios (SVR)**

Two experiments were conducted to evaluate the effects of air exchange rate and SVR on the gaseous emissions. In experiment 1, manure stacks were 43 cm high in two of the four chambers and 81 cm high in the other two, corresponding to a manure volume of 1.20 m<sup>3</sup> or SVR of 2.3 and a manure volume of 2.26 m<sup>3</sup> or SVR of 1.2, respectively. One chamber of each manure height or SVR was ventilated at 10 ACH (35 m<sup>3</sup> h<sup>-1</sup>) based on the air space above the manure surface, whereas the companion chamber of the same SVR was ventilated at 20 ACH (70 m<sup>3</sup> h<sup>-1</sup>) (table 1). The air velocities at 5 and 10 cm above the manure surface at five locations (the center and the center of four quadrants) in each chamber were measured with an omnidirectional air velocity sensor (model 8475-12, TSI, Inc., Shoreview, Minn.), and there was no significant difference between the average surface air velocities (<0.02 m s<sup>-1</sup>) for the two ACHs (p = 0.8). At ACH of 10 or 20, the NH<sub>3</sub> levels in all the chambers were below 300 ppm, the immediately dangerous to life or health (IDLH) concentration specified by the National Institute for Occupational Safety and Health (NIOSH, 1995). An ammonia mask was worn by the operator when briefly entering the chambers or handling the manure samples. The experimental regimens were designated as H43AC10, H43AC20, H81AC10, and H81AC20. For each trial, a new batch of manure was procured and mixed before random allocation to the four emission chambers. All chambers were maintained at an air temperature of 25 °C and dew-point temperature of 10 °C to 24 °C. A preliminary test revealed

**Table 1. Experimental conditions and regimens to evaluate the effects of air exchange rate (air changes per hour, or ACH), surface-to-volume ratio (SVR), manure moisture content (MC), air temperature, and periodic addition of manure to existing stack on NH<sub>3</sub> and greenhouse gas emissions from laying-hen manure storage (assignment of the regimens to chambers was randomized).**

Variable	Experiment 1 <sup>[a]</sup>				Experiment 2				Experiment 3		Experiment 4
	H43AC10	H43AC20	H81AC10	H81AC20	SVR20	SVR10	SVR5	SVR2.5	HMC	LMC	
Manure height (cm)	43	43	81	81	5	10	20	40	5	5	5 to 35
Manure volume (m <sup>3</sup> )	1.2	1.2	2.26	2.26	0.14	0.28	0.57	1.14	0.14	0.14	0.14 to 0.98
Manure weight (kg)	1160	1160	2080	2080	121	242	484	968	95	110	120 kg × 7
SVR (m <sup>-1</sup> )	2.3	2.3	1.2	1.2	20	10	5	2.5	20	20	20 to 2.86
ACH (air changes h <sup>-1</sup> )	10	20	10	20	20	20	20	20	20	20	20
Air temperature (°C)	25	25	25	25	25	25	25	25	21~32	21~32	25
Moisture content (%)	71	71	71	71	72	72	72	72	77	50	75
Sample size (n)	2	2	2	2	2	2	2	2	4	4	4

<sup>[a]</sup> HxxACyy, where xx = manure stack height (cm), and yy = air changes per hour, e.g., H43AC10 = 43 cm stack and 10 ACH.

that NH<sub>3</sub> emission approached stabilization after 40 d ventilated storage. Therefore, emissions from each chamber were measured continuously for 40 d, and two trials were conducted to obtain two replicates of each regimen.

### Experiment 2: Effect of Surface-to-Volume Ratios

Based on the results of experiment 1, experiment 2 focused on further examining the effect of SVR on the NH<sub>3</sub> and GHG emissions. In experiment 2, manure stacks were, respectively, 5, 10, 20, and 40 cm high in the four chambers and the corresponding manure volumes were 0.142, 0.283, 0.566, and 1.13 m<sup>3</sup> with corresponding SVR of 20, 10, 5.0, and 2.5, respectively. All four chambers were ventilated at 20 ACH (70 m<sup>3</sup> h<sup>-1</sup>) (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. As in experiment 1, all four chambers were maintained at an air temperature of 25 °C and dew-point temperature of 10 °C to 24 °C. Emissions from each chamber were measured continuously for 40 d, and each regimen was replicated twice. Loading of manure into the four chambers was done simultaneously to maximize homogeneity of manure stacks among the chambers.

### Experiment 3: Effects of Ambient Temperature and Moisture Content (MC)

Laying-hen manure with two initial MC levels, lower MC (LMC, 50%) or higher MC (HMC, 77%), were used, both involving industry standard diets. The LMC manure was from an MB layer facility where manure was somewhat dried on the belt for three days (with an active drying air duct below the cages) before being transported to the emission chambers; whereas the HMC manure was from the daily removed manure of a commercial MB house without active drying on the belt. For each trial, two LMC stacks and two HMC stacks (each at 5 cm high, SVR of 20) were randomly assigned to the four emission chambers. The results of experiment 2 showed that higher SVR led to higher NH<sub>3</sub> and CO<sub>2</sub> emissions. The SVR of 20 was used in experiments 3 and 4 to quantify NH<sub>3</sub> and GHG emissions under the potential stack scenario of high emissions. All four chambers had the same diurnal cyclic air temperature of 21 °C to 32 °C (daily mean of 26.7 °C) and 20 ACH. The cyclic temperature followed a sinusoidal shape, with the highest temperature (32 °C) occurring at 0000 h and the lowest temperature (21 °C) at 1200 h. Two trials were conducted, yielding four replicates per regimen. The manure from the same flocks was used to minimize the bird effect on the initial manure properties. Emissions from each chamber were measured continuously for 21 d. The actual weights of the LMC and HMC manure stacks in each chamber were 95 kg and 110 kg, respectively. The equivalent fresh manure (at 75% MC) weights based on the dry matter content for the LMC and HMC regimes were 190 and 101 kg, respectively, calculated as:

$$W_{75\%}(\text{kg}) = \frac{W_{act}(\text{kg}) \times (1 - MC)}{0.25} \quad (1)$$

### Experiment 4: Effect of Addition of Manure to the Existing Stack

At the start of experiment 4, all four chambers (representing four replicates) each had a 5 cm manure stack (75% MC, <1 day old). Subsequently, an additional 5 cm

manure layer was added atop the existing manure stack every 2 d. This periodic addition of new manure from the MB house to the existing stack was a simulation of commercial production. A total of seven layers of manure were added to each chamber stack over a 20 d monitoring period. All four chambers were ventilated at 20 ACH and maintained at the same air temperature of 25 °C. The weight of each layer of fresh manure per chamber was 120 kg, equivalent to 2 d manure production of 682 laying hens (i.e., 88 g hen<sup>-1</sup> d<sup>-1</sup>), based on ASABE Standard D384.2 (ASABE Standards, 2005). Manure was loaded into the four chambers at the same time to maximize homogeneity of manure among the chambers. Emission data during the 1 h manure loading and the subsequent 3 h were excluded from the analysis to ensure sufficient time for the system to reach steady state following opening of the chambers.

