Mitigation of Ammonia Emissions from Broiler Houses Using a Biodegradable Litter Amendment

Namanda Sara Senyondo

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Biological Systems Engineering

Jactone A. Ogejo - Chair
Robert Grisso
Rory O. Maguire
Frank W. Pierson
Mary Leigh Wolfe

April 03, 2013
Blacksburg, VA

Keywords: Ammonia Emissions, Broiler Litter, Biodegradable, Litter Amendment, Mitigation.

Mitigation of Ammonia Emissions from Broiler Houses Using a Biodegradable Litter Amendment

Namanda Sara Senyondo

ABSTRACT

Broilers are raised indoors on high density farms with bedding/litter to trap their manure. Ammonia gas, which is produced as the manure decomposes, has adverse effects on human health, bird welfare and the environment. Using litter amendments can reduce the amount and, consequently, the effects of ammonia emitted from broiler houses. The objective of this study was to determine the effectiveness of a biodegradable litter amendment (BLA) in reducing ammonia emitted from a broiler house.

A pilot scale test was set up with six adjacent, individually ventilated rooms and a stocking density of 0.07 m^2 per bird. The birds were fed with a standard commercial, corn and soybean meal based diet and water was provided ad libitum. The first flock was grown on 10 cm of fresh, kiln-dried pine shavings, while subsequent flocks were grown on top-dressed reused litter. The two treatments (control (CTL) and BLA) were randomly assigned to the six rooms after flock 1, to give three replicates per treatment. The exhaust air from the rooms was sampled for ammonia concentration for two days each week starting at four days of age to determine the amount of ammonia emitted.

Over three subsequent flocks, the total mass of ammonia emitted from rooms treated with BLA was 31% to 47% lower than the control. Ammonia emitted per bird grown on treated litter and per kg of harvested bird weight was 32% to 44% lower, and the exhaust fans ran 7% to 22% less than CTL over the same period. For both BLA and CTL, the amount of ammonia emitted generally increased with bird age and litter reuse. The study showed that BLA effectively reduced ammonia emitted from a broiler house and that there are potential energy savings from using the amendment. However, ammonia emitted from the BLA rooms during the final flock was 57% higher than CTL, which was attributed to insufficient water (less than 18% moisture by weight) to support the reaction between BLA and ammonia.

Acknowledgement

My sincere appreciation goes to my advisor, Dr. Jactone A. Ogejo for giving me the opportunity to conduct this research and for his continued guidance throughout my graduate studies and compilation of this dissertation.

I would also like to thank my committee members; Dr. Robert Grisso, Dr. Rory O. Maguire, Dr. F. William Pierson and Dr. Mary Leigh Wolfe, who provided valuable advice, shared scholarly resources, and availed members of their research teams to help with my field study.

I would not have been able to complete the field study without help from fellow students; Andrea, Ashley, Caitlin, Devin, Hassan, Jess, and Liz, and staff at the VT turkey farm, Curt and Dale. We somehow managed to have fun weighing chicken for hours at a time. Thank you.

This journey has been a challenge on many levels but I have seen the goodness of God in family, friends and strangers alike; in people like Eunice Ofori that prayed for and with me, and watched my son so I could work late or simply get some rest. I received an enormous amount of encouragement and support from my parents, siblings and longtime friends, Gloria and Brenda. Thank you.

Finally, to my dear son Bradley; there is so much that I wish for you but hopefully I will inspire you to believe in yourself, work hard and achieve your own dreams. God bless you.

This work was supported by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture, under Agreement No. 2009-55112-05214.

Table of contents

List of figures

List of tables

List of abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AFO	Aninal Feeding Operation
APHA	American Public Health Association
ASABE	American Society of Agricultural and Biological Engineers
ASTM	American Society for Testing and Materials
BLA	Biodegradable Litter Amendment
CAFO	Concentrated Animal Feeding Operation
CAT	Chamber and Acid Trap
CDC	Centers for Disease Control (United States)
CEC	Convective Emissions Chamber
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CTL	Control
ECS	Environment Control System
EF	Emission Factor
EPA	Environmental Protection Agency (United States)
EPCRA	Environmental Planning and Community Right-to-Know Act
ER	Emission Rate (of pollutant)
ERS	Economic Research Service (USDA)
FCR	Feed Conversion Ratio
FPD	Footpad Dermatitis
FTIR	Fourier Transform Infrared
IPCS	International Programme on Chemical Safety
KPF	Kentucky Poultry Federation

MES	Modified Ekstrand Score
NAE	National Academy of Engineering
NCC	National Chicken Council
NCDC	National Climatic Data Center
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council of the National Academies
OSHA	Occupational Safety & Health Administration (United States)
PLT	Poultry Litter Treatment (Litter amendment)
PM	Particulate Matter
PMU	Portable Monitoring Unit
REM	Ross Environmental Management
RH	Relative Humidity
std. dev	Standard deviation
TAN	Total Ammonia Nitrogen
TN	Total Nitrogen
U.S.	United States
USDA	United States Department of Agriculture
vcm	Volume changes per minute (Ventilation Rate)
VDEQ	Virginia Department of Environmental Quality
VPA	Virginia Pollution Abatement Permit Regulation program
VR	Ventilation Rate

List of elements and chemical formulas

$C_4H_6N_4O_3$	Allantoin
$C_5H_4N_4O_3$	Uric Acid
$CaCO_3$	Calcium Carbonate (Lime)
CaO	Calcium Oxide (Burnt Lime)
$Ca(OH)_2$	Calcium Hydroxide (Slaked Lime)
CO_2	Carbon Dioxide
H^+	Hydrogen Ion
H_2O	Water
H_2O_2	Hydrogen Peroxide
H_2SO_4	Sulfuric Acid
HCl	Hydrochloric Acid
HNO_3	Nitric Acid
N	Nitrogen (elemental)
N_2	Dinitrogen gas
N_2O	Nitrous Oxide
$NaOH$	Sodium Hydroxide
NH_3	Ammonia
NH_4^+	Ammonium
NH_4Cl	Ammonium Chloride
NH_4NO_3	Ammonium Nitrate
$(NH_4)_2SO_4$	Ammonium Sulfate
NO	Nitrous Oxide

NO_2^-	Nitrite
NO_3^-	Nitrate
O_2	Oxygen
P	Phosphorus
S	Sulfur

CHAPTER 1: INTRODUCTION

Poultry production in the U.S.

The U.S. is the world's largest producer and second-largest exporter of poultry meat, with over 19.5 billion kilograms and $44 billion in annual sales (ERS, 2012). More than 80% of U.S. poultry production is comprised of broiler meat and turkey, and national consumption of poultry meat is considerably higher than beef or pork (ERS, 2012). Broiler production is concentrated mainly in the southern states, including Georgia, Arkansas, Alabama, North Carolina and Mississippi, which are the top 5 poultry producing states (ERS, 2012). There is intensive poultry production in the region stretching from the state of Delaware, south along the Atlantic coast to Georgia, then westward through Alabama, Mississippi and Arkansas. According to ERS (2012), Virginia was the twelfth largest poultry producing state in 2011 with more than 243 million broilers raised and approximately $603 million in revenues.

Most of the broilers marketed in the U.S. are raised in animal feeding operations (AFOs). Animal feeding operations are defined as agricultural enterprises where animals are raised in confinement for 45 or more days in any 12-month period (EPA, 2011). Concentrated animal feeding operations (CAFOs) are AFOs that meet certain size thresholds, based on the number of animals in the facility. For example, in broiler production, a facility with more than 125,000 birds is defined as a large CAFO (EPA, 2001). Waste generated by AFOs is typically stored on the site and applied to surrounding farmland. As a result, AFOs may be subject to Federal regulations such as the National Pollutant Discharge Elimination System (NPDES), which regulates the discharge of pollutants from point sources to waters of the U.S. (EPA, 2011). There are also State regulations, such as the Virginia Pollution Abatement (VPA) Permit Regulation Program, which govern the management and handling of waste from AFOs at the state level. A separate VPA general permit covers poultry waste management from operations that confine more than 20,000 chickens or 11,000 turkeys (VDEQ, 2012).

Broilers are raised in batches where day old chicks are placed in an empty building and grown to market weight (NCC, 2012). The barn floor is covered with bedding as part of manure management. The combination of the manure, feathers, spilled feed and bedding material is known as litter. The U.S. Egg and Poultry Association (2012) estimates that total litter production for a typical broiler chicken at 47 days of age is approximately 1 kg. Broiler litter has historically been applied to cropland for use as fertilizer (Shah et al., 2012). However, the high price of new bedding materials and the increasing scarcity of cropland for litter application mean that litter is reused, especially when flocks are free of infectious disease (Shah et al., 2012). Only the crust or caked litter is removed between flocks and whole house cleanouts are done less frequently (Shah et al., 2012). Litter reuse results in buildup of ammonia, which is produced by mineralization of manure in the litter. Annual ammonia emissions from U.S. broiler production are approximately 2.9×10^9 kg (Gates et al., 2008). Ammonia produced from AFOs has adverse effects on animal welfare, the environment and human health (Beker et al., 2004; Barthelmie and Pryor, 1998; Jaworski et al., 1997; Kim et al., 2005).

Litter amendments are used to control the generation and emission of ammonia from reused litter. Commercially available products, including sodium bisulfate (PLT^{TM}), granulated sulfuric acid (Poultry Guard^{TM}) and aluminum sulfate (Alum^{+} Clear^{TM}), are made using strong inorganic acids and are corrosive to structures and may be harmful to handlers (Shah, 2012). However, organic litter amendments, such as acetic acid (Roach et al., 2009) and Litter Life^{TM} (HRC, 2013), which are not as corrosive or toxic as inorganic acids have also been used successfully to reduce house ammonia concentrations and improve bird performance. Agblevor et al. (2008) produced a biodegradable litter amendment (BLA) from corn cobs, which effectively reduced ammonia emitted from broiler litter in laboratory tests, but has not been tested in poultry production houses.

Quantification of ammonia emitted from AFOs is important for evaluating mitigation technologies and, if necessary, for formulation and enforcement of regulations for pollution control. Variations in ammonia emitted from each broiler house necessitate continuous monitoring of building ventilation rate and ammonia concentration for reliable quantification, which is expensive and not always feasible (Gates et al., 2002). Models can provide alternatives to direct measurements for determining the amount of ammonia emitted to the atmosphere under varying conditions.

Objectives of the study

The overall objective of this study was to assess the suitability of BLA for mitigation of ammonia emitted from broiler houses. The specific objectives were to:

i. determine the effectiveness of BLA in reducing ammonia emitted from a broiler house

   H_o: The amount of ammonia emitted from broiler houses with BLA-treated and untreated litter is the same.

   H_1: The amount of ammonia emitted from broiler houses with BLA-treated litter is less than that emitted from houses with untreated litter.

ii. determine the effects of using BLA to control ammonia emissions on bird weight, feed conversion, development of footpad dermatitis and litter characteristics.

   H_o: Using BLA to control ammonia emissions has no effect on bird weight, feed conversion, development of footpad dermatitis and litter characteristics

H_1: Using BLA to control ammonia emissions increases bird weight and feed efficiency and reduces development of footpad dermatitis

iii. develop empirical models to estimate ammonia emitted from broiler houses based on ammonia flux from litter treated with BLA and untreated broiler litter.

H_o: Ammonia flux from broiler litter is not affected by air temperature and ventilation rate.

H_1: Ammonia flux from broiler litter increases with air temperature and ventilation rate.

CHAPTER 2: LITERATURE REVIEW

The nitrogen cycle and sources of ammonia in the environment

Nitrogen (N) is an important component of DNA and protein and is therefore required by all living organisms (NAE, 2012). The N cycle (Figure 2-1), shows the movement of different forms of N in the atmosphere.

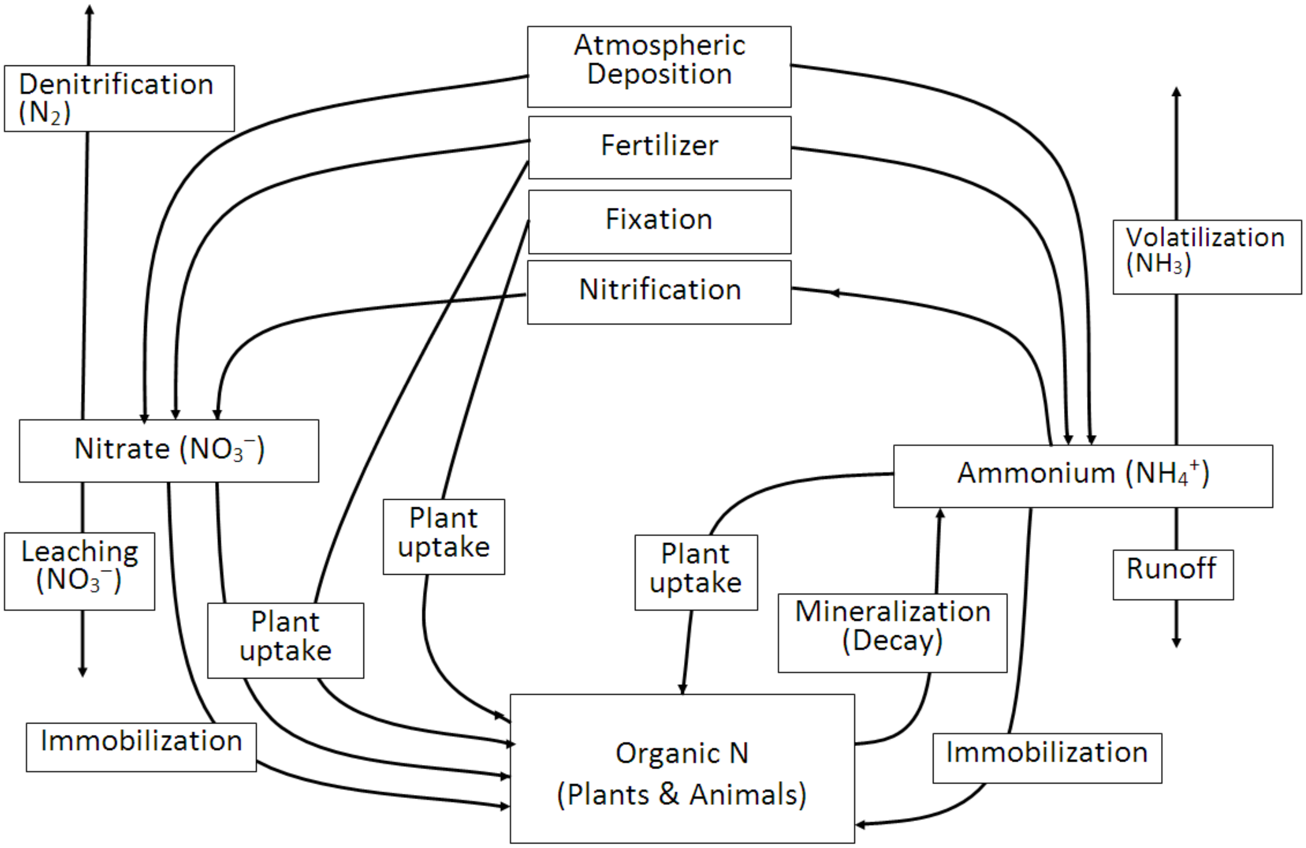


Figure 2-1: **The nitrogen cycle (adapted from U.S. Dept. of Interior - National Parks Service, http://www.nps.gov/plants/restore/pubs/biosolids/img/biosolids14.jpg)**

The N cycle shows the storage pools for N and the processes by which it is exchanged between the pools. Nitrogen cycling is important in food production because it links the earth and various forms of life as plants extract N from the environment to make food (NAE, 2012). In the biosphere, N is converted from one form to another through five main processes; fixation, uptake, mineralization, nitrification and denitrification. Microorganisms play a major role in all these processes and the rate of N transformation is dependent on factors that affect microbial growth such as temperature moisture and pH (NAE, 2012).

Dinitrogen gas (N_2) is a major component that makes up almost 80% of air. However, this form of N is not readily available for use by living organisms. Fixation can occur when microorganisms attain N_2 directly from the atmosphere and convert it to NH_4^+ or during natural events such as lightning, forest fires and volcanic eruptions (NAE, 2012). During fixation, the triple bond between N_2 is broken, making the individual atoms available for chemical reactions. The NH_4^+ produced during fixation is incorporated into protein and other forms of organic nitrogen through uptake by plants and animals. When plants and animals decay, a significant amount of organic N in the dead organism is converted to NH_4^+ through mineralization. In the presence of an oxygen-rich environment, nitrification occurs and NH_4^+ is converted to NO_3^-. However, in the absence of oxygen, denitrification occurs and NO_3^- is converted to nitrous oxide (N_2O) and N_2. This is of significance because N_2O is a greenhouse gas (NAE, 2012), which reacts with and depletes the ozone layer and contributes to global warming (Lashof and Ahuja, 1990).