### ANALYSIS OF MANURE PROPERTIES

Nutrient and physical properties of the manure were analyzed by a certified commercial analytical laboratory (MVTL Laboratories, Nevada, Iowa) at the beginning and the end of the trial. Manure MC was determined by drying the samples in an electric oven at 135 °C for 2 h (AOAC, 1990b). Total nitrogen (total N) was measured using the improved Kjeldahl method (AOAC, 1990c). Total ammoniacal nitrogen (ammonia plus ammonium, TAN) was measured by the cadmium reduction method (AOAC, 1990a), and pH was measured with electrodes (Watson and Brown, 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 (≤5 cm top layer and >5 cm bottom layer) if the height of manure stacks was >5 cm. At the end of the first three experiments (21 or 40 d), a relatively rigid and dry top layer of 5 to 8 cm was observed on the manure stacks. This layer was quite distinctive from the remaining wetter stack. Therefore, manure samples from the surface layer and subsurface of every manure stack were taken and analyzed separately. One composite sample of each layer from every manure stack was sent to the commercial laboratory for analysis.

### CALCULATION OF GASEOUS EMISSIONS

Gaseous emission rate (ER) was calculated using the following equations:

$$ER_G \text{ mg h}^{-1} \text{ kg}^{-1} = \{[G]_e - [G]_i\} \times 10^{-6} \times \frac{Q}{M} \times \frac{\omega}{0.0224 \text{ m}^3 \text{ mol}^{-1}} \times 1000 \text{ mg g}^{-1} \quad (2)$$

$$ER_G \text{ mg h}^{-1} \text{ hen}^{-1} = W \times N \times ER_G \text{ mg h}^{-1} \text{ kg}^{-1} \quad (3)$$

where

- [G]<sub>e</sub>, [G]<sub>i</sub> = gaseous concentrations at exhaust and inlet air, respectively (ppm)
- Q = ventilation rate (m<sup>3</sup> h<sup>-1</sup> chamber<sup>-1</sup>) at standard temperature and pressure (STP, 0 °C and 101.325 kPa)
- M = amount of manure placed in the chamber (kg)
- ω = molar weight of gas (g mol<sup>-1</sup>)
- W = manure production rate of laying hen (kg hen<sup>-1</sup> d<sup>-1</sup>)

$N$  = manure accumulation time on manure belt (d, 2 for experiment 4).

Since the measurement interval of gaseous concentrations was 100 min, linear interpolation was used to determine intermediate and hourly average concentrations. With the hourly data of ventilation rate and gaseous concentration, hourly ERs of each chamber were calculated. Daily emissions were the summation of the dynamic emissions over the 24 h period. Statistical analysis of the daily emissions data were performed with analysis of variance using the general linear models of SAS for least squares means (SAS, 1990). Significant differences for all comparisons were based on  $p < 0.05$ .

## RESULTS AND DISCUSSION

The  $N_2O$  concentrations from the manure piles in this study were below the measurement detection limit (0.03 ppm). Hence,  $N_2O$  emission information was omitted from the presentation.

### PROPERTIES OF THE MANURE STACKS

The manure properties at the onset and end of different storage periods are shown in tables 2 to 5. The dry matter (DM) contents of the nearly fresh manure and the “actively

dried” manure were approximately 23% to 29% and 50%, respectively. After 3 d drying on the belt, the resultant manure had lower TAN and total N (10.9 and 50.9 g  $kg^{-1}$  DM) compared to the nearly fresh manure (30 and 65.2 g  $kg^{-1}$  DM), as revealed in experiment 3. The different N contents contributed to the different  $NH_3$  ER from the LMC and HMC manure stacks. The TAN content of the fresh manure accounted for approximately 48% of the total N, varying from 15 to 19 g  $kg^{-1}$  fresh manure. The variation in manure properties among different batches could have stemmed from differences in bird age, thus dietary composition, and inherent variability in the manure samples.

At the end of the 40 d ventilated storage, the DM content of the stacks increased (47.7% to 68.4%) for the top layer but decreased (22.5% to 23.8%) for the remaining bottom layer when the manure stack height was greater than 10 cm. TAN (both wet and dry basis) in the top layer was lower than that in the bottom layer. The proportions of TAN in the top and bottom layers were approximately 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 experiment 1 after the 40 d ventilated storage. In experiment 2, the surface layer properties of the SVR20 (5 cm) manure stack was different from those of the other manure stacks, and the subsurface layer properties of the SVR10 manure stack was different from those of the SVR5

**Table 2. Mean (standard error) properties of laying-hen manure at start and end of 40 d storage in experiment 1 ( $n = 2$ ) where manure was stacked 43 or 81 cm high on the same base of 1.5 m × 1.8 m and ventilated at 10 or 20 air changes per hour (ACH).**

Stack Layer	Manure Properties	Start or Fresh Manure	After 40 d Ventilated Storage <sup>[a]</sup>			
			H43AC10	H43AC20	H81AC10	H81AC20
Surface layer (≤5 cm depth)	Dry matter (%)	28.9 (1.5)	50.4 (1.8)	51.3 (4.4)	47.7 (1.9)	53 (8.4)
	Total N (g $kg^{-1}$ ) (as-is)	18.5 (0.3)	18.2 (0.8)	17.4 (0.2)	15.6 (1.0)	17 (0.6)
	Total N (g $kg^{-1}$ ) (dry basis)	64 (2.3)	36.1 (0.2)	34.3 (2.6)	33 (3.4)	34.1 (6.6)
	TAN (g $kg^{-1}$ ) (as-is)	7.8 (1.8)	5.9 (0.6)	6.1 (0.9)	6.3 (1.1)	6.7 (0.9)
	TAN (g $kg^{-1}$ ) (dry basis)	27.0 (7.6)	11.8 (1.6)	12.3 (2.8)	13.4 (2.8)	13.8 (3.8)
	pH	7.5 (0.05)	8.1 (0.1)	8.0 (0.05)	8.1 (0.1)	8.0 (0.05)
Subsurface layer (>5 cm depth)	Dry matter (%)	28.9 (1.5)	23.8 (0.2)	23.8 (0.6)	22.5 (0.5)	22.5 (0.35)
	Total N (g $kg^{-1}$ ) (as-is)	18.5 (0.3)	17.1 (0.9)	17.9 (0.8)	16.5 (1.5)	16.1 (1.8)
	Total N (g $kg^{-1}$ ) (dry basis)	64 (2.3)	71.9 (3.2)	75.7 (5.2)	73.5 (8.4)	71.9 (9.3)
	TAN (g $kg^{-1}$ ) (as-is)	7.8 (1.8)	13 (0.8)	13.7 (0.3)	12.4 (1.1)	13.4 (0.7)
	TAN (g $kg^{-1}$ ) (dry basis)	27.0 (7.6)	54.4 (2.8)	57.9 (2.6)	55.4 (6.2)	59.7 (4.1)
	pH	7.5 (0.05)	7.8 (0.05)	7.7 (0.05)	7.8 (0.00)	7.8 (0.05)

<sup>[a]</sup> HxxACyy, where xx = manure stack height (cm), and yy = air changes per hour, e.g., H43AC10 = 43 cm stack and 10 ACH

**Table 3. Mean (standard error) properties of laying-hen manure at start and end of 40 d storage in experiment 2 ( $n = 2$ ) where manure was stacked at a surface to volume ratio (SVR) of 20, 10, 5.0, or 2.5 and ventilated at 20 air changes per hour (ACH).**