The development and rapid adoption of inorganic fertilizers in the early 20th century led to an enormous boom in agricultural productivity, which was crucial for feeding the world's growing population (NAE, 2012). However, not all N applied to the soil is taken up by plants. Free NO_3^- ions from the fertilizer can be washed down the soil profile by water from irrigation or rain (leaching) and may accumulate in surface and ground water bodies. The U.S. Environmental Protection Agency (EPA) established a 10 mg NO_3- N/L drinking water standard because of health problems such as hypertension, increased infant mortality, birth defects, diabetes, spontaneous abortions, respiratory tract infections, and changes to the immune system (CDC, 1996; Dorsch et al., 1984; Gupta et al., 2000; Hill 1999) that have been linked to elevated concentrations of NO_3^- in drinking water. Nitrate concentrations rarely exceed 1 mg NO_3- N/L in water that has not been affected by human activity (NAE, 2012). However, many coastal waters that receive water from polluted rivers usually exceed the 10 mg/L standard (NAE, 2012). The accumulation of N in surface water leads to algal blooms, fish kills and loss of biodiversity (NAE, 2012).

Structure and management of commercial broiler houses

Typical space requirements for broilers range from 0.07 to 0.09 m^2 per bird (NCC, 2012b). In general, commercial broiler houses are about 12.5 m wide with variable lengths depending on the number of birds raised on a farm. For example, a broiler house with an area of 1500 m^2 has a length of 120 m and accommodates approximately 20,000 birds at a density of 0.07 m^2 per bird (Fairchild, 2005). Broiler houses require proper design and environmental control systems to ensure that appropriate temperature, relative humidity (RH) and air quality are maintained throughout the growth cycle, regardless of outdoor conditions (Dozier et al., 2005). The trend is towards tunnel ventilation, where the house has exhaust fans at one end and air inlets on the other (Bucklin et al., 2009). When running, the fans create a lower pressure inside the building, which forces air from the exterior through the openings at the opposite end. The air velocities are approximately 1.8 to 2.3 m/s and can cause a drop in house temperature of up to 5.5^oC depending on incoming air temperature (Bucklin et al., 2009). The effectiveness of heat removal decreases with increasing outdoor air temperature, but tunnel ventilation systems can still produce adequate cooling when outdoor temperature increases beyond 32^{o}C (Bucklin et al., 2009). The drawbacks of tunnel ventilation include the requirement for several exhaust fans, the need for a separate ventilation system during cold weather, and the inability to reduce house temperatures to below outdoor, which necessitates a separate cooling system when temperatures exceed 35 ^{o}C (Donald, 2012). Evaporative coolers, which use energy from the air to evaporate water and cool the air in the process, are typically used (Bucklin et al., 2009).

The objective of house management is to provide an environment that maximizes flock performance to achieve optimum growth rate and feed efficiency without compromising bird welfare or increasing the cost of production (REM, 2010). Providing optimum temperature together with adequate feed and water maximizes bird performance. The target temperature for best broiler performance changes with bird age, typically around 31°C on the first day and approximately 20°C or less at 42 days (REM, 2010). Temperature control during the brooding phase is especially important because chilling, even for a small amount of time can adversely affect bird performance. For example, exposing day-old chicks to an air temperature of 13°C for only 45 minutes can reduce 35 day weights by about 110 grams (REM, 2010). However, bird performance in later stages of the flock is more adversely affected by elevated temperature. Therefore, supplemental heating systems, which are usually required during the brooding period, may not be necessary for other phases of the flock depending on outdoor conditions.

The ideal range for relative humidity (RH) in broiler houses is 60% to 70% (REM, 2010). If RH falls outside this range, then the temperature of the house at bird level should be adjusted. For example, the dry bulb temperature on the first day may be increased from 30 to 33°C if RH in the house is closer to 50% (REM, 2010). Relative humidity above 70% results in buildup of moisture, creating wet and caked litter and, consequently, air quality problems such as ammonia pollution, which can affect bird health (REM, 2010). Adequate ventilation is the most important tool for managing the house environment. Ventilation controls air quality inside broiler houses by providing a continuous flow of air. The static pressure in broiler houses is typically maintained at 12.5 to 25 Pa to keep the inlet air velocity between 3 and 6 m/s to promote good air mixing (Ritz et al., 2004).

Broiler house ventilation rate is adjusted depending on outdoor conditions and bird age to remove heat and moisture, dust and odor, and prevent buildup of ammonia and other harmful gases, and maintain an optimum environment (EPA, 2001). Proper ventilation is especially crucial for removing heat during summer, when a typical flock of 25,000 birds weighing 1.8 kg can produce more than 10^6 Joules of heat per hour (Bucklin et al., 2009). During winter, the main function of ventilation is moisture control when a typical flock of 25,000 birds weighing 1.8 kg can produce more than 150 L of moisture per hour (Bucklin et al., 2009). Supplemental heat is usually supplied to the house to facilitate moisture removal but this is not sustainable during cold weather because of energy costs (Bucklin et al., 2009). During winter a timer is used to control the operation of the exhaust fans to control of indoor air quality (Bucklin et al., 2009).

Commercial broilers are raised on litter, which is reused for several flocks due to economic factors (Coufal et al., 2006). Reusing litter creates management problems related to controlling litter moisture and house ammonia concentration, which can have adverse effects on flock performance (feed efficiency and weight gain). Reused litter is usually top-dressed with a light layer of new bedding between flocks. However, birds grown on litter that is not top-dressed have been reported to do as well as those grown on top-dressed litter (Ritz et al., 2004). The heat produced in reused litter as bacteria degrade organic material can keep floors warmer during brooding, and can be beneficial to bird performance (Ritz et al., 2004). However, adequate house preparation between flocks is required to release ammonia that is trapped in reused litter (Ritz et al., 2004). Heating and ventilating the house for at least 24 hours prior to chick placement is necessary to minimize ammonia release from the litter during brooding (Ritz et al., 2004). Pre-heating the broiler house provides the required temperature and facilitates ammonia removal prior chick placement (Ritz et al., 2004). This is important because baby chicks do not have the ability to regulate their own body temperature and will readily lose heat to their surroundings (HHI, 2013). Chicks that are allowed to cool off in the early days of life will have stunted growth, lower feed efficiency and increased mortality (HHI, 2013).

Formation of ammonia in broiler houses

Broiler manure contains about 1% N as excreted (ASABE, 2010) and approximately 26% N on a dry weight basis (Bolan, 2010). About 50% of N in broiler manure is uric acid ($C_5H_4N_4O_3$), which can be converted to ammonia through mineralization (Ritz et al., 2004):

$$C_5H_4N_4O_3 + 1.5O_2 + 4H_2O \longrightarrow 4NH_3 + 5CO_2 \qquad 2\text{-}1$$

Mineralization involves a series of biological and chemical processes that may depend on diet, manure handling and environmental conditions, and occurs in a series of steps mediated by the action of microbial enzymes as shown in Figure 2-2 (Klemperer, 1945). Hydrolysis of uric acid is the first step in the production of ammonia from poultry manure. During hydrolysis, diureine carboxylic acid, a very unstable compound, is formed, which breaks down to urocanic acid or allantoin depending on pH (Klemperer, 1945). Allantoin is broken down to urea and glyoxalic acid, and the urea is further broken down to ammonia and carbon dioxide (Klemperer, 1945). The entire process of mineralization occurs rapidly (within hours) and conversion is usually complete in a few days (Muck, 1982; Sommer and Olsen, 1991).

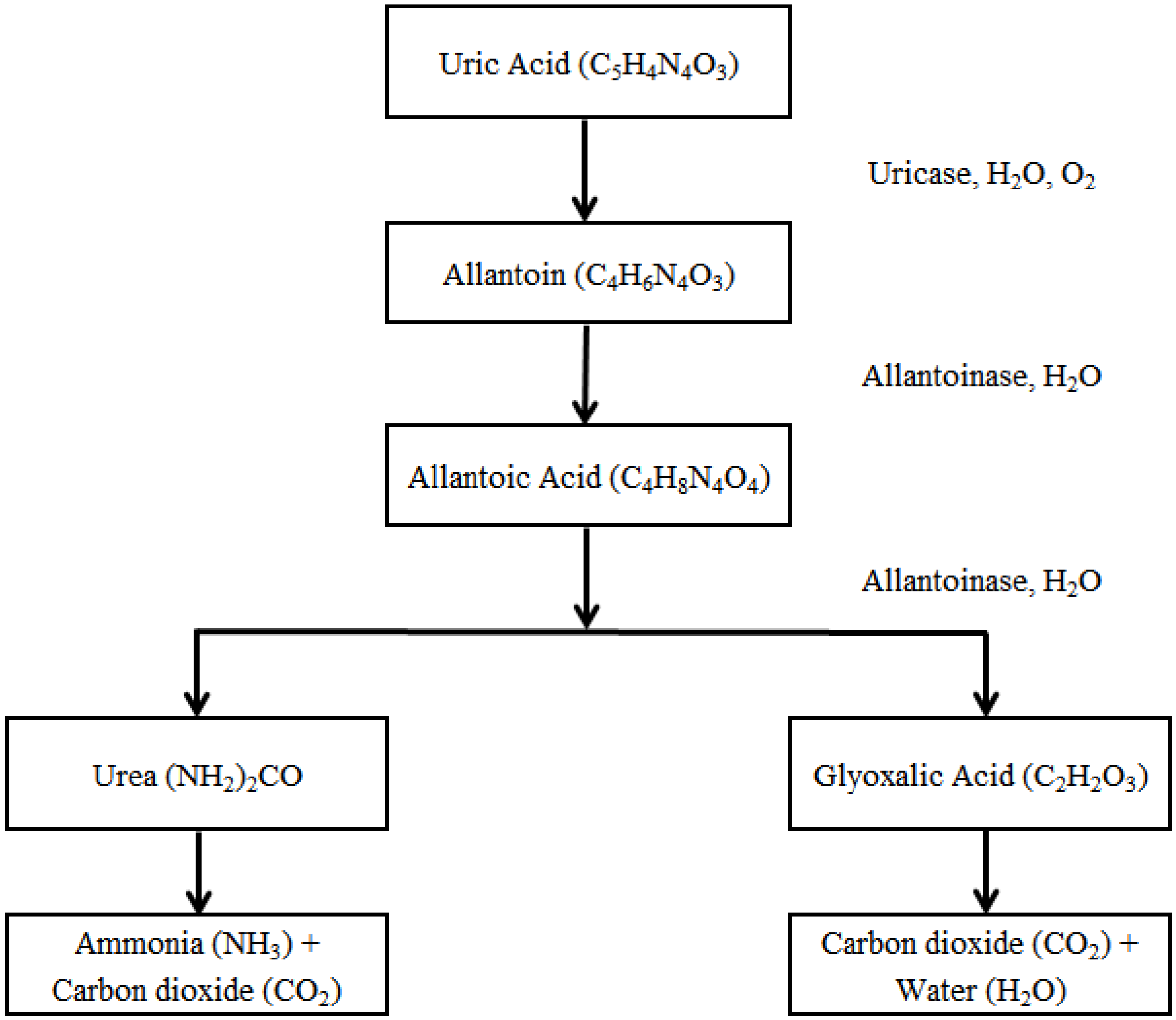


Figure 2-2: Mineralization of uric acid to ammonia (adapted from Klemperer, 1945)

Uricolytic and ureolytic bacterial species are responsible for degradation of uric acid in poultry manure to produce ammonia (Rothrock et al., 2010; Rothrock et al., 2006). The major enzymes that catalyze this process are urease and uricase (Machida and Nakanishi, 1980). Uricase is active during the initial step in the conversion of uric acid to ammonia, while urease catalyzes the final step (Rothrock et al., 2010; Rothrock et al., 2006). Enzyme activity depends on substrate availability, temperature and pH. The optimum activity for uricase occurs at 45^oC and pH 9.5 (Bongaerts and Vogels 1979). Machida and Nakanishi (1980) reported that uricase activity increased with temperature between 20^oC and 45^oC, reaching a maximum at 45^oC. They also observed that enzyme activity was low below pH 7 and above pH 10.

Chemistry of ammonia

Ammonia exists in three forms: salt - NH_4^+, gas - NH_3 (g) and dissolved in aqueous solution - NH_3 (aq). The ammonia formed in poultry manure exists in the salt [$NH_4^+{}_{(aq)}$] or un-dissociated [$NH_{3\,(aq)}$] forms (Srinath and Loehr, 1974). The three ammonia species can exist in equilibrium as defined by equations 2-2 and 2-3.

$$NH_4^+{}_{(aq)} \longleftrightarrow NH_{3\,(aq)} + H^+_{(aq)} \qquad 2\text{-}2$$

$$NH_{3\,(aq)} \longleftrightarrow NH_{3\,(g)} \qquad 2\text{-}3$$

The concentrations of the dissolved species depend on the pH of the solution and are governed by the acid ionization constant, K_a (Srinath and Loehr, 1974). The abundance of H^+ at low pH causes the reaction in equation 2-2 to proceed to the left to maintain the equilibrium (Srinath and Loehr, 1974). However, as pH increases, the reaction described by equation 2-3 proceeds to the right and gaseous ammonia is released from the litter (Srinath and Loehr, 1974). Assuming the activity coefficients of the species in equation 2-2 are equal to unity, K_a can be expressed as follows (Srinath and Loehr, 1974):

$$K_a = \frac{\left[NH_{3(aq)}\right]\left[H^+_{(aq)}\right]}{\left[NH^+_{4\,(aq)}\right]} \qquad 2\text{-}4$$

where

K_a = acid ionization constant

$[NH_4^+{}_{(aq)}]$ = concentration of ammonium species in solution

$[NH_{3(aq)}]$ = concentration of ammonia species in solution

$[H_4^+{}_{(aq)}]$ = concentration of hydrogen ions in solution

The concentration of $NH_{3\,(aq)}$ represents the maximum amount of ammonia that can be emitted from solution (Srinath and Loehr, 1974). However, direct measurement of the free ammonia $[NH_{3\,(aq)}]$ concentration in solution is not possible; the measurable quantity, which is used in ammonia emission studies, is the total ammonia concentration (TAN), $[NH_{3\,(aq)}] + [NH_4^+{}_{(aq)}]$ (Srinath and Loehr, 1974). Ammonia chemistry shows that the pH of the solution determines the amount of free ammonia present for a given TAN concentration. Using the relationship between $NH_{3\,(aq)}$ and $NH_4^+{}_{(aq)}$ during equilibrium (equation 2-2), the relationship between pH, K_a and TAN concentration is defined (Srinath and Loehr, 1974) as:

$$pH = pK_a + \log\left(\frac{\alpha\, C_{T,\ NH_3}}{(1-\alpha)\, C_{T,\ NH_3}}\right) \qquad 2\text{-}5$$

where

$C_{T, NH3}$ = total ammonia nitrogen (TAN) in solution and

α = fraction of $NH_{3\,(aq)}$ in solution

K_a = ionization constant for ammonia

p = - $\log_{10}$

Equation 2-5 can be simplified to yield the fraction of free ammonia in solution (α) which can then be used to determine the concentration of $NH_{3\,(aq)}$ (Srinath and Loehr, 1974) as:

$$\alpha = \frac{10^{(\mathrm{pH} - \mathrm{pK_a})}}{10^{(\mathrm{pH} - \mathrm{pK_a})} + 1} \qquad 2\text{-}6$$

The value of the dissociation constant, K_a depends on temperature. Equation 2-7, derived by Jayaweera and Mikkeson (1990), is commonly used to express K_a as a function of temperature. It is based on Van't Hoff's equation for determining the effect of temperature on the position of equilibrium.

$$\mathrm{K_a} = 10^{-\left(0.0897 + \frac{2729}{\mathrm{T}}\right)} \qquad 2\text{-}7$$

Using equation 2-6, it can be shown that the fraction of free ammonia (α) increases with increasing pH; consequently, ammonia emission from solution is enhanced at higher pH (Srinath and Loehr, 1974).

Factors affecting ammonia volatilization

Ammonia volatilization is the release of $NH_{3\ (g)}$ from a source where it is formed to the surroundings. Aerobic conditions and values of air temperature, litter temperature, pH, litter age and moisture content that favor bacterial growth, enhance ammonia volatilization.

Aerobic conditions

Mineralization of uric acid is more rapid under aerobic conditions. Kirchmann and Witter (1989) investigated ammonia volatilization from decomposing poultry manure with 0.28% TAN by weight under aerobic conditions by supplying air from the atmosphere at 30 mL/hr per gram and reported that up to 25% of the total N was lost in the first 7 weeks. Mahimairaja et al. (1994) observed rapid increase in pH and 17% loss of total N after 48 days during decomposition of poultry manure under aerobic conditions at $25^{o}C$; N loss from manure under anaerobic conditions was almost 95% less compared to aerobic conditions.

Air temperature

Air temperature affects the gas phase vapor pressure and the ability of the substance to volatilize. The vapor pressure of a substance increases with increasing temperature (Denmead, 1982). The higher temperatures (30 to 33 ^{o}C) required during brooding have been linked to elevated ammonia concentrations in broiler houses (Fairchild, 2012). Al Homidan (2004) raised two sets of broilers starting at $35^{o}C$ and gradually lowered the temperature every two days to final temperatures of $28^{o}C$ and $21^{o}C$. At the end of the grow-out period (5 to 6 weeks), the ammonia concentration in the room at $28^{o}C$ was significantly higher compared to the room at $21^{o}C$, which he attributed to the difference in temperature between the two rooms.