Stack Layer	Manure Properties	Start or Fresh Manure	After 40 d Ventilated Storage <sup>[a]</sup>			
			SVR20 <sup>[b]</sup>	SVR10	SVR5	SVR2.5
Surface layer (≤5 cm from top)	Dry matter (%)	28.1 (0.8)	68.4 (6.7)	54.1 (2.3)	54.9 (0.9)	56.6 (5.9)
	Total N (g $kg^{-1}$ ) (as-is)	16.2 (0.1)	19.9 (2.6)	19.9 (1.6)	15.5 (2.1)	20.1 (2.0)
	Total N (g $kg^{-1}$ ) (dry basis)	57.7 (1.3)	28.9 (0.9)	37.2 (4.4)	28.4 (4.2)	37.0 (7.3)
	TAN (g $kg^{-1}$ ) (as-is)	8.8 (0.5)	4.6 (0.8)	6.0 (0.5)	6.0 (0.05)	5.9 (1.3)
	TAN (g $kg^{-1}$ ) (dry basis)	31.3 (0.8)	7.1 (1.7)	11.3 (1.3)	10.9 (0.3)	11.2 (3.5)
	pH	7.4 (0.2)	8.6 (0.00)	8.6 (0.05)	8.5 (0.1)	8.6 (0.1)
Subsurface layer (>5 cm from top)	Dry matter (%)	28.1 (0.8)	68.4 (6.7)	32.5 (1.5)	23.7 (0.8)	23.3 (1.2)
	Total N (g $kg^{-1}$ ) (as-is)	16.2 (0.1)	19.9 (2.6)	12.2 (1.5)	16.7 (0.2)	15.9 (0.5)
	Total N (g $kg^{-1}$ ) (dry basis)	57.7 (1.3)	28.9 (0.9)	38.1 (6.3)	70.8 (3.3)	64.6 (3.4)
	TAN (g $kg^{-1}$ ) (as-is)	8.8 (0.5)	4.6 (0.8)	8.2 (1.1)	10.5 (0.8)	10.8 (0.7)
	TAN (g $kg^{-1}$ ) (dry basis)	31.3 (0.8)	7.1 (1.7)	25.5 (4.5)	44.3 (1.8)	44.2 (1.8)
	pH	7.4 (0.2)	8.6 (0.00)	8.5 (0.05)	8.0 (0.00)	8.0 (0.1)

<sup>[a]</sup> Thickness or height of the manure stacks (cm): SVR20 = 5 cm, SVR10 = 10 cm, SVR5 = 20 cm, and SVR2.5 = 40 cm.

<sup>[b]</sup> Surface and subsurface layers were the same because the stack was only 5 cm high.

**Table 4. Mean (standard error) properties of laying-hen manure at start and end of 21 d storage in experiment 3 ( $n = 4$ ) where manure was stacked at a surface to volume ratio (SVR) of 20 and ventilated at 20 air changes per hour (ACH) with a diurnal air temperature of 21°C to 32°C.<sup>[a]</sup>**

Manure Properties	Start or Fresh Manure		After 21 d Ventilated Storage	
	LMC	HMC	LMC	HMC
Dry matter (%)	50.4 (4.7)	23.3 (0.7)	82.4 (3.5)	60.3 (0.9)
Total N (g kg <sup>-1</sup> ) as-is:	23.5 (2.2)	15.2 (1.2)	17.9 (5.6)	21.0 (3.1)
dry basis:	46.6 (4.3)	65.2 (4.3)	21.7 (6.8)	34.8 (4.8)
TAN (g kg <sup>-1</sup> ) as-is:	5.5 (0.8)	7.0 (0.4)	1.6 (0.2)	3.6 (0.6)
dry basis:	10.9 (1.9)	30.0 (0.6)	1.94 (0.3)	6.00 (0.9)
pH	8.4 (0.3)	7.1 (0.2)	8.8 (0.1)	8.6 (0.1)

<sup>[a]</sup> LMC = low moisture content; HMC = high moisture content.

**Table 5. Mean (standard error) properties of laying-hen manure at start and end of 20 d storage (after six additions) in experiment 4 ( $n = 4$ ) where 120 kg (5 cm thick layer) manure (2 d production by approximately 682 hens) was added atop every 2 d at a constant air temperature of 25°C.**

Manure Properties	Start or Fresh Manure	After 20 d Storage
	Dry matter (%)	25.4 (0.2)
Total N (g kg <sup>-1</sup> ) (as-is)	16.3 (0.4)	15.8 (0.3)
Total N (g kg <sup>-1</sup> ) (dry basis)	63.4 (1.5)	65.3 (1.2)
TAN (g kg <sup>-1</sup> ) (as-is)	7.5 (0.3)	7.9 (0.2)
TAN (g kg <sup>-1</sup> ) (dry basis)	29.2 (1.2)	32.6 (0.9)
pH	7.2 (0.1)	7.4 (0.1)

and SVR2.5 stacks ( $p < 0.001$ ). In experiment 3, the manure properties of the LMC and HMC were significantly different after 21 d storage ( $p < 0.01$ ). However, the manure properties in experiment 4 changed slightly due to the short exposure (2 d) before the new layer was added on top.

The relationship between pH and degradation of uric acid (the major nitrogen source in poultry manure) had been reported such that a sharp increase in pH was associated with a decrease in the uric acid content of poultry manure (Burnett et al., 1969). The degradation of uric acid is faster under aerobic conditions than under anaerobic conditions. The high pH in the stored manure would result in the majority of nitrogen loss as NH<sub>3</sub> (Elliot and Collins, 1982). The manure pH (8.0 to 8.5) of the surface layer was higher than the pH (7.8 to 8.0) of the subsurface because of the more aerobic process in the surface manure and more anaerobic process 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<sub>3</sub> loss due to the larger air pores, which would result in lower mass transfer resistance. Second, anaerobic conditions presumably existed in the subsurface due to the high moisture content of the manure. Finally, in the subsurface manure, the majority of the total N existed in the form of TAN (77%) after 40 d storage when the manure stack was >10 cm, and NH<sub>3</sub> would be more easily retained in the subsurface because of high resistance to the nutrient diffusion.

#### EFFECTS OF AIR EXCHANGE RATE AND SVR

In experiment 1, the effects of ACH and SVR, each at two levels, were assessed. The daily NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> ERs in

the unit of g d<sup>-1</sup> kg<sup>-1</sup> fresh manure during the 40 d trial are depicted in figure 3. ERs of NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> for the 43 cm (SVR2.3) and 81 cm high (SVR1.2) stacks peaked on the second day of storage and then decreased exponentially at different rates. The NH<sub>3</sub> ER gradually decreased throughout the first 21 d and stabilized thereafter. However, CH<sub>4</sub> ER quickly diminished after about 10 d. It took about 16 d for CO<sub>2</sub> ER to stabilize. The effect of ACH was evaluated for NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> ERs on the basis of per kg manure and per m<sup>2</sup> surface area and was found to be non-significant at 10 vs. 20 ACH ( $p = 0.36$  to  $0.94$ ). On the basis of emission per kg manure, the SVR2.3 stacks had higher ER of NH<sub>3</sub> ( $p = 0.008$ ) and CO<sub>2</sub> ( $p = 0.046$ ) than the SVR1.2 stacks, but no difference in CH<sub>4</sub> ER was found between the two SVRs ( $p = 0.94$ ). On the basis of emission per m<sup>2</sup> surface area, the SVR1.2 stack emitted more CH<sub>4</sub> and CO<sub>2</sub> than that of the SVR2.3 stack ( $p < 0.001$ ), but no difference in NH<sub>3</sub> ER was found between the two SVRs ( $p = 0.73$ ). From the standpoint of mass transfer theory, increasing partial gaseous pressure in the boundary air by reducing ACH should reduce the partial pressure gradient and thus gaseous emissions. However, this effect was not apparent in the current experiment. Several factors might have contributed to this outcome, namely, thermal condition, surface air velocity, air flow pattern, MC, and uniformity of the manure.

Experiment 2 further tested the SVR effect on NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> emissions while the ACH was kept constant (ACH = 20). The ERs and cumulative emissions of NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> for the four treatments of manure stack height or SVR are shown in figure 4. NH<sub>3</sub> ER and cumulative emission on the basis of per kg fresh manure showed significant differences among the four SVR regimens during the 40 d storage ( $p < 0.01$ ). The maximum NH<sub>3</sub> ERs were 0.15, 0.26, 0.45, and 0.90 g d<sup>-1</sup> kg<sup>-1</sup> fresh manure, which occurred on the second or third days. Generally, NH<sub>3</sub> ER and cumulative emission per kg manure were higher for manure stacks with higher SVR (i.e., shallow stacks). The 40 d cumulative NH<sub>3</sub> emissions per kg fresh manure (mean ± SE) were 3.5 ± 0.01, 6.4 ± 0.05, 9.7 ± 0.15, and 12.4 ± 1.32 g for SVR20, 10, 5.0, and 2.5, respectively, with corresponding daily average ERs (mean ± SD) of 0.09 ± 0.02, 0.16 ± 0.03, 0.24 ± 0.07, and 0.31 ± 0.23 g d<sup>-1</sup> kg<sup>-1</sup> manure ( $p < 0.001$ ). However, NH<sub>3</sub> ER of the 5 cm stack (SVR20) continually declined with storage time, presumably resulting from depletion of limited nitrogen present in the smaller manure stack. The result suggests that the stack will reach its limit of emission after a certain time. On the basis of per surface area, NH<sub>3</sub> ER for the higher manure stacks was greater, presumably because the subsurface manure provides a nutrient supply (moisture and TAN) to sustain the emission from the surface of the stack. Total N and TAN content (dry basis) decreased for the top 5 cm surface layers of all SVRs and subsurface layers in SVR20 and SVR10 regimens, but increased for the subsurface layers in SVR5, SVR2.5, and SVR1.2 regimens (tables 2 and 3). It should be noted that the surface and subsurface layers were essentially the same for SVR20 because the stack was only 5 cm thick. The dynamic MC of the manure stacks is depicted in figure 5. Moisture continually evaporated from the surface of the manure stack. Carr et al. (1990) concluded that ammonia loss from stored broiler litter was only reduced when MC was below 30%. The ammonia ER decreased with decreasing manure MC in the surface layer. High MC of the manure surface layers may

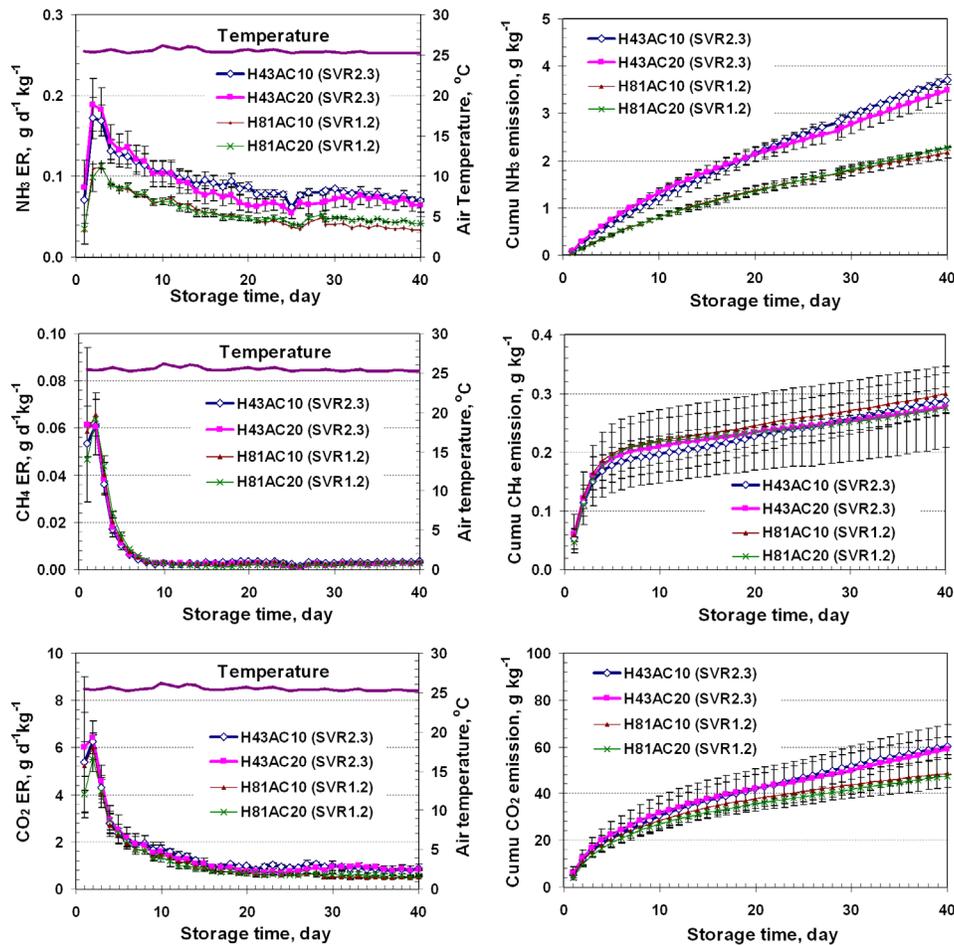


Figure 3. Daily emission rate (ER) and cumulative emission of NH<sub>3</sub>, CH<sub>4</sub>, and CO<sub>2</sub> (mean and standard error,  $n = 2$ ), in g per kg initial manure weight, of laying-hen manure stacked at a surface to volume ratio (SVR) of 1.2 or 2.3 and ventilated at air change rate of 10 or 20 ACH (HxxACyy, where xx indicates height of the manure stack (cm), and yy indicates ventilation rate in air changes per hour) (experiment 1).

stimulate NH<sub>3</sub> volatilization due to high NH<sub>3</sub> diffusivity in the “wet” manure. Compared with the result (0.18 g NH<sub>3</sub> d<sup>-1</sup> kg<sup>-1</sup> dry manure) reported by Pratt et al. (2002) under similar storage conditions (25 °C storage temperature and 69% manure MC) and for a longer storage period (18 weeks), NH<sub>3</sub> ERs (0.19 to 1.11 g d<sup>-1</sup> kg<sup>-1</sup> dry manure for SVR1.2 to SVR20) in the current study tended to be higher. The possible reasons could be different stacking configurations, manure properties, and storage time.