Litter temperature

The generation and volatilization of ammonia from broiler litter increases with litter temperature (Miles et al., 2011). Litter temperatures between 30^{o}C and 40^{o}C are the most favorable for bacterial growth and conversion of uric acid to ammonia (Al Homidan, 2003). Liu et al. (2008) reported that ammonia release from broiler litter increased with increasing litter temperature between 15^{o}C and 25^{o}C but was more sensitive to changes in air flow at 15^{o}C compared to 25^{o}C.

While studying the emission of different gaseous pollutants from broiler houses over 28 flocks of broilers grown on reused litter, Miles et al. (2006) observed that ammonia flux was most affected by litter temperature and was greatest in the brood area on the first day of the flock. Miles et al. (2011) reported that ammonia generation increased with litter temperature between 18.3°C and 40.6°C and that the maximum ammonia generated at 40.6°C was up to 7 times greater than at 18.3°C.

Ammonia emission generally increases with source temperature at constant air flow, as observed in studies by Arogo et al. (1999) on liquid manure and aqueous ammonia at temperatures between 15^{o}C and 35^{o}C and air velocities between 0.1 and 0.3 m/s. This is because the diffusivity of solutes in liquids increases with liquid temperature, which results in a corresponding increase in mass transfer rate (Arogo et al., 1999). The solubility of ammonia in water also decreases with increasing temperature resulting in a larger mass transfer rate (Dutta, 2007).

pH

Ammonia volatilization is highly dependent on pH because it controls the fraction of the ammonia species present in solution. The dependence of the NH_4^+/NH_3 equilibrium on pH is shown in Figure 2-3. Under acidic conditions, $NH_{3\,(aq)}$ reacts with H^+ to form $NH_4^+{}_{(aq)}$; and $NH_4^+{}_{(aq)}$ dissociates to $NH_{3(aq)}$ under basic conditions. The fraction of free ammonia (α) relative to the total ammonia nitrogen (TAN) in solution can be calculated for any given pH and temperature combination using equation 2-6. As shown in Figure 2-3, α increases with pH and temperature from zero at 15°C and pH 6.0 to about 50 percent at pH 8.0 and approximately 90 percent just above pH 9.0. The activity of $NH_{3\,(aq)}$ decreases with temperature meaning that at low temperatures and low pH the volatilization of ammonia is limited. Figure 2-3 suggests that volatilization of ammonia from litter would be negligible below pH 7 because nearly all the ammonia exists in the non-volatile ammonium form.

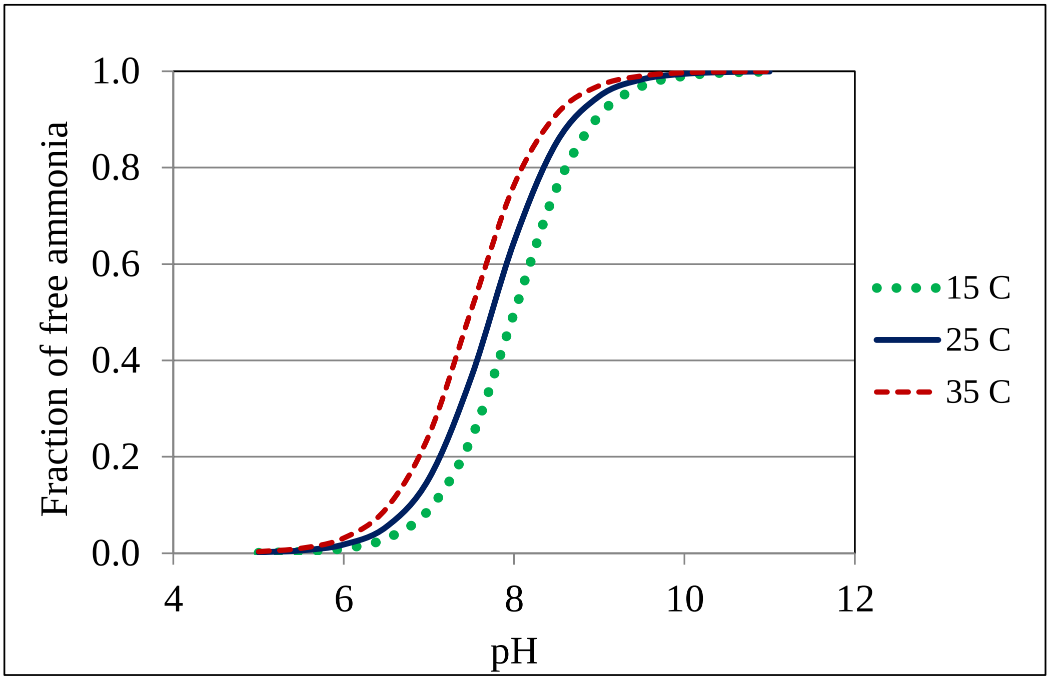


Figure 2-3: Fraction of ammonia species as a function of temperature and pH

The activity of uricase and mineralization are inhibited at low pH. Degradation of uric acid and undigested protein in poultry manure increases rapidly after pH 5.5 and reaches a maximum at pH 9.0, which is the optimum value for the activity of uricase enzyme (Burnett and Dondero, 1969). Reece et al. (1979) also reported that volatilization of ammonia increased significantly above pH 7, which is not surprising since less than 7% of the TAN is in the form of NH_3 over the range of temperatures likely for field conditions at pH 7.5 (Weast et al., 1988).

Litter age

Due to the expense associated with procuring new bedding materials and the difficulty of handling and disposing of used litter, litter reuse is common in commercial broiler production (Ritz et al., 2004). Growing broilers on built-up litter provides considerable management challenges for ammonia mitigation because microbial activity increases with substrate availability as the litter ages, enhancing formation and volatilization of ammonia. The ability to control litter moisture and ammonia emission are valid concerns with built-up litter, and the challenge of maintaining optimal in-house environment intensifies each time another flock is grown on the same litter (Ritz et al., 2004). Litter pH increases with use, age and number of flocks grown (Elliott and Collins, 1982). Knížatová et al. (2010) monitored ammonia emissions from a commercial broiler house over six flocks of birds grown on built-up litter and observed an overall increase (40%) in ammonia emissions.

Litter N concentration

The amount of ammonia formed in broiler houses depends on the quantity and the N concentration of the manure produced by the birds. Over the grow-out period of 6 to 7 weeks, a broiler can produce approximately 1.2 kg of manure with approximately 1% N as excreted (ASABE, 2010). Kelleher et al. (2002) reported that up to 90% of all N in the manure could be converted to ammonia. Litter N and ammonia loss from the litter significantly increase with litter age (Coufal, 2005; Malone, 1998). Based on samples from six flocks grown on the same litter, Malone (1998) estimated that nutrients accumulate at a rate of 1% and 3% per flock for N and phosphorus (P), respectively. Coufal (2005) observed that during summer conditions, N retention for litter that had been reused for several flocks was lower than for new litter. Coufal (2005) also suggested older litter may retain more N than newer litter during cooler weather and attributed this to reduced microbial activity and decreased NH_3 emission from the litter. Accumulation of N that occurs with litter reuse increases the potential for elevated ammonia concentrations in broiler houses and, subsequently, ammonia emitted to the atmosphere. Ammonia emitted from reused litter can be up to six times higher than new litter at the start of the grow-out (Brewer and Costello, 1999). Coufal et al. (2006) observed that the average nitrogen emission rate during the production of 18 flocks of broilers on recycled litter ranged between 4.13 and 19.74 grams per kilogram of marketed broiler weight (g N/kg) and increased with litter reuse.

Ventilation rate

Ammonia mass transfer from broiler litter increases with ventilation rate (VR). This is because the thickness of the boundary layer (between liquid and gas phases) decreases with increasing air flow over the litter surface, which results in higher mass release rate (Arogo et al., 1999). Liu et al. (2008) reported that ammonia release from broiler litter increased with increasing air velocity above the litter surface between 0.05 and 2.0 m/s. Nimmermark and Gustafsson (2005) reported that increasing ventilation rate from 1.04 m^3/hr per bird to 2.85 m^3/hr per bird decreased exhaust ammonia concentration from 12.5 mg/m^3 to 3.3 mg/m^3. However, increasing VR also increases the amount of ammonia emitted to the atmosphere (Kavolelis, 2003). Zhang et al. (2008) studied the effect of ventilation control strategies on ammonia emissions and reported that the amount of ammonia released increased with increasing airflow. Ye et al. (2008) observed that ammonia emission rate (ER) increased 2.9 times from 0.052 to 0.152 mg/s-m^2 when VR increased 10 times from 0.002 to 0.020

m^3/s. Rachhpal-Singh and Nye (1986) also observed that the mass transfer coefficient of ammonia increased with increasing air velocity over the emission surface. Turbulence increases with VR and also increases the rate of ammonia mass transfer (Liu et al., 2008). Liu et al. (2008) and Rong et al. (2009) reported that the ammonia mass transfer coefficient increased with increasing air velocity under turbulent flow conditions.

Litter moisture content

The conversion of uric acid to ammonium may be affected by litter moisture content because water is required for the hydrolysis reaction shown in equation 2-8 (Sims and Wolf, 1994).

$$C_5H_4N_4O_3 + O_2 + H_2O \longrightarrow C_4H_6N_4O_3 + CO_2 + H_2O_2 \qquad \text{2-8}$$

Hydrolysis proceeds rapidly under warm, moist conditions with urea being transformed to ammonium in a few days (Sahrawat, 1981). The activity of uricase increases with moisture content and keeping litter moisture content below 30% can be effective for ammonia control (Carr et al., 1990). Yadav et al. (1987) stated that hydrolysis increased (non-linearly) with moisture content between the ranges of 20% to 80% of field capacity. However, increasing moisture content beyond 50% field capacity had no further effect on the activity of uricase (Yadav et al., 1987).

In a laboratory study on ammonia emissions from broiler litter, Liu et al. (2008) observed that litter TAN concentration and ammonia release from the litter increased with litter moisture content. Miles et al. (2011) tested ammonia emissions using litter from commercial broiler houses with 20% to 55% moisture content at temperatures between 18.3°C and 40.6°C. They observed that the amount of ammonia emitted increased with litter moisture content up to a critical level between

37.41% and 51.1% depending on the temperature, above which ammonia emissions from the litter reduced.

McGarry et al. (1987) observed the effect of moisture on ammonia volatilization from urea treated pasture and noted that simulation of rainfall greatly reduced ammonia volatilization. They reported that ammonia emissions were lowest for flooded soils and determined that below the permanent wilting point, urea hydrolysis decreased with decreasing moisture content. They concluded that ammonia volatilization could not occur under warm, dry conditions or cool, wet conditions.

Studies that detail the relationship between water content and ammonia volatilization from poultry litter are sometimes contradictory. For instance, Elliott and Collins (1982) developed a model that predicted that increasing moisture content would decrease ammonia production in the first week with reused litter. The model also predicted higher ammonia emissions for litter with 15% moisture than that with 35% moisture content, which was in agreement with observations by Valentine (1964) that excessively wet litter does not support volatilization of ammonia. Elliot and Collins (1982) further stated that wet litter is associated with high ammonia concentrations in broiler houses but lack of oxygen under very wet conditions may inhibit microbial activity. However, Ernst and Massey (1960) could not establish a direct correlation between ammonia volatilization and moisture content. Turnbull and Snoeyenbos (1973) advised that when litter became too dry, there was insufficient moisture for microbial activity and hydrolysis of urea, while Ritz et al. (2006) stated that very dry litter results in dust and particulates that may transport ammonia.

Diet

Up to two-thirds of the N consumed by broilers may be excreted and can be converted to ammonia (Ritz et al., 2004). The large amount of N in broiler manure is due feed formulation, which is typically based on total amino acid content, yet certain crystalline amino acids including cystine, tryptophan and threonine are necessary to meet the total requirements of the broilers (Nahm, 2007). The unbalanced ratios of amino acids in the grains used to formulate the feed causes an over consumption of the abundantly present, non-essential amino acids in order to meet the minimum requirements for essential amino acids (Ritz et al., 2004).

High concentrations of sodium in the feed increase water consumption, which can lead to excessively wet litter (De Jong and Van Harn, 2012). Litter quality may also be impacted by feed with low digestibility and high fiber content, which can affect gut integrity and excreta characteristics (De Jong and Van Harn, 2012).

Effects of ammonia on broiler health

Young chicks are especially susceptible to elevated ammonia concentrations due to their rapid growth and high metabolic requirements (Reece et al. 1980). The first 28 days of the growth cycle are critical, and ammonia concentrations in excess of 34 mg/m^3 may have a severe impact on bird growth rates and feed conversion (Reece et al. 1980). House ammonia concentrations above 15 mg/m^3 have been linked to lower weight gains; decreased feed efficiency and ocular damage (Carlile, 1984; Miles et al., 2004; Shah et al., 2012). Beker et al. (2004) observed increased feed to weight gain ratio at 41 mg/m^3, while Kling and Quarles (1974) reported that birds growing in an ammonia free environment had higher body weight and higher feed efficiency than those exposed to 17 mg/m^3 ammonia. Caveny et al. (1981) reported that exposure to 17 mg/m^3 for 42 days resulted in decreased feed efficiency. Continuous exposure to 13 mg/m^3 of ammonia increases susceptibility to Newcastle disease (Moum et al., 1969) and may increase the severity of coccidiosis (Quarles and Caveny, 1979). Anderson et al. (1964) showed that ammonia compromised the immune system of chickens and caused damage to the respiratory system at concentrations as low as 13 mg/m^3.

Long term exposure to ammonia causes changes in the liver and spleen of the birds (Moum et al., 1969). At a concentration of 69.5 mg/m^3, there is vaccination stress (Kling and Quarles, 1974) and an increase in blood pH, which causes the brain to decrease ventilation rate (Carlile, 1984). Between 41 and 48 mg/m^3, birds are predisposed to viral and bacterial respiratory diseases, secondary infections and increased mortality (Valentine et al., 1964; Kling and Quarles, 1974; Chang and Flint, 1976; Carlile, 1984). At concentrations between 39 and 69 mg/m^3, there are changes in the respiratory system including loss of cilia and increased production of mucus secreting cells, which predisposes the bird to bacterial and viral respiratory diseases and increased mortality (Al-Mashhadani and Beck, 1985).

Ammonia may cause eye damage because it is water-soluble and can dissolve in the moisture on mucus membranes and eyes (IPCS, 1986). This can lead to keratoconjunctivitis and even blindness due to exposure to 31 to 71 mg/m^3 (Carr and Nicholson, 1990). Birds affected by keratoconjunctivitis huddle in groups, rub eyes with their wings and their eyes may become sensitive to light (Bullis et al., 1950). These birds may have difficulty locating food, resulting in decreased body weight (Ritz et al., 2004). Other problems related to ammonia exposure include increase in breast blisters and delay in reaching sexual maturity (Charles and Payne, 1966). Birds grown on reused litter may be susceptible to the harmful effects of ammonia during the first few days when temperatures are high and ventilation rates are low, since these birds could be exposed to ammonia concentrations in excess of 348 mg/m^3 (Carlile, 1984).

Effects of ammonia on the environment

Ammonia is a precursor for particulate matter ($PM_{2.5}$), which is a regulated air pollutant (Lester, 2007). The residence time of ammonia in the atmosphere is about 30 days (Tsunogai and Ikeuchi, 1968). In the atmosphere, ammonia reacts with acidic species to form ammonium sulfate, nitrate and chloride particulates as shown in equations 2-9, 2-10 and 2-11, respectively. Particulate matter can be transported over large areas and affects regional environmental quality by forming hazy conditions and reducing visibility (Barthelmie and Pryor, 1998).

$$2NH_3 + H_2SO_4 \longrightarrow (NH_4)_2SO_4 \qquad 2\text{-}9$$

$$NH_3 + HNO_3 \longrightarrow NH_4NO_3 \qquad 2\text{-}10$$

$$NH_3 + HCl \longrightarrow NH_4Cl \qquad 2\text{-}11$$

Deposition of ammonium salts can result in soil acidity; although this source of acidity is generally less significant than wet and dry deposition of free acids (Van Breemen et al., 1982). Ammonium salts on the surfaces of vegetation are present as sulfates or nitrates, formed by reaction of ammonia volatilized from animal manure with sulfur dioxide and oxides of nitrogen from burning of fossil fuels (van Breemen et al., 1982). The environmental consequences of deposition of ammonium salts are most significant in areas with intensive AFOs (van Breemen et al., 1982). Ammonium and nitrate ions present in surface water and soils can enter the atmosphere as smog (NO and N_2O), which can cause excessive growth of algae and loss of biodiversity if blown to N sensitive environments (Paerl, 1997). Nitrous oxides are also responsible for a significant portion of the acidity in acid rain, which has caused destruction of forests in Europe and the northeastern United States (Paerl, 1997).

Eutrophication is a natural, slow-aging process for water bodies as the concentration of nutrients, especially phosphates and nitrates increase (Nolan and Ruddy, 1996). However, excessive input of nutrients to water bodies promotes rapid growth of algae. The high concentrations of organic matter created as the algae die and decompose deplete the water of oxygen and cause the death of fish and other aquatic organisms. Atmospheric deposition of nitrate and ammonia species has been identified as a major factor in the decline of water quality in the Chesapeake Bay (Jaworski et al., 1997).

In areas of intensive broiler production, litter is applied to agricultural land to supply N for crop requirements. Ammonia emitted from the litter represents N loss, which decreases its N to P ratio and fertilizer value. Using this type of manure for fertilizer leads to application of P in surplus of crop requirements (Sims, 1998). As concentrations of P in the soil increase, so does the amount of dissolved P in water that passes over or through the soils, and can cause major nonpoint source pollution problems in surface and ground waters (Maguire and Sims, 2002).

Effects of ammonia on human health

The reported effects of ammonia on human health include irritation of the eyes, nose and throat with exposure to concentrations between 20 and 35 mg/m^3 (Ferguson et al., 1977). Exposure to higher concentrations can cause burns in the respiratory tract, which result in respiratory distress or failure, and concentrations greater than 3476 mg/m^3 can be lethal (Pedersen and Selig, 1989). The odor from ammonia provides warning of its presence but prolonged exposure may cause olfactory fatigue or adaptation, reducing awareness of its presence at low concentrations (Pedersen and Selig, 1989). Children exposed to the same concentrations of air pollutants as adults may receive a larger dose because they have greater lung surface area-to-body weight ratio (Asgharian et al., 2004). They may also be exposed to higher concentrations of pollutants from sources near the ground because they are shorter than adults (Cooper and Harrison, 2009).

Airborne particulate matter (PM), which is formed when ammonia reacts with acid gases, poses potential health risks to various groups. Inhaled particles that are not filtered out by the nose or mouth can be deposited in different areas of the lungs, where they are absorbed or cleared by different biological mechanisms (Kim et al., 2005). The quantity of PM delivered to the lungs depends on particle characteristics and physiological factors such as lung structure (Asgharian et al., 2003). Adverse effects associated with PM exposure include chronic cough, bronchitis and chest illness (Asgharian et al., 2003). Children are more susceptible to the effects of airborne particulate matter (PM) (Kim et al., 2005); and those with a history of asthma living in areas with high particulate pollution often show symptoms of respiratory distress (Asgharian et al., 2004).

Due to known effects of ammonia on human health, the American Conference of Governmental Industrial Hygienists (ACGIH) established exposure limits for workers (CDC, 2011). The threshold exposure limit for humans for a normal 8-hr work day and a 40-hr work week is 17.4 mg/m^3. This is a time weighted average concentration to which nearly all workers may be repeatedly exposed daily without experiencing adverse effects (OSHA, 2003). The short-term exposure limit to which workers can be exposed continuously for a short period of time without suffering adverse effects is 24.4 mg/m^3. Short term exposures should be no longer than 15 minutes, four times a day, with at least 60 minutes between successive exposures (OSHA, 2003).

Quantification of ammonia emissions

Ammonia emissions from AFOs can be expressed as an emission rate (ER) or emission factor (EF) that describe the amount of pollutant emitted to the atmosphere over some period of time (Gates et al., 2008). In order to obtain an ER, the concentration of the aerial pollutant of concern at the source and the corresponding air exchange rate through the source are required (Gates et al., 2002). It is an immense task to reliably quantify either of the variables, on a continuous and extended basis, for AFO applications (Gates et al., 2008).

Making credible estimates of ammonia emission from AFOs is complex because NH_3 generation and transport are affected by several environmental factors and farm management practices (Gates et al., 2002). Seasonal trends in exhaust ammonia concentration and ventilation rates show highest ammonia concentrations occurring during cold weather, when ventilation rates are lowered for energy conservation (Wheeler et al., 2006). Building ventilation rate also greatly depends on mechanical condition and degree of maintenance, which can significantly affect actual fan capacity and introduce large errors in estimating VR (Gates et al., 2008). Therefore, obtaining good data requires measurements to be made over extended periods that are representative of actual production phases and conditions (Gates et al., 2008).

Standard methods for quantifying and reporting ammonia emissions from AFOs have not been established for the U.S. (Gates et al., 2008). There are generally accepted techniques for collecting emissions data but test conditions that can provide representative ER estimates and standards for making comparisons have not been defined (EPA, 2001). The amount of ammonia emitted can be determined through direct measurements or estimated using empirical equations and process-based models, and is often linked to a unit of confinement capacity or mass of an animal product (EPA, 2001). However, there are cases where this link is not reported or cannot be established (EPA, 2001).

Determining the amount of ammonia emitted from a building requires the VR and concentration of the gas in the building exhaust to be established. Direct measurement of exhaust ammonia concentration and VR at every AFO would be ideal, but it is expensive and not always possible to implement (Heber et al., 2001). The challenges to direct measurement are related to the costs of analytical instruments and the fact that these precision instruments are often not designed to handle the moist, dusty and even corrosive nature that is typical of air samples from broiler houses (Gates et al., 2008). The cost of gas analyzers varies depending on technology but spectrophotometers and devices that utilize Fourier Transform Infrared (*FTIR*) spectroscopy and can provide real time analysis of exhaust gas can cost between 65,000 and 80,000 U.S. dollars (Larry Marcus, Personal communication, March 20, 2013).

The relatively immobile instrument set-up, large number of fans with inherent variations in airflow rate at mechanically ventilated facilities, and difficulty in determining VR for naturally ventilated facilities also pose significant challenges to accurate determination of ammonia emissions (Gates, 2008). Less costly options for determining exhaust ammonia concentration include standalone or handheld sensors or laboratory analysis with an acid scrubber system (Liu et al., 2008). Acid scrubbers typically provide average concentrations of ammonia captured over relatively long periods of time, usually several hours or days (Liu et al., 2008). Ammonia sensors, on the other hand, can be used to obtain continuous, real-time measurements.

Determining ammonia emissions using the nitrogen mass balance approach accounts for inputs and outputs of N to the facility. The method uses total N losses over a period of time to estimate ammonia emitted from a source and is the basis of "process-based" models for determining ERs (Liu et al., 2008). The total nitrogen inputs and outputs of a broiler house are quantified, and the difference is assumed to be volatilized nitrogen. This method does not distinguish N lost as NH_3, N_2 or NO_x but can provide an estimate of the upper limits of ammonia emissions (Liu et al., 2008).

Measuring ammonia emissions in the laboratory

Laboratory tests provide cost effective, reliable and replicable methods for determining ammonia fluxes from broiler litter (Ndegwa et al., 2009). The chamber acid trap (CAT) system, which is comprised of a convective emissions chamber (CEC) containing the NH_3 source, forced air flow over the source and an acid trap to capture the ammonia, is commonly used in laboratory studies on ammonia volatilization (Ndegwa et al., 2009). These systems have been used for measuring NH_3 released from animal manures and evaluating the effectiveness of treatments (Woodward et al., 2011; Miles et al., 2008; Todd et al., 2006; Cole et al., 2005); however, they cannot be used to separate particulate NH_4^+ from gaseous NH_3 and loss of acid volume and decreasing efficiency become concerns during long term applications (Ndegwa et al., 2009).

Ammonia captured in the acid trap is affected by air flow rate, concentration and volume of acid in the trap, temperature and relative humidity (Ndegwa et al., 2009). Acid traps are more efficient at air flow rates below 0.5 Lpm but recoveries greater than 99% have been reported at 1.54 Lpm (Ndegwa et al., 2009). The choice of acid for the trap depends on the method of analysis for the ammonia that is captured. Boric acid traps are used if the ammonia concentration is to be determined by titration while sulfuric acid is used if calorimetric methods are to be employed. Sulfuric acid can also be used for concentrations as low as 2 mg/L (Ndegwa et al., 2009).

Estimating the amount and strength of acid solution required is important to ensure that most of the ammonia emitted is captured (Ndegwa et al., 2009). Using excessive acid may result in trapping ammonia below the detection limit of the selected analysis method, while having too little acid may result in inadequate capacity to capture all the ammonia that is released (Ndegwa et al., 2009). There are contradictory reports regarding the effect of acid volume and the number of acid traps on ammonia capture in emissions studies. Xue et al. (1998) reported that one trap was adequate to capture all ammonia released and that flow rate had no effect on trap efficiency. However, Ndegwa et al. (2009) observed that for the same volume of acid, trap efficiency increased with depth of acid and that, at any given depth, the trap efficiency decreased with the amount of ammonia going through the trap.

Modeling ammonia emissions

The goal of modeling ammonia emissions from broiler litter is to estimate the amount of ammonia released from broiler houses under a given set of environmental conditions such as air temperature, air velocity and relative humidity (NRC, 2003). The resulting models may be empirical or process-based and can be useful for predicting ammonia release when direct measurements cannot be made (NRC, 2003). Empirical models define correlations between factors that affect ammonia emissions from a source and can be used to predict emissions under different conditions by varying the model factors (NRC, 2003). Process-based models, on the other hand, follow the ammonia emission process from the source to the atmosphere, and provide estimates of ER using the chemical transformations that take place between elements such as carbon (C) and N (NRC, 2003). Process-based models simulate and track the impact of varying conditions within the system on ER and can be powerful tools for determining ERs from animal houses (NRC, 2003). Semi-empirical models enable the use of data collected from part of a system to make deductions for the whole system, and can be used to assess short and long term emissions and could provide a basis for management of air pollutants (NRC, 2003).

Understanding the release mechanism and the factors that affect ammonia formation and release from broiler litter are crucial for modeling emission of ammonia from the litter (Liu et al., 2008). Volatile compounds, such as ammonia, partition between liquid and the gas above the liquid. Many gas transfer models use Lewis and Whitman's (1924) two film theory, which assumes that there are hypothetical thin films on both sides of the liquid-gas interface, to describe the volatilization of a gas from a liquid to the surrounding air. The volatile substance moves through the films by diffusion and, for highly soluble gases, the gas film offers more resistance to diffusion than the liquid film (Schwarzenbach et al., 2003; Thakre et al., 2008). Mass transfer in gas-liquid systems is also influenced by the physical properties of the gas and liquid and gas flow characteristics. Factors that affect the solubility of the gas in the liquid, such as the presence of another solute, mixing and turbulence in the flow field will also affect the rate of mass transfer (Dutta, 2007).

Mass transfer coefficients obtained from modeling incorporate resistance to partitioning of gases between the different phases and form an important basis for estimating the emission of ammonia and other volatile gases from AFOs (Dutta, 2007). Interrelations between the many factors that affect ammonia mass transfer present challenges to modeling ammonia emissions from broiler litter (Dutta, 2007). Models based on laboratory study data only correlate ammonia flux to some of these factors within a range of conditions set by experimental limits (Rong et al., 2009; Liu et al., 2008, Arogo et al., 1999). Therefore, the values of ammonia mass transfer coefficients reported in literature vary widely, ranging from 0.005 to 42 m/hr (Ni, 1999).

Mitigation of ammonia volatilization from broiler litter

Maintaining broiler house ammonia concentrations lower than 17.4 mg/m^3 is an immense challenge under the current practices of commercial broiler production (Ritz et al., 2004). However, growing concerns about the effects of ammonia emissions from AFOs are driving the search for more effective measures for mitigation. Loss of ammonia from poultry manure can be controlled by inhibiting the conversion of uric acid to ammonia and/or reducing volatilization of the ammonia from the litter (Arogo et al., 2006). Since ammonia volatilization increases with pH and temperature, maintaining low litter pH and temperature greatly reduces the potential for volatilization (Ritz et al., 2004). Common strategies for controlling ammonia emissions from poultry houses include ventilation, diet manipulation and manure management (Ritz et al., 2004).

Litter amendments

Litter is often treated with chemical amendments before reusing it for another flock. Chemical amendments reduce ammonia concentrations in the poultry house using pH control and have been shown to improve bird performance and health (Moore et al., 2000; Pope and Cherry, 2000). Partial house brooding, where chicks are restricted to about one-third of the house during the first 10 to 14 days, is used as a fuel conservation measure (Dozier et al., 2004). Litter amendments for ammonia control are only applied to the brooding section of the house since young birds are more susceptible to elevated ammonia concentrations (Dozier et al., 2005). Proper ventilation during the brooding period is essential to prevent condensation of moisture and caking of litter, which can have a negative effect on the effectiveness of the amendment (Dozier et al, 2005).

House preparation, amendment application, litter moisture, bird type and incidence of disease will affect the effectiveness of litter treatment products (Malone, 1998; Ritz et al., 2004). Amendments that achieve the most significant decrease in pH result in the greatest reduction in ammonia emitted (Choi and Moore, 2008). The neutralizing capacity of the amendments decreases and litter pH increases as the birds grow older, produce more manure and are allowed to occupy the untreated section of the house (Moore et al., 1995). Usually by the fifth week, litter pH is above 7 and conditions are ideal for ammonia volatilization (Moore et al., 1995). Elevated litter moisture from previous flocks also reduces the effectiveness of chemical amendments and may significantly affect ammonia concentrations during later stages of production (Ritz et al., 2004).

Common litter amendments can be divided into five categories depending on their mode of action (Shah et al., 2012): acidifiers, alkaline material, adsorbers, inhibiters, and microbial and enzymatic treatments. Acidifiers such as alum (Moore et al., 2000), Poultry Guard (McWard and Taylor, 2000), and Poultry Litter Treatment (Pope and Cherry, 2000) reduce the pH of the manure/litter, microbial activity (Shah et al. 2012), pathogens and the incidence of diseases (Pope and Cherry, 2000), improve bird performance and lower the energy requirements for ventilation (Moore et al. 1996). Ammonia concentrations below 17.4 mg/m^3have been reported for 3 to 4 weeks after application of the amendments (Shah et al., 2012). Moore et al. (1995) reported that up to 99% reduction in ammonia volatilization could be achieved using alum. Armstrong et al. (2003) reported that application of liquid alum doses of 45 and 135 kg over an area of 93 m^2 could maintain ammonia concentrations below 17.4 mg/m^3 during the second and fourth week of the grow-out period. Kithome et al. (1999) reported 10% decrease in ammonia loss after adding 20% calcium chloride solution to poultry manure.

Certain minerals such as zinc and copper also inhibit enzyme activity. Kim and Patterson (2003) observed that zinc and copper decreased the activity of uricase by more than 90% and significantly decreased the growth and numbers of microbes that had been isolated from poultry manure, especially when pH was below 3 or above 11. The reduction in ammonia volatilization and subsequent increase in N retention in litter treated with these amendments was attributed to the pH reducing effect of the minerals (Kim and Patterson, 2003). Kim et al. (2009) reported that nitropropanol and nitropropanoic acid also significantly reduced the growth of uric acid utilizing bacteria and increased N retention in the manure incubated at 23^{o}C for 7 days. Enzyme inhibitors such as phenyl phosphorodiamidate lower the rate of conversion of uric acid and urea to ammonia (McCrory and Hobbs, 2001). The effectiveness of enzyme inhibitors has been demonstrated in the laboratory (Varel, 1997; Varel et al.; 1999) but they have not been adopted in full scale commercial operations because the long term effects on animals and crops that will receive the resulting manure is still largely unknown (Ndegwa et al., 2008).

Certain clay-based products absorb moisture and have hydrous silicates that can act as ion-exchangers and absorbents (Nakaue et al., 1981). These materials inhibit microbial activity and formation of ammonia by lowering litter moisture content (Ritz et al., 2006; Shah et al., 2012). It is generally thought that binding agents either trap ammonia in the microscopic pits in their structures or adsorb it on their surface (Ndegwa et al., 2008). Zeolite is one naturally occurring mineral with a high cation exchange capacity and a specific affinity for ammonium ions (Ndegwa et al., 2008). Kithome et al. (1999) reported that a layer of 30% zeolite placed over the surface of poultry manure during composting reduced ammonia volatilization by 44%, and Nakaue and Koelliker (1981) observed 35% reduction in ammonia loss after adding 5 kg zeolite/m^2 of broiler litter. However, Amon et al. (1997) reported significant increases in ammonia concentrations when clinoptilolite (natural zeolite) was applied to poultry litter.

The benefits of litter amendments continue to increase as more effective products are developed (Ritz et al., 2004). New products increasingly address the environmental concerns related to ammonia emission, such as limiting water soluble P, increasing fertilizer value of the litter, and also reducing food-borne pathogens (Ritz et al., 2004). Using litter amendments is also less costly for controlling house ammonia concentrations than increasing ventilation (Moore et al., 1995) and significant savings can be made by reusing litter with good housekeeping. Ritz et al. (2004) estimated that annual savings of $700 to $2500 per house compared to new litter and cleanout costs.