Daily ER of CH<sub>4</sub> during the 40 d storage exhibited different patterns from that of NH<sub>3</sub> (fig. 3). CH<sub>4</sub> emissions per kg manure showed significant differences among the four SVR regimens during the 40 d storage ( $p < 0.01$ ). The 40 d cumulative CH<sub>4</sub> emissions (mean  $\pm$ SE) were 0.34  $\pm$ 0.03, 0.44  $\pm$ 0.03, 0.26  $\pm$ 0.02, and 0.31  $\pm$ 0.02 g kg<sup>-1</sup> fresh manure for SVR2.5, 5, 10, and 20, respectively. For SVR > 5, CH<sub>4</sub> ER was the highest on the first day of the storage (0.086 g d<sup>-1</sup> kg<sup>-1</sup> or 0.008 kg d<sup>-1</sup> m<sup>-2</sup> for SVR10, and 0.089 g d<sup>-1</sup> kg<sup>-1</sup> or 0.004 kg d<sup>-1</sup> m<sup>-2</sup> for SVR20). Manure stacks at SVR2.5 showed lower CH<sub>4</sub> ER on the first day than on the second day (0.054 vs. 0.077 g d<sup>-1</sup> kg<sup>-1</sup> or 0.019 vs. 0.028 kg d<sup>-1</sup> m<sup>-2</sup>), while manure stacks at SVR5 showed the same CH<sub>4</sub> ERs (0.096 g d<sup>-1</sup> kg<sup>-1</sup> or 0.017 kg d<sup>-1</sup> m<sup>-2</sup>) on the first and second

days (fig. 4). On the basis of emission per kg, the 20 and 40 cm stacks (SVR5 and SVR2.5) had higher CH<sub>4</sub> ERs than the 5 or 10 cm stacks (SVR20 and SVR10). Overall, the stacks with greater height always emitted more CH<sub>4</sub>, and most (>75%) of the CH<sub>4</sub> emissions occurred during the first 10 d period. The higher stacks could retain water and anaerobic conditions in the manure for a longer period, hence promoting more CH<sub>4</sub> generation.

Figure 4 also reveals that the stacks with larger SVRs led to higher CO<sub>2</sub> ER per kg manure ( $p < 0.01$ ). The significant changes of CO<sub>2</sub> ER per kg manure happened when SVR was in the range of 2.5 to 10. The CO<sub>2</sub> ER varied from 18.2 to 0.8 g d<sup>-1</sup> kg<sup>-1</sup> or from 2.2 to 0.04 kg d<sup>-1</sup> m<sup>-2</sup> for the four SVRs, with the maximum ER occurring on the first or second day of storage. On per kg manure basis, CO<sub>2</sub> ERs for SVR20 and SVR10 were higher than those for SVR5 and SVR2.5 ( $p < 0.001$ ). On per m<sup>2</sup> manure surface area basis, the CO<sub>2</sub> ER increased as SVR decreased ( $p < 0.01$ ). The cumulative CO<sub>2</sub> emissions were 55.8, 99.8, 150, and 135 g kg<sup>-1</sup> fresh manure (20, 17.9, 13.4, and 6.1 kg m<sup>-2</sup>) for SVR2.5, 5, 10, and 20, respectively; and 50% of the total CO<sub>2</sub> emissions during the 40 d storage occurred during the first 10 d. For practical purposes, emission per kg of manure is a better representation

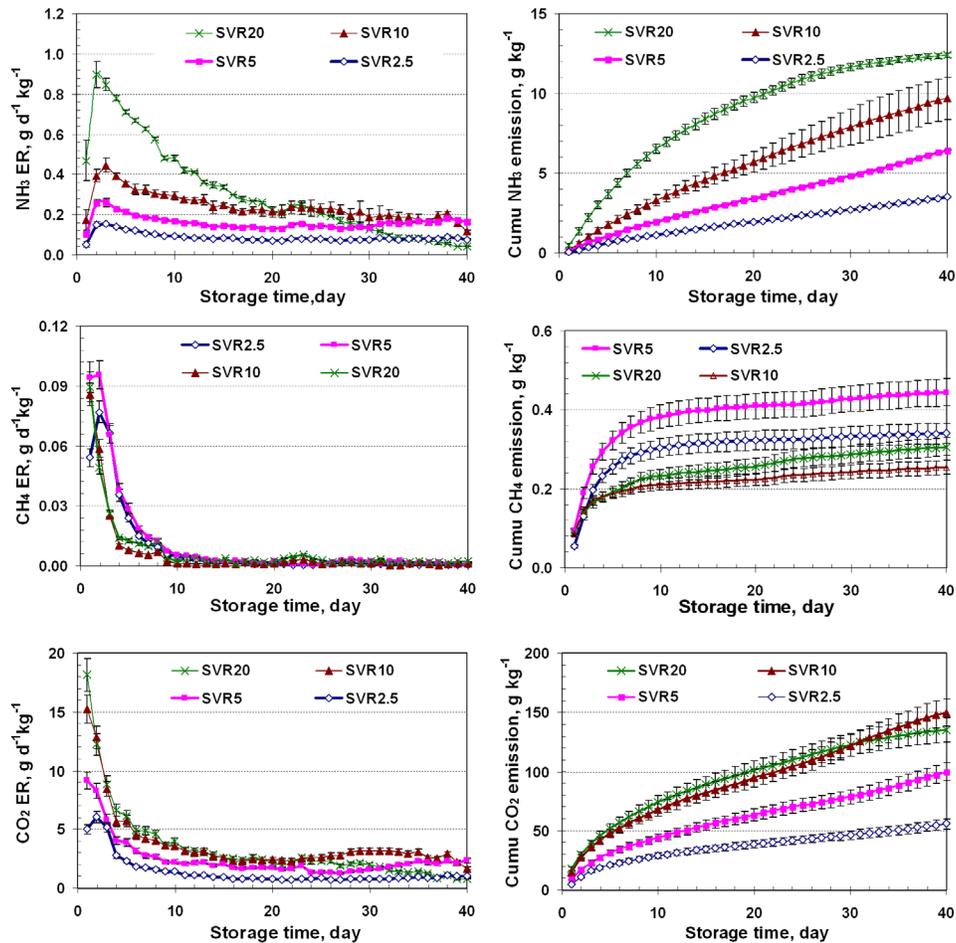


Figure 4. Daily emission rate (ER) and cumulative emission of  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  (mean and standard error,  $n = 2$ ), in g per kg initial manure weight, of laying-hen manure stacked at a surface to volume ratio (SVR) of 20, 10, 5, or 2.5 during a 40 d storage period (experiment 2).

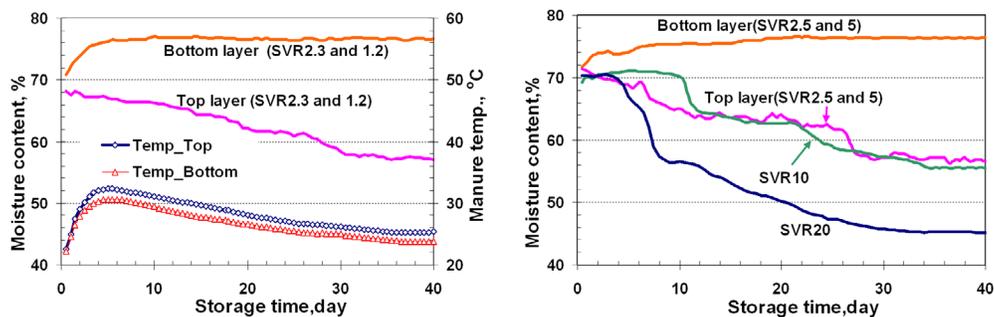


Figure 5. Dynamic moisture content (MC) and temperature of laying-hen manure stacks during a 40 d storage period for (left) experiment 1 and (right) experiment 2. The surface (top) layer MC was measured at 2.5 cm below the surface of manure stacks, and the subsurface layer MC was measured at 2.5 cm above the bottom of manure stacks.

of the emission magnitude because manure weight reflects the number of hens involved.

To quantify the relationship of cumulative emission vs. stack SVR and storage time at  $25^\circ\text{C}$  air temperature, a nonlinear empirical model was developed for  $\text{NH}_3$  emission based on the “chemical reaction” model from the model

library in JMP 6.0 (SAS Institute, Inc., Cary, N.C.), of the following form:

$$Q_{\text{NH}_3} = \frac{a \times ST \times \text{SVR}}{b + c \times ST \times \text{SVR}} \quad (R^2 = 0.9954) \quad (4)$$

where

- $Q_{NH_3}$  = cumulative ammonia emission for a given storage time of <40 d ( $\text{g NH}_3 \text{ kg}^{-1}$  fresh manure)
- $ST$  = storage time of the manure (<40 d)
- $SVR$  = surface-to-volume ratio of the manure stack ( $\text{m}^{-1}$ , ranging from 1.2 to 20)
- $a, b, c$  = regression coefficients ( $a = 157, b = 3600, c = 7.6$ ).

The degree of fitness between the predicted and measured cumulative ammonia emissions is shown in figure 6. With a regression coefficient ( $R^2$ ) of 0.995, the empirical model represents the data well.

**EFFECTS OF MC AND AMBIENT TEMPERATURE**

Data in figure 7 (from experiment 3) show that the  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs of LMC (50%) and HMC (77%) manure stacks followed the air temperature. The  $\text{NH}_3$  and  $\text{CO}_2$  ERs clearly varied with temperature changes during the three-week storage time. The temperature effect on  $\text{CH}_4$  emission diminished after 8 d. The peak  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs occurred on the first or second day, corresponding to the daily air temperature peak. The  $\text{NH}_3$  ER for the HMC stack was consistently greater than that for the LMC stack during the

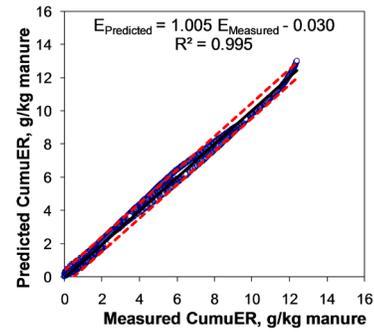


Figure 6. Relationship of cumulative  $\text{NH}_3$  emission from measurement vs. from prediction model with constant air temperature of  $25^\circ\text{C}$ , MC of 72%, and 20 ACH when SVRs were 1.2, 2.5, 5, 10, and 20. The dash lines below and above the regression lines represent 95% confidence intervals of the observations.

21 d period. The data also revealed that the HMC stack had higher  $\text{CH}_4$  ER before the seventh day and higher  $\text{CO}_2$  ER after the sixth day ( $p < 0.001$ ).

The cumulative  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  emissions of the LMC manure over the 21 d storage were 25.2, 0.68, and 182  $\text{g kg}^{-1}$  dry manure, respectively, which were 64%, 36%, and

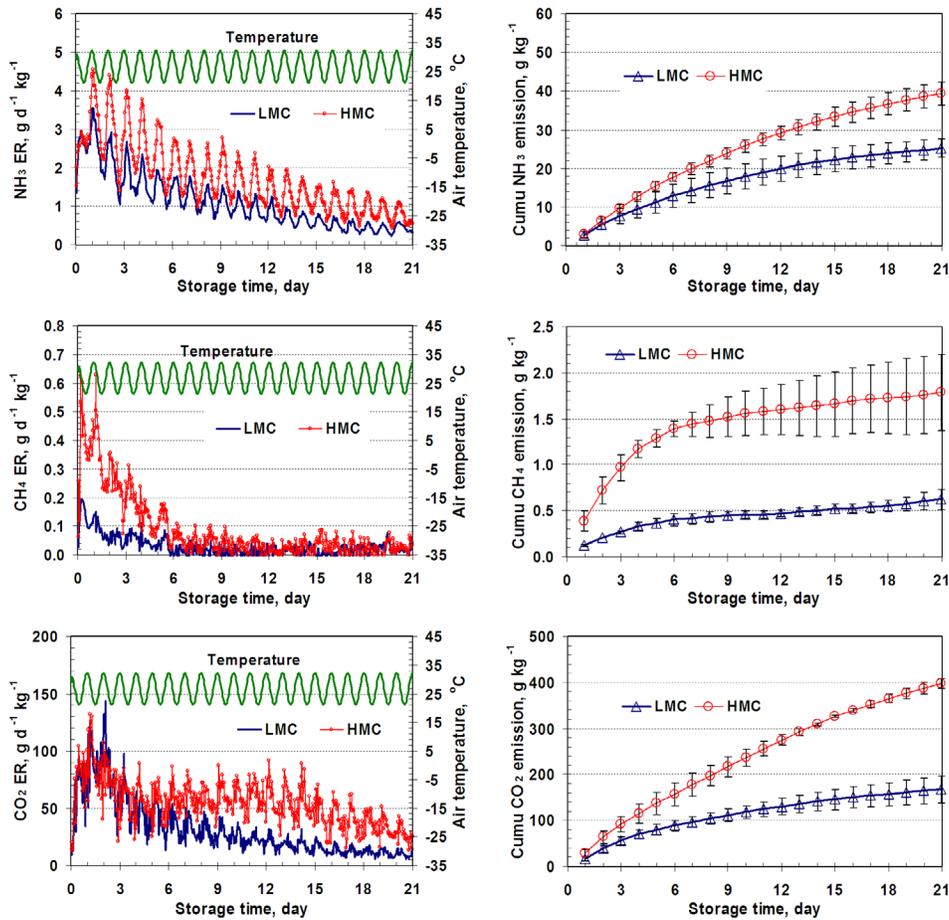


Figure 7. Dynamic gaseous emissions of laying-hen manure stacks (5 cm height or 20 SVR), in g per kg dry manure, at initial moisture content of 50% (LMC) or 77% (HMC) under a sinusoidal diurnal air temperature of  $21^\circ\text{C}$  to  $32^\circ\text{C}$  (experiment 3).