House management

Moisture control coupled with the use of litter amendments makes it possible to reuse the litter for several flocks. Litter moisture content greatly depends on waterer management, VR and house relative humidity (RH). Ideal broiler house RH is between 60% and 70% (De Jong and Van Harn, 2012). House RH increases with bird age and can greatly influence litter moisture and ammonia formation and release from the litter. The presence of elevated moisture in the litter not only increases ammonia production but also seems to decrease the service life of many litter amendments (Ritz et al., 2004). Keeping house RH below 70% reduces occurrence of wet and caked litter. However, when RH falls below 50%, the litter material may become too dry, creating dusty conditions within the house (De Jong and Van Harn, 2012).

Litter around feeders may have high moisture content since birds tend to excrete while feeding. However, the elevated moisture content of litter around the waterers is primarily due to spilled water. Waterer management, including repairing/replacing leaking equipment and height adjustment is crucial for litter moisture control (Patterson and Adriz, 2005). It has been reported that lower litter moisture content and decreased N loss can be achieved with nipple drinkers compared to bell drinkers (Patterson and Adriz, 2005). Currently, most broiler houses are equipped with nipple drinker systems, which control water spillage and wastage and, consequently, reduce the moisture content and caking of the litter (Dozier et al., 2005; Ritz et al., 2004). The waterer height and water pressure are adjusted as birds grow, to meet bird requirements while minimizing spillage and wastage.

Between flocks, watering systems are checked for leaks, and wet spots and caked litter that developed during the previous flock are removed and replaced with clean, dry bedding (Ritz et al., 2004). Cake removal is necessary to rid the house of excessive moisture and manure, which can contribute to elevated ammonia release from the litter in the ensuing flock (Shah et al., 2012). Moisture control can extend the service life of litter amendments. However, even with good moisture control, a number of amendments are only effective in the first three weeks of brooding and have limited effects during later stages of production (Ritz et al., 2004).

Use of litter amendments cannot replace the role of ventilation in controlling broiler house air quality (Ritz et al., 2004). Ventilation removes excess moisture, and inadequate ventilation could lead to more ammonia volatilization even with amendments (Ritz et al., 2004). Ammonia concentrations in poultry houses are reportedly higher in winter when increasing VR is not cost effective due to energy costs associated with heating fresh air (Wheeler et al. 2006; Ritz et al., 2006).

Diet manipulation

More than 60% of N consumed by broilers may be excreted (Ritz et al., 2004). Improving diet formulation to reduce crude protein (CP) levels and increase amino acid digestibility can reduce N excretion and ammonia emitted from poultry manure (Nahm, 2007; Hale, 2012). Elwinger and Svensson (1996) reported that reducing CP from 22% to 18% resulted in 7% reduction in N loss. Ferguson et al. (1998) demonstrated that reducing dietary CP by 2% and maintaining similar levels of dietary amino acids could reduce broiler litter N by more than 16%, and Nahm (2007) reported that reductions in N excretion of up to 40% could be achieved by improving amino acid and CP digestibility.

Certain feed additives, such as clay minerals, synthetic amino acids and enzymes may also improve N digestibility and reduce the amount of N excreted in the manure (Ritz et al., 2004). Some non-starch enzymes may be added to wheat-based diets as a tool for improving gut health and controlling litter quality (De Jong and Van Harn, 2012). Enzyme supplementation decreases intestinal viscosity and increases amino acid digestibility (Nahm, 2007). Other feed additives such as clay mineral binders, zinc and biotin have a water binding capacity and result in drier droppings and litter. A diet comprising 2% powdered clinoptilolite by weight and gypsum as the source of supplemental calcium (45%) provided a 47% reduction in ammonia emissions compared to the standard broiler diet (Hale, 2012). Adding whole wheat to feed can also be beneficial for flocks with recurring intestinal problems (De Jong and Van Harn, 2012).

Evaluation of flock performance

The performance of a flock of broilers can be evaluated using a number of factors including feed efficiency, growth rate and mortality (KPF, 2010). Since feed is typically the biggest expense in broiler production, feed efficiency is particularly useful for evaluating flock performance (KPF, 2010). Feed efficiency is defined using the feed conversion ratio (FCR), which is the ratio of feed intake, to weight gain. Lower numbers for FCR indicate a more efficient use of the feed supplied to the flock but typical FCR values for 42 day old broilers are around 1.8 (KPF, 2010).

There has been a major increase in broiler growth rates in recent years (McKay et al., 2000). In 1956, it took 84 days for broilers to reach 1.8 kg, compared to 60 days in 1966 and 34 days in the year 2000 (McKay et al., 2000). The common killing weight of 2.0 kg can be attained at 36 days (McKay et al., 2000). Modern broilers tend to overeat and grow rapidly while maintaining a low feed conversion ratio (McKay et al., 2000). This rapid increase in growth rate comes with associated risks such as “flip-over” disease, which is reportedly a major cause of bird mortality in areas with intensive broiler production (Collett, 2011).

“Flip-over” disease is assumed to be related to high carbohydrate intake and metabolism, and results in sudden death from severely abnormal heart rhythm (Collett, 2011). It is not known whether a genetic predisposition plays a factor but the disease causes young, otherwise healthy, fast-growing broiler chickens to die with short and terminal convulsions. Many of the affected broilers just “flip over” and die on their backs; 60% to 80% of the affected birds are males (Collett, 2011). The condition is not common when low-density feed is used and the feed conversion ratio is less 2.5 at 6 weeks, or when broilers take 8 weeks to reach 2 kg (Collett, 2011). Incidence of “flip over” disease in a rapidly growing healthy broiler flock is typically 1% to 4% with peak mortality happening between days 12 and 28 (Collett, 2011). Gonzales et al. (1998) reported that “flip-over” disease was responsible for about 70% of total mortality in Cobb and Hubbard broilers that had been raised to a final weight of 2.5 kg with a FCR of 1.75.

Footpad dermatitis (FPD) in broiler chickens appears as lesions on the bottom of the birds’ feet, primarily caused by wet litter (Abbott et al., 1969; Harms et al., 1977; Nairn and Watson, 1972). The skin of the footpad becomes eroded, and sometimes ulcerated, and is probably painful (Berg, 1998). Footpad dermatitis is receiving increasing attention in the broiler industry because it affects animal welfare and the growth rate of birds affected by severe lesions is slower (Martland, 1985). Chicken feet are also part of human diets in certain parts of the world; but those affected by FPD cannot be sold for this purpose, leading to financial loss for the farmers (De Jong and van Harn, 2012).

Footpad dermatitis in broilers has been attributed to wet and sticky litter, with increased occurrence and severity as litter moisture increases (De Jong and van Harn, 2012). Youssef et al. (2011) reported that the severity of FPD was markedly higher (about 3 times) on wet litter compared to dry litter, and that exposure of birds to wet litter for only 8 hours per day was sufficient to develop foot pad lesions. Wu and Hocking (2011) observed a linear relationship (increasing) between FPD severity and moisture content and advised that FPD prevalence and severity was minimal when litter moisture content was less than 30%. This means that litter management is crucial for prevention of FPD, especially during the brooding period, when birds appear more susceptible to lesion development (De Jong and van Harn 2012).

Stocking density, chemical irritants and bedding material may have an impact on the development and severity of FPD in a flock (De Jong and van Harn 2012). Higher stocking densities result in higher fecal load in the litter and higher relative humidity, especially when ventilation is insufficient. De Jong and van Harn (2012) reported that FPD prevalence was higher at a stocking density of 20 birds/m^2 compared to 13 birds/m^2; however, the effect of nitrogenous irritants in the litter on FPD development and severity could not be substantiated (Youssef et al. 2011). Reports regarding effects of litter material on FPD development are contradictory (De Jong and van Harn, 2012). "De Baere and Zoons (2004) compared chopped wheat straw and wood shavings as litter material for broilers and reported less FPD on wood shavings than on chopped straw but van Harn et al (2009) did not find a difference in severity of FPD between the two materials" (De Jong and van Harn, 2012).

Footpad dermatitis can be reported using prevalence in a population of birds or how severely individual birds are affected from the size of the lesions (Pagazaurtundua and Warriss, 2006). The combination of prevalence and severity gives a measure of the overall seriousness of the condition in a flock (Pagazaurtundua and Warriss, 2006). There are two commonly accepted scales for quantifying the severity of the FPD lesions. Ekstrand et al. (1998) used a three point scale with scores of 0, 1 and 2, representing no lesions, mild lesions and severe lesions, respectively. Martrenchar et al. (2001) described a four-point scale (0-3) with a 0, 1, 2 and 3 representing no lesions and lesions covering less than one quarter, between one-quarter and a half, and more than half of the area of the pad, respectively.

The severity of FPD in a flock can be reported as the percentage of the birds that showed evidence of FPD, regardless of the degree of damage to the footpad, or using the Modified Ekstrand Score (MES). The MES is based on the scheme devised by Ekstrand et al. (1998), and is obtained by multiplying a particular score by its frequency then adding the weighted scores (Pagazaurtundua and

Warriss, 2006). For example, if 1000 birds are scored, the MES would range from 0 to 4000 and an MES of 4000 would mean that all feet had been assigned a score of 2.

Summary

1. Ammonia produced from broiler production has adverse effects on animal welfare, the environment and human health. Mitigation measures that are cost effective and easy to implement are required to reduce ammonia emitted without significantly increasing production costs.

2. Determining the amount of ammonia emitted from broiler houses is important for development and evaluation of mitigation technologies. Continuous monitoring of ammonia emitted from broiler production facilities is required to capture daily and seasonal variations in emissions but is not always implementable.

3. Emission models can be useful for estimating ammonia emissions as alternatives to direct measurements. Interrelations between the factors that affect ammonia release from broiler litter create challenges to accurately modeling ammonia emissions from the litter in laboratory studies.

4. It is often not possible to fully explain all the variations in ammonia emissions from broiler houses using changes in quantifiable factors, but models based on the most significant factors affecting ammonia emission can give relatively accurate estimates.

5. Litter amendments control ammonia formation from broiler litter and make it possible to reuse litter to grow multiple flocks while minimizing the effect on bird performance; however, the amendments are also corrosive to structures and harmful to handlers and birds.

6. A biodegradable litter amendment (BLA) produced from agricultural residues could provide a possible alternative for mitigation of ammonia emissions from broiler litter and a market for agricultural residues.

References

Abbott, W. W., J. R. Couch, and R. L. Atkinson. 1969. The incidence of foot-pad dermatitis in young turkeys fed high levels of soybean meal. Poultry. Sci. 48(6): 2186-2188.

Agblevor, F. A., J. A. Ogejo, S. W. Gay 2008. Patent Application Publication No. US 2008/0050273 A1.

Al Homidan, A. 2004. Effect of temperature and light regime on ammonia, dust concentrations and broiler performance. Brit. Poultry Sci. 45: S35-S36.

Al Homidan, A., J. F. Robertson and A. M. Petchey. 2003. Review of the effect of ammonia and dust concentrations on broiler performance. World Poultry Sci. J. 59: 340-349.

Al-Mashhadani, E. H. and M. M. Beck. 1985. Effect of atmospheric ammonia on the surface ultrastructure of the lung and trachea of broiler chicks. Poultry. Sci. 64:2056–2061.

Amon, M., M. Dobeic, R. W. Sneath, V. R. Phillips, T. H. Misselbrook, and B. F. Pain. 1997. A farm-scale study on the use of clinoptilolite zeolite and De-odorase for reducing odour and ammonia emissions from broiler houses. Bioresource Technol. 61:229-237.

Armstrong, K. A., R. T. Burns, F. R. Walker et al. 2003. Ammonia concentrations in poultry broiler production units treated with liquid alum. Proc. of the Air Pollution from Agr. Operations III Res. Triangle Park, North Carolina. pp 116-122.

Arogo, J., P. Westerman, A. Heber, W. Robarge, and J. Classen. 2006. Ammonia emissions from animal feeding operations. In Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers, 41-88.

Arogo, J., R. H. Zhang, G. L. Riskowski, L. L. Christianson and D. L. Day. 1999. Mass transfer coefficient of ammonia in liquid swine manure and aqueous solutions. J. Agric. Eng. Res. 73(1): 77-86.

Asgharian, B., Ménache, M.G., and Miller, F.J. 2004. Modeling age-related particle deposition in humans. J. Aerosol. Med. 17:213-224.

Asgharian, B., R. P. Subramaniam, J. I. Freijer, F. J. Miller and S. Anjivel. 2003. Analysis of lobar differences in particle deposition in the human lung. Inhal. Toxicol. 15:1-21.

Barthelmie, R.J. and S. C. Pryor. 1998. Implications of ammonia emissions for fine aerosol formation and visibility degradation: a case study from the lower Fraser valley, British Columbia. Atmos. Environ. 32: 345-352.

Beker, A.; S. L. Vanhooser; J. H. Swartzlander; R.G. Teeter. 2004. Atmospheric Ammonia Concentration Effects on Broiler Growth and Performance. J. Appl. Poult. Res. 13(1):5-9.

Berg, C. C. 1998. Foot-pad dermatitis in broilers and turkeys. Prevalence, risk factors and prevention. PhD Dissertation. ISBN 91-576-5442-5.

Bolan, N. S., A .A. Szogi, T. Chuasavathi, B. Seshadri, M. J. Rothrock Jr. and P. Anneerselvam. 2010. Uses and management of poultry litter. World Poultry Sci. J. 66: 673-698.

Bongaerts, G. P. A and Vogels, G. D. 1979. Mechanism of uricase action. Biochem Bioph. Res. Co. 567: 295-308.

Brewer, S. K. and T. A. Costello. 1999. In situ measurement of ammonia volatilization from broiler litter using an enclosed air chamber. Trans. ASAE. 42(5): 1415-1422.

Bucklin, R. A., J. P. Jacob, F. B. Mather, J. D. Leary and I. A. Naas. 2009. Tunnel Ventilation of Broiler Houses. Publication #PS-46. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Bullis, K. L., G. H. Snoeyenbos and H. van Roekel, 1950. A keratoconjunctivitis in chickens. Poultry. Sci. 29: 386-389.

Burnett, W.E. and N.C. Dondero. 1969. Microbiological and chemical changes in poultry manure associated with decomposition and odor generation. Proc. Cornell University Conference of Agric. Waste Management, pp. 271–291.

Carlile, F. S. 1984. Ammonia in Poultry Houses: A Literature Review. World Poultry Sci. J. 40: 99-113.

Carr, L. E. and J. Nicholson. 1990. Empirical models to determine ammonia concentrations from broiler chicken litter. Trans. ASAE. 33(4):1337-1342.

Caveny D. D., C. L. Quarles and G. A. Greathouse. 1981. Atmospheric ammonia and broiler cockerel performance. Poultry Sci. 60: 513-516.

Centers for Disease Control and Prevention (CDC). 1996. Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water—LaGrange County, Indiana, 1991–1994. Morb. Mortal Wkly Rep. 45(26):569-572.

Centers for Disease Control and Prevention (CDC). 2011. 1988 OSHA PEL Project Documentation: ammonia. Available at: http://www.cdc.gov/niosh/pel88/7664-41.html Accessed: April 2013

Chang, T. S. and D. Flint. 1976. The rate of ammonia production in chicken excreta. Poultry. Sci. 55:2018.

Charles, D. R. and Payne, C. G. 1964. The effects of ammonia on the performance of laying hens. Proceedings of the 2nd European Poultry Conference Bologna pp. 100-112.

Choi, I. H.; P. A. Moore Jr. 2008. Effect of Various Litter Amendments on Ammonia Volatilization and Nitrogen Content of Poultry Litter. J. Appl. Poultry Res. 17: 454-462.

Collett, S. R. 2011. Flip-over Disease. Available at: http://www.merckmanuals.com/vet/poultry/sudden_death_syndrome_of_broiler_chickens/overview_of_sudden_death_syndrome_of_broiler_chickens.html?qt=flip%20over&alt=sh. Accessed January 23, 2013.

Cooper, R. G and A. P. Harrison. 2009. The uses and adverse effects of beryllium on health Indian J. Occup Environ Med. 13(2): 65-76.

Coufal, C. D., C. Chavez, P. R. Niemeyer, and J. B. Carey. 2006. Measurement of broiler litter production rates and nutrient content using recycled litter. Poultry Sci. 85:398-403.

De Jong, I. and J. van Harn. 2012. Management Tools to Reduce Footpad Dermatitis in Broilers. Available at:

http://en.aviagen.com/assets/Tech_Center/Broiler_Breeder_Tech_Articles/English/AviaTech-FoodpadDermatitisSept2012.pdf. Accessed January 17, 2013.

Denmead, O. T., J. R. Freney, and J. R. Simpson. 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. Soil Sci. Soc. Am. J. 46:150-155.

Donald, J. 2012. Getting the most from evaporative cooling systems in tunnel ventilated broiler houses. Available at: http://www.aces.edu/poultryventilation/documents/GetMostEC.PDF. Accessed April 08, 2013.

Dorsch, M. M., R. K. R. Scragg, A. J. McMichael, P. A. Baghurst and K. F. Dyer. 1984. Congenital malformations and maternal drinking water supply in rural South Australia: a case-control study. Am. J. Epidemiol. 119:473-486.