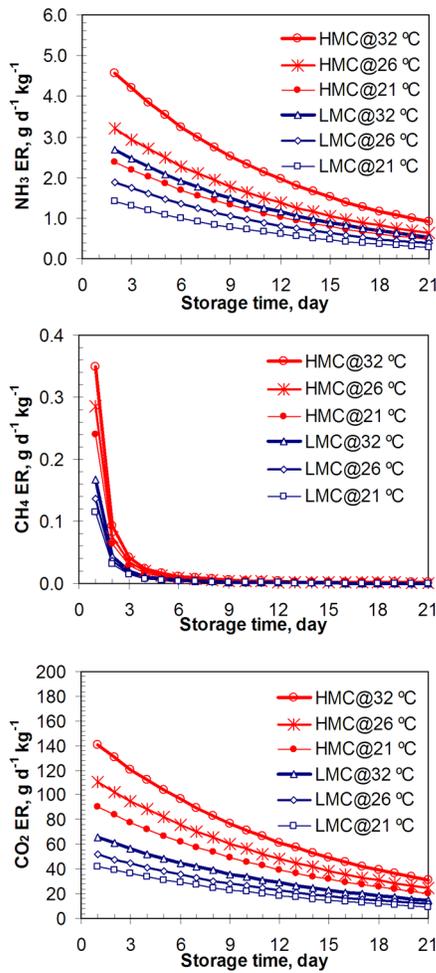


Figure 8. Gaseous ( $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ ) emission rates of laying-hen manure stacks (5 cm height or SVR20) with storage time, in g per kg dry manure, as affected by MC of 50% (LMC) or 77% (HMC) and air temperature of 21 °C to 32 °C.

42% of the cumulative  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  emissions of the HMC manure, 39.4, 1.9 and 432  $\text{g kg}^{-1}$  dry manure. These results for the HMC, SVR20 stack compared favorably with the first 21 d cumulative  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  emissions of 45, 1.2, and 469  $\text{g kg}^{-1}$  dry manure, as observed in experiment 2 (initial MC of 72%, SVR20, ambient temperature of 25 °C).

Three regression models were derived using the SAS program to relate ER to manure storage time, manure MC, and air temperature, of the following form:

$$ER_{\text{NH}_3} = e^{(-0.73+0.53 \times \text{MC} - 0.085 \times \text{ST} + 0.059 \times T_a)}, R^2 = 0.95 \quad (5)$$

$$ER_{\text{CH}_4} = e^{(-2.88+0.74 \times \text{MC} - 1.92 \times \ln(\text{ST}) + 0.034 \times T_a)}, R^2 = 0.53 \quad (6)$$

$$ER_{\text{CO}_2} = e^{(2.98+0.76 \times \text{MC} - 0.075 \times \text{ST} + 0.04 \times T_a)}, R^2 = 0.78 \quad (7)$$

where

$ER$  = emission rate ( $\text{g d}^{-1} \text{kg}^{-1}$  dry manure)

$MC$  = initial moisture content ( $MC = 0$  for 50% initial MC; or 1 for 77% initial MC)

$ST$  = storage time (d)

$T_a$  = air temperature (°C).

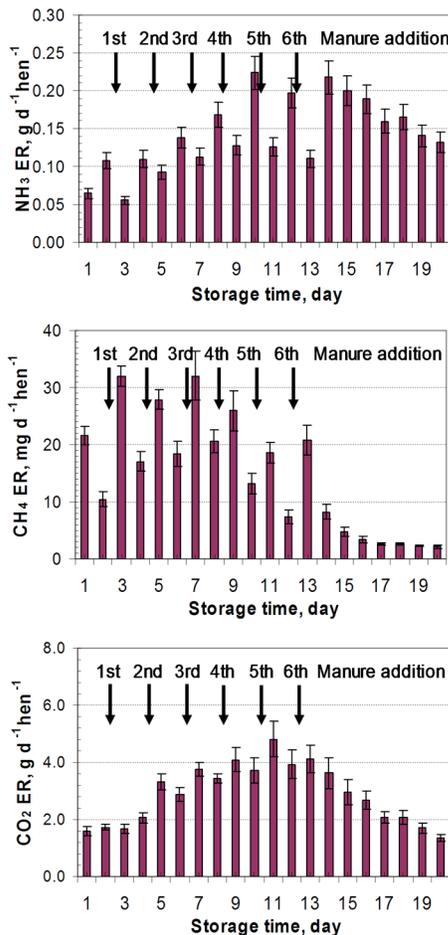
Figure 8 shows the profiles of  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs derived from equations 5, 6, and 7 at different storage time (ST), initial MC, and  $T_a$ . For  $T_a$  varying from 21 °C to 32 °C,  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs would increase by 6.1% [ $e^{(0.059)} - 1$ ], 3.5% [ $e^{(0.034)} - 1$ ], and 4.1% [ $e^{(0.04)} - 1$ ] per 1 °C  $T_a$  rise for a given ST and MC. At a given  $T_a$  and ST,  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs for the LMC stacks would be, respectively, 59% [ $e^{-0.53}$ ], 48% [ $e^{-0.74}$ ], and 47% [ $e^{-0.76}$ ] lower than ERs for the HMC stacks. HMC manure stacks provide an environment that is more conducive to the growth of  $\text{CH}_4$  bacteria by limiting oxygen ( $\text{O}_2$ ) penetration. Higher temperature positively influences breakdown of uric acid, bacterial activities under anaerobic or aerobic condition, and thus generation of gases. The effect of temperature was a combination of degradation and volatilization processes. For example, the dissociation of  $\text{NH}_3$  on the manure surface increases under higher temperature, which causes the gas phase  $\text{NH}_3$  on the manure surface to increase and more  $\text{NH}_3$  to be emitted into the surrounding air. Pratt et al. (2002) reported a linear trend of nitrogen loss from stored laying-hen manure with air temperature increasing from 12.3 °C to 24.4 °C.

### EFFECTS OF MANURE ADDITION ON EMISSIONS

In experiment 4, an additional layer (5 cm) of hen manure was added to each chamber every 2 d to simulate on-farm operation. All the chambers were ventilated with 20 ACH and maintained at 25 °C air temperature. A total of seven layers of manure were applied per chamber during 20 d storage. The  $\text{NH}_3$  ERs decreased after addition of new manure, presumably because overlay of the new layer hinders  $\text{NH}_3$  emission from the previous layers. The  $\text{CH}_4$  and  $\text{CO}_2$  ERs peaked during the first day, whereas  $\text{NH}_3$  ER peaked on the second day of the manure addition.