Dozier III, W.A., M. P. Lacy and L. R. Vest. 2004. Broiler Production and Management. Available at http://www.thepoultrysite.com/articles/155/broiler-production-and-management. Accessed: April, 9, 2013.

Dozier III, W. A., B. D. Lott, and S. L. Branton. 2005. Growth responses of male broilers subjected to increasing air velocities at high ambient temperatures and a high dew point. Poultry. Sci. 84:962-966.

Dutta, B. K. 2007. Principles of mass transfer and separation processes. Prentice-Hall of India, New Delhi. PHI Learning Pvt. Ltd. ISBN 8120329902.

Ekstrand, C., T. E. Carpenter, I. Andersson and B. Algers. 1998. Prevalence and control of foot pad dermatitis in Sweden. Brit. Poultry. Sci. 39: 318-324.

Elliott, H. A. and Collins, N. E. 1982. Factors affecting ammonia release in broiler houses. Trans ASAE 25 (2) pp 413 – 424.

Elwinger, K. and L. Svensson. 1996. Effect of dietary protein content, litter and drinker type on ammonia emission from broiler houses. J. Agric. Engng. Res. 64: 197-208.

EPA (U.S. Environmental Protection Agency). 2001. Emissions from Animal Feeding Operations. Emission Standards Division. Office of Air Quality Planning and Standards. Research Triangle Park, NC 27711.

EPA. (U.S. Environmental Protection Agency). 2004. NPDES Permit Writers' Manual for AFOs. Available at: http://www.epa.gov/npdes/pubs/cafo_permitmanual_chapter2.pdf . Accessed September 12, 2012.

EPA (U.S. Environmental Protection Agency). 2011. Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors. Available at http://www.epa.gov/ttnchie1/ap42/ Accessed: March 1, 2013.

Ernst, J. W and Massey, H. F. 1960. The effect of several factors on ammonia volatilization from urea in the soil. Science and Soil society proceedings pp 87-90.

ERS. USDA 2012. Poultry Production Statistics. http://www.ers.usda.gov/topics/animal-products/poultry-eggs/statistics-information.aspx. Accessed August 17, 2012.

Fairchild, B. D. 2012. Environmental Factors to Control when Brooding Chicks. Available at: http://www.caes.uga.edu/publications/pubDetail.cfm?pk_id=7388. Accessed: April 08, 2013.

Fairchild, B. D. 2005. Broiler Tip… Broiler Stocking Density. The University of Georgia Cooperative Extension Service. Available at: http://www.poultry.uga.edu/extension/tips/documents/01%2005%20B%20tip%20B%20F%20(web).pdf. Accessed January 24, 2013.

Ferguson, N. S., R. S. Gates, J. L. Taraba, A. H. Cantor, A. J. Pescatore, M. L. Straw, M. J. Ford and D. J. Burnham. 1998a. The effect of dietary protein and phosphorus on ammonia concentration and litter composition in broilers. Poultry Sci. 77:1085-1093.

Ferguson, N. S., R. S. Gates, J. L. Taraba, A. H. Cantor, A. J. Pescatore, M. J. Ford and D. J. Burnham. 1998b. The Effect of Dietary Crude Protein on Growth, Ammonia Concentration, and Litter Composition in Broilers Poultry Sci. 77:1481–1487.

Ferguson, W. S., W. C. Koch, L. B. Webster, et al. 1977. Human physiological response and adaption to ammonia. J. Occup. Med. 19:319-326.

Gates, R.S., K.D. Casey, E.F. Wheeler, H. Xin and A.J. Pescatore. 2008. U.S. broiler housing ammonia emissions inventory. Atmos. Environ. 42(14): 3342–3350

Gates, R. S., H. Xin and E. F. Wheeler. 2002. Ammonia losses, evaluations and solutions for poultry systems. Proc. Natl. Poultry Waste Mgmt. Symp. Birmingham, AL.

Gates, R. S., J. L. Taraba, N. S. Ferguson and L. W. Turner. 1997. A technique for determining ammonia equilibrium and volatilization from broiler litter. Presented at ASAE Annual Intl. Meeting. Paper No. 97-4074, ASAE, St. Joseph, MI.

Gates, R. S., K. D. Casey, E. F. Wheeler, H. Xin and A. J. Pescatore. 2008. U.S. broiler housing ammonia emissions inventory. Atmos. Environ. 42 (14): 3342-3350.

Gonzales, E., J. Buyse, T. S. Takita, J. R. Sartori and E. Decuypere. 1998. Metabolic Disturbances in Male Broilers of Different Strains. 1. Performance, mortality, and right ventricular hypertrophy. Poultry Sci. 77: 1646-1653.

Groot Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, and J. Seedorf. 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. J. Agr. Engr. Res 70(1): 79-95.

Gupta S. K., R. C. Gupta, A. B. Gupta, A. K. Seth, J. K. Bassin and A. Gupta. 2000. Recurrent acute respiratory infections in areas with high nitrate concentrations in drinking water. Environ. Health Perspect. 108:363-366.

Hale E. C. III. 2012. Reduction of Ammonia Emission and Phosphorus Excretion in Laying Hen Manure Through Feed Manipulation. Available at: http://www.cals.ncsu.edu/waste_mgt/natlcenter/sanantonio/Hale.pdf. Accessed February 08, 2012.

Harms, R. H., B. L. Damron and C. F. Simpson. 1977. Effect of wet litter and supplemental biotin and/or whey on the production of foot pad dermatitis in broilers. Poultry. Sci. 56(1): 291-296.

Haslam, R., L. Hershey, and R. Keen. 1924. Effect of gas velocity and temperature on rate of absorption. Ind. Eng. Chem. 16(2): 1224-1230.

Heber, A. J., T. Lim, D. Ni et al. 2001. Odor, ammonia and hydrogen sulphide emission factors for grow-finish buildings. Final Report National Pork Producers Council.

HHI (Hired Hand Inc.) 2013. Is it really worthwhile to take the trouble to pre-heat a house before chick placement? Available at: http://www.hired-hand.com/FAQ/Default.aspx?ProdCatID=2&intIndID=0. Accessed: March 11, 2013.

Hill, M. J. 1999. Nitrate toxicity: myth or reality? Br. J. Nutr. 81:343-344.

International Programme on Chemical Safety (IPCS). 1986. Ammonia. Environmental Health Criteria 54. World Health Organization, Geneva.

Jaworski, N. A., R. W. Howarth, and L. J. Hetling. 1997. Atmospheric deposition of nitrogen oxides onto the landscape contributes to coastal eutrophication in the northeast United States. Environ. Sci. Technol. 31: 1995-2004.

Jayaweera, G. R., and D. S. Mikkelsen, 1990. Ammonia volatilization from flooded soil systems: A computer model. I. Theoretical aspects. Soil Sci. Soc. Am. J. 54:1447-1455.

Kavolelis, B. 2003. Influence of ventilation rate on ammonia concentration and emission in animal house. Polish J. Environ. Studies. 12(6): 709-712.

Kelleher, B. P.; J. J. Leahy, A. M. Henihan, T. F. O’Dwye, D. Sutton and M. J. Leahy. 2002. Advances in poultry litter disposal – A review. Bioresource Technol. 83: 27-36.

Kentucky Poultry Federation. 2010. Poultry Production Manual. Chapter 6 - Factors affecting broiler performance. Available at: http://www.ca.uky.edu/poultryprofitability/Production_manual/Chapter6_Factors_affecting_feed_conversion/Chapter6.html. Accessed January 17, 2013.

Kim J. H, D.H. Lim, J. K. Kim , et al. 2005. Effects of particulate matter (PM10) on the pulmonary function of middle-school children. J. Korean Med. Sci. 20(1): 42-45.

Kim, W. K. and P. H. Patterson. 2003. Effect of minerals on activity of microbial uricase to reduce ammonia volatilization in poultry manure. Poultry Sci. 82: 223–231.

Kim, W. K., L. J. Weeks, R. C. Anderson, D. J. Nisbet, K. Dunkley and S. C. Ricke. 2009. Effects of nitrocompounds on uric acid-utilizing microorganisms, nitrogen retention, and microbial community in laying hen manure. J. Environ. Sci. Heal. B. 44(4): 403-406.

Kirchmann, H and E. Witter 1989. Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant Soil 115: 35-41.

Kithome, M., J. W. Paul, and A. A. Brooke 1999. Reducing nitrogen losses during simulated composting of poultry manure using adsorbents or chemical amendments. J. Environ. Qual. 28(1): 194-201.

Klemperer, F. W. 1945. Enzymic oxidation of uric acid. Harvard University Medical School Publication No. 86.

Kling, H. F. and C. L. Quarles. 1974. Effect of atmospheric ammonia and the stress of infectious bronchitis vaccination on leghorn males. Poultry Sci. 53:1161-1167.

Knížatová, M., Š. Mihina, J. Brouček, I. Karandušovská and J. Mačuhová. 2010. The influence of litter age, litter temperature and ventilation rate on ammonia emissions from a broiler rearing facility. Czech J. Anim. Sci. 55(8): 337-345.

Kostraba, J. N., E. C. Gay, M. Rewers and R. F. Hamman. 1992. Nitrate levels in community drinking waters and risk of IDDM. An ecological analysis. Diabetes Care. 15(11):1505-1508.

Lashof, D. A. and D. R. Ahuja. 1990. Relative contributions of greenhouse gas emissions to global warming. Nature. 344:529 – 531.

Lester, J. 2007. Ammonia: A Particulate Matter Precursor. Available at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_008858.pdf. Accessed April, 2013.

Lewis, W. K. and W. G. Whitman. 1924. Principles of gas absorption. Ind. Eng. Chem. 16(12): 1215–1220.

Liu, Z., L. Wang and D. B. Beasley. 2008. Comparison of three techniques for determining ammonia emission fluxes from broiler litter. Trans. ASABE 51(5): 1783-1790. Liu, Z., L. Wang, D. Beasley and E. Oviedo. 2007. Effect of moisture content on ammonia emissions from broiler litter: A laboratory study. J. Atmos. Chem. 58 (1): 41-53.

Machida, Y. and T. Nakanishi. 1980. Purification and properties of uricase from enterobacter cloacae. Agr. Biol. Chem. 44(12): 2811-2815.

Maguire, R.O. and J. T. Sims. 2002. Soil testing to predict phosphorus leaching. J. Environ. Qual. 31:1601-1609.

Mahimairaja, S; N. S. Bolan, M. J. Hedley and A. N. Mcgregor. 1994. Losses and transformation of nitrogen during composting of poultry litter with different amendments. Bioresource Technol. 47: 265-273.

Malone, G. W. 1998. Overview of in-house litter treatments. Proc. Natl. Poult. Waste Manage. Symp., Harrisburg, PA. 131–132.

Martland, M.F. 1984. Wet litter as a cause of plantar pododermatitis, leading to foot ulceration and lameness in fattening turkeys. Avian Pathol. 13: 241-252.

Martrenchar, A., D. Boilletot, D. Huonnic, and F. Pol. 2001. Risk factors for foot-pad dermatitis in chicken and turkey broilers in France. Prev. Vet. Med. 52: 213-226.

McCrory, D. F., and P. J. Hobbs. 2001. Additives to reduce ammonia and odor emissions from livestock wastes: A review. J. Environ. Qual. 30:345-355.

McGarry, S. J., P. O'Toole and M. A. Morgan. 1987. Effects of soil temperature and moisture content on ammonia volatilization from urea-treated pasture and tillage soils. Irish J. Agric. Res. 26(2/3): 173-182.

McKay J. C., N. F. Barton, A. N. M. Koerhuis and J. McAdam, 2000. The challenge of genetic change in the broiler chicken. British Society of Animal Science. Occasional Publication No. 27.

McWard, G. W., and D. R. Taylor. 2000. Acidified clay litter amendment. J. Appl. Poultry. Res. 9:518-529.

Miles, D. M., D. E. Rowe, and T. C. Cathcart. 2011. High litter moisture content suppresses litter ammonia volatilization. Poultry Sci. 90:1397-1405.

Miles, D. M.; P. R. Owen; P. A. Moore Jr.; D. E. Rowe. 2008. Instrumentation for Evaluating Differences in Ammonia Volatilization from Broiler Litter and Cake. J. Appl. Poultry Res. 17:340-347.

Miles, D. M., S. L. Branton, and B. D. Lott. 2004. Atmospheric Ammonia is Detrimental to the Performance of Modern Commercial Broilers. Poultry Science 83:1650-1654.

Moore Jr., P. A., T. C. Daniel, D. R. Edwards, and D. M. Miller. 1996. Evaluation of chemical amendments to reduce ammonia volatilization from poultry litter. Poultry Sci. 75: 315-320.

Moore Jr., P. A., T. C. Daniel, D. R. Edwards, and D. M. Miller. 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. J. Environ. Qual. 24: 293-300.

Moore, P. A., T. C. Daniel and D. R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. J. Environ. Qual. 29:37-49.

Moum, S. G., W. Seltzer, and T. M. Goldhaft. 1969. A simple method of determining concentrations of ammonia in animal quarters. Poultry Sci. 48:347-348.

Muck, R. E 1982. Urease activity in bovine feces. J. Dairy Sci. 65 (11): 2157-2163.

Nahm. 2007. Feed formulations to reduce N excretion and ammonia emission from poultry manure. Bioresource Technol. 98: 2282-2300.

Nairn, M. E. and A. R. A. Watson. (1972). Leg weakness of poultry: A clinical and pathological characterisation. Aust. Vet. J. 48(12): 645-656.

Nakaue, H. S., and J. K. Koelliker. 1981. Studies with clinoptilolite in poultry. I. Effect of feeding varying levels of clinoptilolite (zeolite) to dwarf single comb white leghorn pullets and ammonia production. Poultry. Sci. 60:944-949.

National Academy of Engineering (NAE). 2012. Manage the Nitrogen Cycle. Available at: http://www.engineeringchallenges.org/cms/8996/9132.aspx. Accessed July 17, 2012.

National Chicken Council (NCC). 2012a. U.S. Broiler Production. Available at: http://www.nationalchickencouncil.org/about-the-industry/statistics/u-s-broiler-production. Accessed August 17, 2012.

NCC. (National Chicken Council). Animal Welfare for Broiler Chickens. 2012b. Available at http://www.nationalchickencouncil.org/industry-issues/animal-welfare-for-broiler-chickens/ Accessed: March 07, 2013.

National Research Council (NRC) of the National Academies. 2003. Emissions from animal feeding operations – Current knowledge, future needs NRC Press Washington, DC.

Ndegwa, P. M., V. K. Vaddella, A. N. Hristov and H. S. Joo. 2009. Measuring Concentrations of Ammonia in Ambient Air or Exhaust Air Stream using Acid Traps. J. Environ. Qual. 38:647–653.

Ndegwa, P. M., A. N. Hristov, J. Arogo and R. E. Sheffield, 2008. A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosystems Engr. 100: 453-469.

Ni, J.Q. 1999. Mechanistic models of ammonia release from liquid manure: a review. J. Agric. Engng. Res. 72: 1-17.

Nimmermark, S. and G. Gustafsson. 2005. Influence of temperature, humidity and ventilation rate on the release of odour and ammonia in a floor housing system for laying hens. Agricultural Engineering International: The CIGR Ejournal 7: Manuscript BC 04 008.

Nolan, B. T. and C. B. Ruddy. 1996. Nitrates in Ground Waters of the United States – Assessing the Risk. U.S. Geological Survey. Fact Sheet FS-092-96. Denver, Colorado.

O'dell, B. L., W. D Woods, O. M. Leardal, et al. 1960. Distribution of major nitrogen compounds and amino acids in poultry urine. Poultry Sci. 39 426-432

Occupational Health and Safety Administration (OSHA). 2003. Safety and Health Topics – Ammonia. Available at: http://www.osha.gov/dts/chemicalsampling/data/CH_218300.html. Accessed January 30, 2013.

Paerl, H. W. 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnol. Oceanogr. 42(2): 1154-1165.

Pagazaurtundua, A. and P. D. Warriss. 2006. Measurements of footpad dermatitis in broiler chickens at processing plants. Vet. Rec. 158: 679-682.

Patterson, P. H. and Adrizal. 2005. Management Strategies to Reduce Air Emissions: Emphasis – Dust and Ammonia. J. Appl. Poult. Res. 14(3): 638-650.

Pedersen, F. and R. S. Selig. 1989. Predicting the consequences of short-term exposure to high concentrations of gaseous ammonia. Journal of Hazardous Materials. 21(2):143-159.

Pope, M. J., and T. E. Cherry. 2000. An evaluation of the presence of pathogens on broilers raised on Poultry Litter Treatment-treated litter. Poultry. Sci. 79:1351-1355.

Quarles, C. L. and D. D. Caveny. 1979. Effect of air contaminants on performance and quality of broilers. Poultry. Sci. 58:543-548.

Rachhpal-Singh and P. H. Nye. 1986. A model of ammonia volatilization from applied urea II. Experimental testing. J. Soil Sci. 37: 21-29.

Reece, F. N., B. D. Lott and J. W. Deaton. 1979. Ammonia control in broiler houses. Poultry Sci. 58: 754-755.

Reece, F. N., B. D. Lott and J. W. Deaton. 1980. Ammonia in the atmosphere during brooding affect performance of broiler chickens. Poultry Sci. 59: 486-488.

Ritz, C. W., B. D. Fairchild and M. P. Lacy. 2009. Litter quality and broiler performance University of Georgia Cooperative Extension Bulletin No. 1267.

Ritz, C. W., B. W. Mitchell, B. D. Fairchild, M. Czarick III and J. W. Worley. 2006. Improving in-house air quality in broiler production facilities using an electrostatic space charge system. J. Appl. Poultry. Res. 15:333–340.

Ritz, C. W.; B. D. Fairchild and M. P. Lacy. 2004. Implications of ammonia production and emissions from commercial poultry facilities: A review J. Appl. Poultry. Res. 13: 684-692.

Rong, L., P. V. Nielsen and G. Zhang . 2009. Effects of airflow and liquid temperature on ammonia mass transfer above an emission surface: experimental study on emission rate. Bioresource Technol. 100(20):4654-4661.

Ross Environmental Management (REM). 2010. Environmental Management in the Broiler House. Available at: http://en.aviagen.com/assets/Tech_Center/Ross_Broiler/Ross_Environmental_Management_in_the_Broiler_House.pdf. Accessed January 23, 2013.

Rothrock M. J. Jr., K. L. Cook, J. G. Warren, M. A. Eiteman and K. Sistani . 2010. Microbial mineralization of organic nitrogen forms in poultry litters. J Environ Qual. 39(5):1848-57.

Sahrawat, K. L. 1981. Effect of temperature and moisture on urease activity on semi-arid tropical soils. Plant Soil. 78: 401-408.

Sanyal, S. K. and S. K. De Datta. 1991. Chemistry of phosphorus transformations in soil. Adv. Soil Sci. 16: 1–120.

Schefferle, H. E 1965. The decomposition of poultry manure in built up poultry litter. J. Appl. Bact. 28 (3): 412-420

Shah, S., P. Westerman and J. Parsons. 2012. Pair quality education in animal agriculture - Poultry litter amendments. Available at: http://www.extension.org/sites/default/files/Litter%20Amendments%20FINAL.pdf. Accessed August 31, 2012.

Sims, J. T. and D. C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. Adv. Agron. 52: 1-83.

Sims, J.T. 1998. Phosphorus soil testing: Innovations for water quality protection. Commun. Soil Sci. Plant Anal. 29:1471–1489.

Sloan, D. R., R. H. Harms, D. Barnard and R. Nordstedt 1995. Effect of diet on feces composition and the implications on environmental quality. J Appl. Poultry Res. 4: 379-383.

Sommer, S. G. and J. E. Olesen. 1991. Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. J. Agr. Sci. 117:91-100.

Srinath, E. G. and R. C. Loehr 1974. Ammonia desorption by diffused aeration. J. Water Pollut. Control Fed. 46(8): 1939-1957

Tarrant , R. C. A. 2010. Influence of a biodegradable litter amendment on the pyrolysis of poultry litter. Master's Thesis Report. Virginia Tech. Available at: http://scholar.lib.vt.edu/theses/available/etd-09202010-154735/unrestricted/Tarrant_RCA_T_2010.pdf . Accessed: 09 September, 2012.

Thakre S. B., L. B. Bhuyar and S. J. Deshmukh. 2008. Mathematical models for overall gas transfer coefficient using different theories and evaluating their measurement accuracy. Int. J. Chem. Biomol. Eng. 1(4): 203-207.

Tsunogai, S. and K. Ikeuchi. 1968. Ammonia in the atmosphere. Geochem. J. 2: 157-166

Turnbull, P. C. B. & Snoeyenbos, G. H. 1973. The roles of ammonia, water activity, and pH in the salmonellacidal effect of long-used poultry litter. Avian Dis. 17: 72-86.

U.S. Department of Interior – National Park Service. 2012. The Nitrogen Cycle. Available at: http://www.nps.gov/plants/restore/pubs/biosolids/img/biosolids14.jpg. Accessed February 04, 2013.

U.S. Egg and Poultry Association. 2012. Industry FAQ: How much litter does a chicken produce? Available at http://www.uspoultry.org/faq/faq.cfm. Accessed January 31. 2013.

Valentine, H. 1964. A study of the effect of different ventilation rates on the ammonia concentration in the atmosphere of broiler houses. Brit. Poultry. Sci. 5:149-159.

Van Breemen, N., P. A. Burrough, E. J. Velthorst, et al. 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. Nature 299:548- 550.

Varel V. H., J. A. Nienaber and H. C. Freetly (1999). Conservation of nitrogen in cattle feedlot waste with urease inhibitors. J. Anim. Sci. 77: 1162-1168.

Varel V. H. (1997). Use of urease inhibitors to control nitrogen loss from livestock waste. Bioresour Technol 62(1): 11-17.

Virginia Department of Environmental Quality. 2012. Virginia Poultry Waste Management Requirements. Available at: http://www.deq.virginia.gov/Programs/Water/LandApplicationBeneficialReuse/LivestockPoultry/VirginiaPoultryWastenbspManagementRequirement.aspx. Accessed January 23, 2012.

Weast, R. C., M. J. Astle and W. H. Beyer. 1988. CRC Handbook of Chemistry and Physics. CRC Press, Inc., Boca Raton, Florida. Wheeler, E. F., K. D. Casey, R. S. Gates, H. Xin, J. L. et al. 2006. Ammonia emissions from twelve U.S. broiler chicken houses. Trans. ASABE 49(5): 1495−1512. Woodward, T. R., W. H. Frame, M. M. Alley, G. B. Whitehurst and B. M. Whitehurst. 2011. Design and Validation of a Laboratory System for Measurement of Volatilized Ammonia Agronomy J. 103(1):38-44.

Wu, K. and P. M. Hocking . 2011. Turkeys are equally susceptible to foot pad dermatitis from 1 to 10 weeks of age and foot pad scores were minimized when litter moisture was less than 30%.Poult Sci. 90(6):1170-8.

Xue, S.K., S. Chen, and R.E. Hermanson. 1998. Measuring ammonia and hydrogen sulfide emitted from manure storages. Trans. ASAE 41:1125–1130.

Yadav, D. S., V. Kumar, M. Singh and P. S. Relan. 1987. Effect of temperature and moisture on kinetics of urea hydrolysis and nitrification. Aust. J. Soil. Res. *2*5(2): 185 -191

Ye, Z.Y., G. Q. Zhang, B. M. Li, J. S. Stroem and P. J. Dahl. 2008. Ammonia emissions affected by airflow in a model pig house: effects of ventilation rate, floor slat opening and headspace height in a manure storage pit. Trans. ASABE 51(6): 2113–2122.

Youssef, I. M., A. Beineke , K. Rohn and J. Kamphues J. 2011. Effects of litter quality (moisture, ammonia, uric acid) on development and severity of foot pad dermatitis in growing turkeys. Avian Dis. 55(1):51-58.

Zhang, B. J. S. Bjerg, S. Strøm, P. Morsing, G. Kai, P. Tong and Ravn. 2008. Emission effects of three different ventilation control strategies- A scale model study, Biosystems Eng. 100(1): 96-104.

CHAPTER 3: MITIGATING AMMONIA EMISSION FROM BROILER HOUSES USING A NOVEL BIODEGRADABLE LITTER AMENDMENT

Abstract: Broilers are raised indoors on high density farms with bedding/litter to trap their manure. Ammonia gas, which is produced as the manure decomposes, has adverse effects on human health, bird welfare and the environment. Using litter amendments can reduce the amount and, consequently, the effects of ammonia emitted from broiler houses. The objective of this study was to determine the effectiveness of a biodegradable litter amendment (BLA) in reducing ammonia emitted from a broiler house.

A pilot scale test was set up with six adjacent, individually ventilated rooms and a stocking density of 0.07 m^2 per bird. The birds were fed with a standard commercial, corn and soybean meal based diet and water was provided ad libitum. The first flock was grown on 10 cm of fresh, kiln-dried pine shavings, while subsequent flocks were grown on top-dressed reused litter. The two treatments (control (CTL) and BLA) were randomly assigned to the six rooms after flock 1, to give three replicates per treatment. The exhaust air from the rooms was sampled for ammonia concentration for two days each week starting at four days of age to determine the amount of ammonia emitted.

Over three subsequent flocks, the total mass of ammonia emitted from rooms treated with BLA was 31% to 47% lower than the control. Ammonia emitted per bird grown on treated litter and per kg of harvested bird weight was 32% to 44% lower, and the exhaust fans ran 7% to 22% less than CTL over the same period. For both BLA and CTL, the amount of ammonia emitted generally increased with bird age and litter reuse. The study showed that BLA effectively reduced ammonia emitted from a broiler house and that there are potential energy savings from using the amendment. However, ammonia emitted from the BLA rooms during the final flock was 57% higher than CTL, which was attributed to insufficient water (less than 18% moisture by weight) to support the reaction between BLA and ammonia.

Keywords: *Ammonia, broiler litter, biodegradable, amendment, mitigation*

Introduction

Poultry production in the U.S. has increased immensely over the last 60 years, growing from 0.63 billion kg in 1950 to 16.7 billion kg in 2011 (NCC, 2012). The combined value of poultry production in 2011 was $35.6 billion, of which 65% was from broilers, 21% from eggs, 14% from turkeys, and less than 1% from chickens (USDA, 2012). The remarkable increase in production has been followed by a shift in the way the birds are raised. About half of U.S. broiler production is done on large farms with 1 to 4 houses with more than 20,000 birds each; operations with 5 or more houses account for slightly more than one quarter of total production (MacDonald, 2008). Broiler houses are large, covering approximately 1,500 to 3,000 square meters each, with about 15 birds per square meter (NCC, 2012). The birds are raised on bedding material (litter) for manure management. The litter is reused to grow several flocks to control production costs. Ammonia formed as manure in the litter decomposes accounts for almost 15% of total ammonia emitted to the environment from agricultural sources (EPA, 2004).

Previous studies have shown that ammonia released to the atmosphere has adverse effects on the environment (Barthelmie and Pryor, 1998, Jaworski et al., 1997, van Breemen et al., 1982), human health (Kim et al., 2005) and bird health (Beker et al., 2004, Carlile, 1984, Kling and Quarles, 1974). Therefore, control of ammonia emitted from production facilities is necessary to meet the growing demand for broiler meat without compromising bird welfare, environmental health or public health. Federal regulations (CERCLA Section 103 and EPCRA Section 304) currently exempt broiler farms that confine less than 125,000 birds at a time, from the reporting requirements for gaseous releases (including ammonia) to the atmosphere (EPA, 2009). However, production facilities still incorporate mitigation measures to decrease the effects and economic implications of ammonia on bird health, growth rate and feed efficiency (Shah et al., 2012).

Determining the amount of ammonia emitted from a broiler house requires building ventilation rate (VR) and ammonia concentration in the exhaust air to be ascertained, and is crucial in selection and evaluation of mitigation measures (Gates et al., 2002, Moody et al., 2008). Direct measurement of ammonia emitted from production facilities would be ideal but cannot always be implemented (Gates et al., 2002). Wide variations observed in ammonia emitted depending on season, time of day, type, age and number of birds (Burns et al., 2003, Burns et al., 2007, Wheeler et al., 2006) necessitate measurements over extended periods of time to capture all production phases (Gates et al., 2002).

Using a litter amendment such as Al^+ Clear, Poultry Guard^{TM} or PLT^{TM} is the most common method for reducing ammonia emitted from broiler houses (Shah et al., 2012). These are acidic compounds that control litter pH, inhibit microbial activity, slow conversion of uric acid to ammonia and keep ammonia in the non-volatile form. The effectiveness of amendments is typically highest immediately after application and decreases significantly towards the end of the flock. More than 80% reduction in ammonia emitted from broiler houses has been achieved using these products [Al^+ Clear (Moore et al., 2000), Poultry Guard^{TM} (McWard and Taylor, 2000) and PLT^{TM} (Pope and Cherry, 2000)]. However, Al^+ Clear, Poultry Guard^{TM} and PLT^{TM} which are made using strong inorganic acids, are corrosive to structures and may be harmful to handlers (Shah, 2012). Chemical amendments also decrease N mineralization in soils where the litter is used as fertilizer, reducing N availability to crops (Watts et al., 2012). Organic litter amendments such as acetic acid (Roach et al., 2009) and Litter Life^{TM} (HRC, 2013), which are not as corrosive or toxic as inorganic amendments, have been used successfully to reduce house ammonia concentrations and improve bird performance.

Agblevor et al. (2008) created biodegradable litter amendments (BLA) from agricultural residues for controlling the emission of ammonia and other odorous substances from organic waste. The BLA used for this study was developed from corn cobs through a steam treatment process, which is a combination of thermal, mechanical, and chemical processes (Agblevor et al., 2008). The corn cobs are loaded into a continuous steam explosion reactor with a coaxial feeder assembly. Steam is introduced into the reaction chamber and the temperature is raised to the appropriate value ranging from 180 to 240 °C for fixed residence times ranging from 1 min to 5 min (Agblevor et al., 2008). The combination of time and temperature defines the severity factor (Agblevor et al., 2008). By changing the severity factor, the properties, including acidity, surface area and particle size of the steam exploded corn cob material can be changed. The final product (BLA) has a level of acidity or pH ranging from 2 to 4 depending on the raw material and severity of the treatment (Agblevor et al., 2008). . This material could provide an alternative to inorganic litter amendments and a market for agricultural residues. The objective of this study was to determine the effectiveness of BLA in reducing ammonia emitted from a broiler house.

Materials and methods

House layout and equipment setup

This study was approved by the Virginia Tech Institutional Animal Care and Use Committee. A pilot scale test was conducted at the Virginia Tech Turkey Research Farm in Blacksburg, Virginia. The broiler house layout is shown in Figure 3-1.

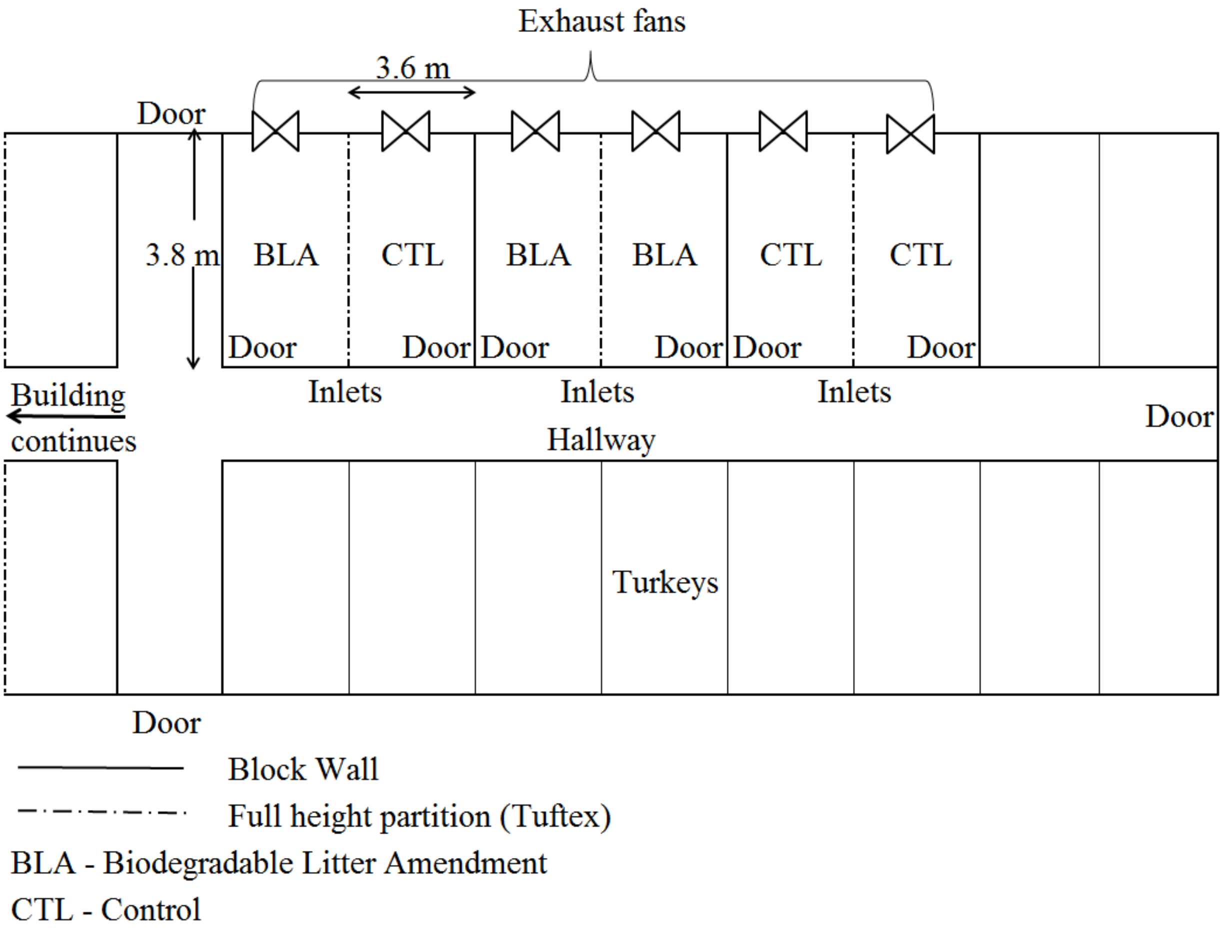


Figure 3-1: Broiler house layout (drawing not to scale)

Six adjacent rooms, each measuring 3.8m long by 3.6m wide and tapering in height from 3.3m at the inner wall to 2.7m at the external wall, were selected from a building with 36 similar rooms. Each room was separately ventilated using a 0.46m diameter, 230V exhaust fan (Model V4E4011M601004E40Q, Multifan, Vostermans Ventilation Inc, Bloomington, IL) and supplemental heat was provided with a 115V heating unit (Model 3UG73 Dayton, Grainger, Lake Forest, IL). The fans were turned on and off by a timer/thermostat controller (Model ECS-2M, Varifan, Vostermans Ventilation Inc, Bloomington, IL). Fresh air to each room was provided from a common hallway in the building via five inlets mounted on the wall at a height of approximately 0.5 m.