The daily fresh manure production rate was estimated to be 88  $\text{g d}^{-1} \text{hen}^{-1}$  (ASABE Standards, 2005), and  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs in  $\text{g d}^{-1} \text{kg}^{-1}$  were converted to per-hen basis while the top layer of fresh manure in each chamber (120 kg) was equivalent to 2 d manure production of 682 laying hens. The daily  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs in  $\text{g d}^{-1} \text{hen}^{-1}$  from the progressively growing manure stack are shown in figure 9. After each manure addition, the first-day  $\text{NH}_3$  ERs, ranging from 0.06 to 0.13  $\text{g d}^{-1} \text{hen}^{-1}$  (mean of 0.10 and SE of 0.03), were significantly lower than the second-day ERs, ranging from 0.11 to 0.22  $\text{g d}^{-1} \text{hen}^{-1}$  (mean of 0.17 and SE of 0.05) ( $p < 0.001$ ). The first-day  $\text{CH}_4$  ERs (mean of 25.6  $\pm$  5.4 SE  $\text{mg d}^{-1} \text{hen}^{-1}$ ), were significantly higher than the second-day  $\text{CH}_4$  ERs (13.6  $\pm$  5.2  $\text{mg d}^{-1} \text{hen}^{-1}$ ), ranging from 7.4 to 21.6  $\text{mg d}^{-1} \text{hen}^{-1}$  ( $p < 0.001$ ). The  $\text{CO}_2$  ERs varied from 1.6 to 4.8  $\text{g d}^{-1} \text{hen}^{-1}$ . There was no significant difference in  $\text{CO}_2$  ERs between the first two days (3.4  $\pm$  1.2 vs. 3.0  $\pm$  0.9  $\text{g d}^{-1} \text{hen}^{-1}$ ) after each manure addition ( $p = 0.2$ ).

Considerable variations in gas ERs were observed among the manure additions, which could have been caused by non-uniformity in the manure. Daily  $\text{NH}_3$  ER (0.22  $\text{g d}^{-1} \text{hen}^{-1}$ ) peaked on the second day of the fourth addition, whereas daily  $\text{CH}_4$  ER peaked (32  $\text{mg d}^{-1} \text{hen}^{-1}$ ) in the second addition. The daily  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  ERs for the seven additions during a 14 d period averaged 0.13  $\pm$  0.05  $\text{g NH}_3 \text{d}^{-1} \text{hen}^{-1}$ , 20.4  $\pm$  7.6  $\text{mg CH}_4 \text{d}^{-1} \text{hen}^{-1}$ , and 3.2  $\pm$  1.1  $\text{g CO}_2 \text{d}^{-1} \text{hen}^{-1}$ . The global warming potential (GWP) of  $\text{CH}_4$  is 72, 25, and 7.6 times that of  $\text{CO}_2$  for 20, 100, and 500-year horizons, respectively (IPCC, 2007). Hence, the average daily  $\text{CH}_4$  ER



**Figure 9.** Daily gaseous ( $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ ) emission rate (ER,  $\text{g d}^{-1} \text{hen}^{-1}$ ) from laying-hen manure storage at  $25^\circ\text{C}$  air temperature, where fresh manure was added at 5 cm thickness to the existing stack on days 2, 4, 6, 8, 10, and 12 (experiment 4).

was  $0.52 \pm 0.2 \text{ g CO}_2\text{e d}^{-1} \text{hen}^{-1}$  for a 100-year horizon, which was 16.2% of the direct  $\text{CO}_2$  emission from the manure.

$\text{NH}_3$  emissions from on-farm manure storage of MB houses need to be included to estimate the whole-farm  $\text{NH}_3$  emissions. If the daily fresh manure from MB layer houses was added to the same manure pile under the conditions of  $25^\circ\text{C}$  air temperature, manure MC of 75% to 77%, and SVR20, the average  $\text{NH}_3$  ER would be approximately  $0.13 \text{ g d}^{-1} \text{hen}^{-1}$ . Liang et al. (2005) reported  $0.87 \text{ g NH}_3 \text{ d}^{-1} \text{hen}^{-1}$   $\text{NH}_3$  ER for HR layer houses in Iowa and Pennsylvania and  $0.05 \text{ g NH}_3 \text{ d}^{-1} \text{hen}^{-1}$  ER for MB houses with daily manure removal. Hence, including  $\text{NH}_3$  ER from manure storage (under the specific conditions examined in the current experiment), the total  $\text{NH}_3$  ER from MB houses and manure storage would be estimated to be  $0.05 + 0.13 = 0.18 \text{ g d}^{-1} \text{hen}^{-1}$ . This ER value may be used as a reference for estimating the reportable quantity of  $\text{NH}_3$  emissions for laying hens in MB production systems; however, the user should be aware of the limitation of the data applicability.

Fabbri et al. (2007) reported  $\text{CH}_4$  emission for MB houses to be  $0.08 \text{ kg year}^{-1} \text{hen}^{-1}$  (averaging  $0.22 \text{ g d}^{-1} \text{hen}^{-1}$ ) with manure removal every 3 to 4 d. In comparison, the  $\text{CH}_4$  ER ( $0.03 \text{ g d}^{-1} \text{hen}^{-1}$ ) from manure storage obtained in the current study was only 14.6% of the house-level  $\text{CH}_4$  emission

reported by Fabbri et al. (2007). The  $\text{CO}_2$  ERs varied from 1.6 to  $4.8 \text{ g d}^{-1} \text{hen}^{-1}$  for the seven additions. The respiratory  $\text{CO}_2$  production of laying hens normally ranges from 70 to  $80 \text{ g d}^{-1} \text{hen}^{-1}$  (Chepete et al., 2004). Hence,  $\text{CO}_2$  production from the manure storage amounts to only 2% to 6% of that from respiration of the birds.

## CONCLUSIONS

Lab-scale studies were conducted to assess emissions of ammonia ( $\text{NH}_3$ ) and greenhouse gases (GHGs) ( $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{N}_2\text{O}$ ) from laying-hen manure storage at various manure stacking configurations and environmental conditions. Emission of  $\text{N}_2\text{O}$  from the manure storage was below the detection limit of the measuring instrument and hence not reported. The following conclusions were drawn:

- Air change rate of 10 or 20 ACH (air changes per hour), with an air velocity of  $<0.02 \text{ m s}^{-1}$  near the manure stack surface, showed no significant effect on gaseous emissions during a 40 d ventilated storage period at a constant air temperature of  $25^\circ\text{C}$ .
- Manure stacking configuration, as expressed by surface-to-volume ratio (SVR), had significant effects on  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  emissions from the stored laying-hen manure, with larger SVR stacks leading to higher  $\text{NH}_3$  and  $\text{CO}_2$  but lower  $\text{CH}_4$  emissions per unit manure weight.
- Gaseous emissions were positively related to air temperature ( $21^\circ\text{C}$  to  $32^\circ\text{C}$ ) and manure moisture content (MC, 50% vs. 77%). Empirical equations were developed that delineate the relationships between the gaseous ( $\text{NH}_3$ ,  $\text{CO}_2$ , and  $\text{CH}_4$ ) emissions and storage time, manure MC, and air temperature.
- At the storage conditions of  $25^\circ\text{C}$  air temperature, 20 ACH (surface air velocity  $<0.02 \text{ m s}^{-1}$ ), and every 2 d topical addition of 120 kg (5 cm thickness) laying-hen manure at 75% MC (equivalent to 2 d manure production by 682 laying hens) to a flat base storage area of  $2.8 \text{ m}^2$ , the gaseous emission rates were  $0.06$  to  $0.22 \text{ g NH}_3 \text{ d}^{-1} \text{hen}^{-1}$ ,  $1.6$  to  $4.8 \text{ g CO}_2 \text{ d}^{-1} \text{hen}^{-1}$ , and  $7.4$  to  $32 \text{ mg CH}_4 \text{ d}^{-1} \text{hen}^{-1}$  (or  $0.18$  to  $0.8 \text{ g CO}_2\text{e d}^{-1} \text{hen}^{-1}$ ).

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