Performance curves (e.g. Figure 3-2) were developed for each fan by measuring air flow and the static pressure drop (ΔSP) across the fan. Air flow measurements were taken at the center of each rectangle (88 total) in a protective mesh around the fan using an anemometer (Testo 425, Testo GmbH & Co., Lenzkirch, Germany), and ΔSP cross the fan was measured using differential pressure transducers (Model 264, Setra, Boxborough, MA). This was repeated for three air inlet settings to provide different values for ΔSP. The average flow rate at each inlet setting was plotted against ΔSP to generate the performance curve for each fan. Room ventilation rates were determined from the fan performance curves using ΔSP, which was monitored continuously. The volume of air exhausted from each room over a given time period was calculated as the product of the VR (m^3/s) and the fan run time (s).

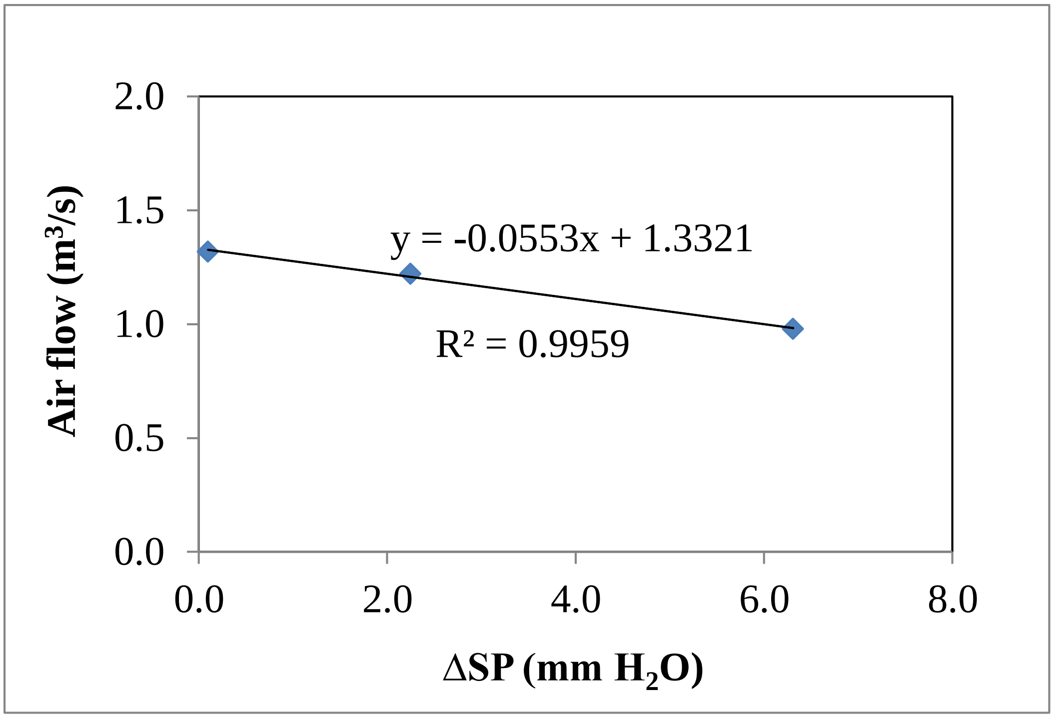


Figure 3-2: Fan performance curve showing the relationship between air flow and static pressure drop across the fan (ΔSP)

Birds, diet and house management

Five flocks of broilers were grown between March 30, 2011 and January 10, 2012. At the beginning of each flock, 180 day-old, straight run chicks (Cobb-Hubbard cross) were randomly placed in each room at 0.07 m^2 per bird and grown to 42 days (flock duration). The birds were fed a standard commercial corn and soybean meal based diet from three tube feeders using a 3-phase feeding program based on age for starters (0 to 18 days), growers (18 to 33 days) and finishers (33 to 42 days), with 24%, 18% and 20% protein respectively. Water was provided ad libitum via nipple drinkers and at 42 days the birds were euthanized by manual cervical dislocation. The relative location of feeders, waterer, fans and portable monitoring units (PMU) are shown Figure 3-3.

During the first week of the flock, room temperature was set at 32 °C and minimum ventilation was managed by a timer set to turn the fans on for 30 seconds every three minutes. The room temperature was reduced by 2 °C every week until 20 °C was attained. When the room temperature exceeded the desired setting, the exhaust fan was switched on to maintain the desired indoor temperature. Between flocks, the fans were operated on a timer at 60 seconds every three minutes for about 7 days to prevent buildup of ammonia within the rooms.

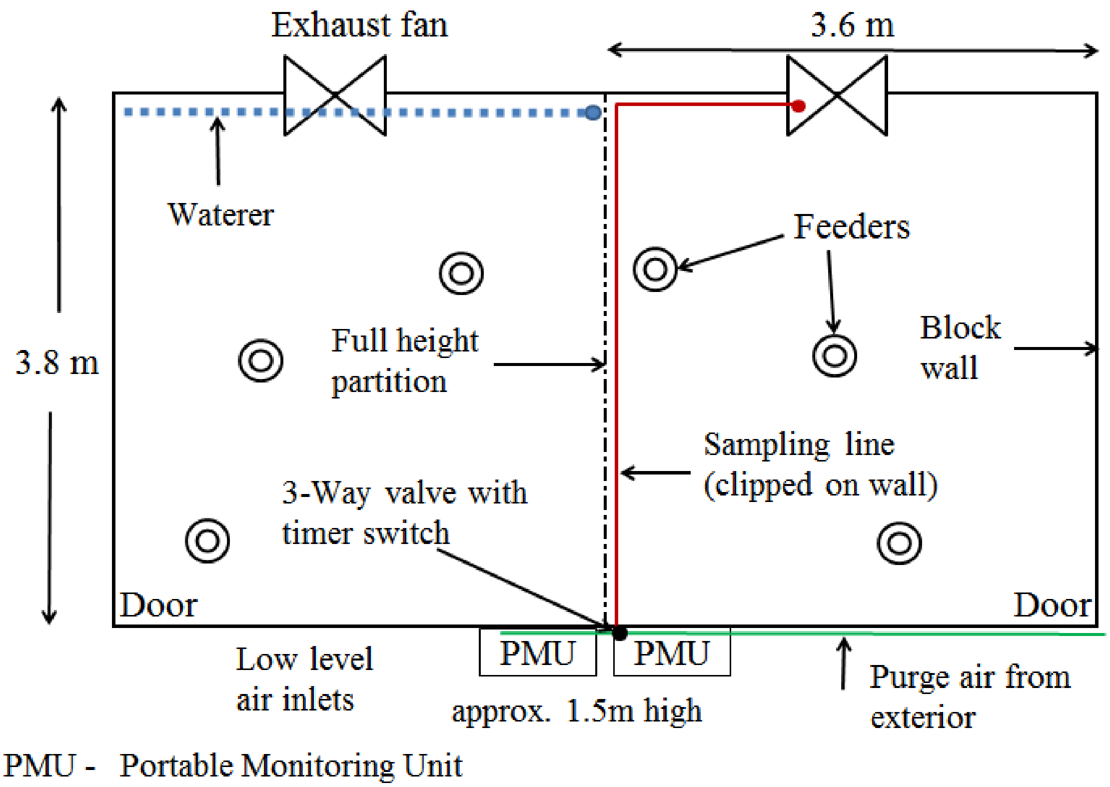


Figure 3-3: Setup of equipment within rooms (drawing not to scale)

Litter management and BLA application

The BLA used for the study was produced by Agblevor et al. (2008). The first flock was grown on 10 cm of fresh, kiln-dried pine shavings, while subsequent flocks were grown on top-dressed reused litter. The two treatments (CTL and BLA) were randomly assigned to the six rooms after flock 1, to give three replicates per treatment. Between flocks, caked litter was manually removed but was not weighed. Application of BLA was done using handheld spreaders 24 hours after the caked litter was removed. The BLA application rate was calculated based on expected manure production over each flock. Ammonia in the litter and organic acids in BLA react according to equation 3-1. The BLA dose (0.67 kg/m^2) was the amount required to react with ammonia produced from 1.2 kg of manure per bird with 1% total N concentration as excreted (ASABE, 2010).

$$C_nH_{n+2}COOH + NH_3 \longrightarrow NH_4(C_nH_{n+2}COO) \qquad 3\text{-}1$$

All rooms received a 2.5 cm top-dress of new shavings and were pre-heated for 24 hours before the next flock was introduced. Assignment of treatments to rooms was maintained for flocks 2 through 5.

Ammonia emissions data collection

Ammonia concentration data were collected once a week starting on day 4, for 48 continuous hours (assessment period). The duration of data collection was restricted by the logging capacity of the ammonia sensors. Exhaust ammonia and carbon dioxide concentrations were measured using Pac III (Dräger Inc., Pittsburgh, PA) and Model GMT222 (Vaisala, Vantaa, Finland) sensors, respectively, located in the PMU (Figure 3-4) and configured to record data every 30 seconds. Exhaust air analysis was done for five minutes, followed by a twenty-five minute purge with outdoor air to prevent saturation of the ammonia sensors. The sensors were calibrated before and after each assessment period using outdoor air (0 ppm) and 30ppm ammonia gas certified ± 5% (Airgas, Radnor, PA). A two-point calibration was used because the response of the electrochemical sensors is linear over the measurement range, with 0% to 2% tolerance (Dräger, 2007). The same cylinder of certified gas was used for all calibrations.

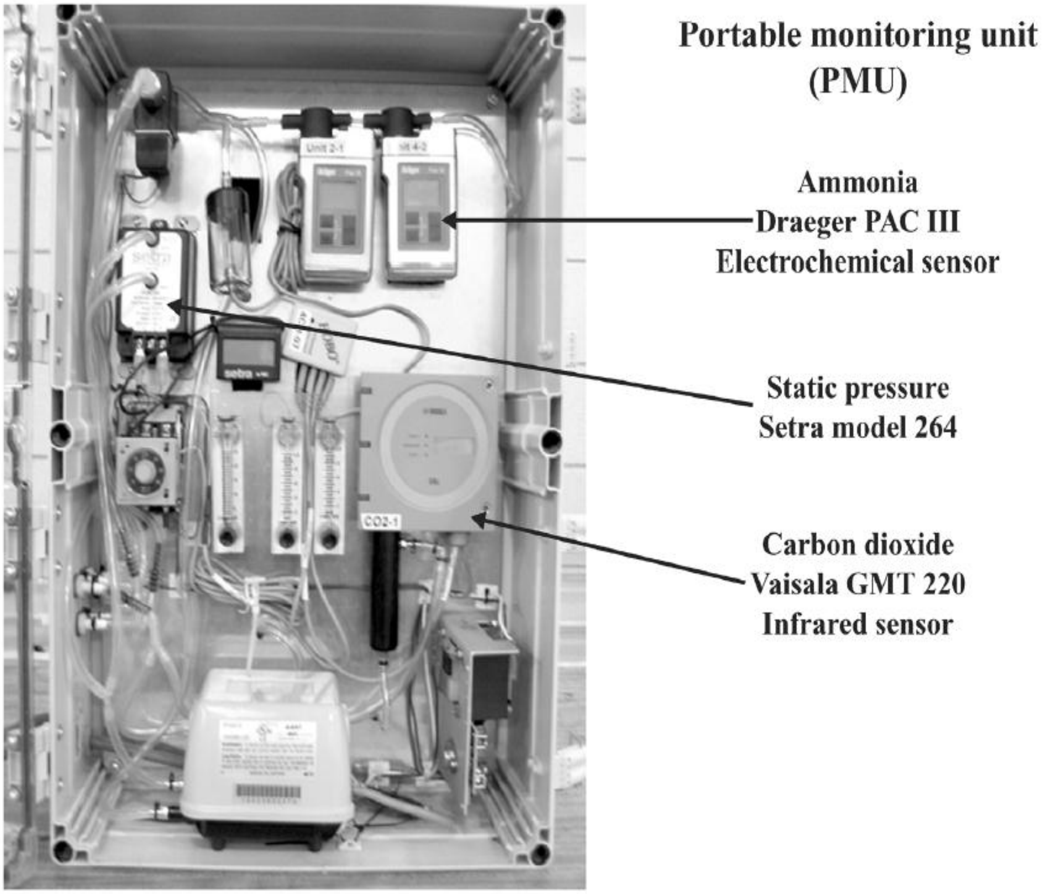


Figure 3-4: Layout of sensors in a portable monitoring unit (Gates et al., 2005)

The outdoor temperature range during the study was obtained from observed weather data for Blacksburg, VA (NCDC, 2013). Room temperature and relative humidity were recorded at one-minute intervals using stand-alone data loggers (OM-EL-USB-2-LCD, Omega Engineering, Stamford, CT). Litter temperature was also measured at one-minute intervals using air/water/soil temperature sensors (HOBO TMC6-HD, Onset Computer Corp, Cape Cod, MA) and recorded using 4-Channel External Data Loggers (HOBO U12-006, Onset Computer Corp, Cape Cod, MA). The operational status (on vs. off) of each fan was recorded using Motor On/Off Data Loggers (HOBO U9-004, Onset Computer Corp, Cape Cod, MA). The fan run time during any given time interval was determined from motor logger data as the duration of the "on" status.

Calculating mass of ammonia emitted

The assessment period was subdivided into 30-minute intervals, based on the sample (5 minutes) and purge (25 minutes) requirements of the ammonia sensors. Ammonia concentration from the first and last minutes of each 5-minute sampling period were excluded from the analysis because of possible residual effects from switching between sample and purge states. The residual effects were characterized by sharp rises or drops in ammonia concentration before a stable reading was attained. The average ammonia concentration during the sampling period was assumed to be representative of the exhaust air during the 30-minute (sample/purge) interval (Amaral et al., 2007). The mass of ammonia emitted from the building during each 30-minute sampling interval was calculated using equation 3-2, adapted from Wheeler et al., (2006).

$$\mathrm{ER} = \left(\mathrm{VR} * \frac{\mathrm{W_m}}{\mathrm{V_m}} * \frac{\mathrm{T_{Std}}}{\mathrm{T_{rm}}} * \frac{\mathrm{P_a}}{\mathrm{P_{std}}} * [\mathrm{NH_{3\,out}} - \mathrm{NH_{3\,in}}\,] * 10^{-6} * \mathrm{time} \right) \qquad 3\text{-}2$$

where

ER = mass of NH_3 emitted during 30-minute period (g NH_3)

VR = ventilation rate (m^3/s)

W_m = molar weight of NH_3 (17.031 g/mole)

V_m = molar volume of NH_3 at standard temperature (0 °C) and pressure (101.325 kPa)

T_{Std} = standard temperature (273.15 K)

T_{rm} = absolute room temperature, (°C + 273.15) K

Pa = Atmospheric pressure for Blacksburg, VA (kPa)

P_{Std} = standard atmospheric pressure (kPa)

$NH_{3\ out}$ = NH_3 concentration in exhaust air (ppmv)

$NH_{3\ in}$ = NH_3 concentration in inlet air (ppmv)

time = total fan run time during a 30-minute interval (s)

Ammonia emitted during 30-minute intervals (calculated above) was summed and divided by the duration of assessment period (2 days) to obtain the average daily emissions. The total ammonia emitted each week was estimated as the product of the average daily emissions and the total fan run time (days) between assessment periods. Ammonia emissions for each week were summed to determine the total amount of ammonia emitted during a given flock.

The total mass of ammonia emitted during the each flock was divided by the number of birds grown and flock duration to obtain ERs (g/bird^{-}day) for comparison to published data. The amount of ammonia emitted per kilogram of live weight (g/kg) at different growth stages was calculated by dividing the ammonia emissions by the total live flock weight.

Litter sampling and analysis

Litter samples were collected within 24 hours of harvesting the birds, from three locations in each room: around the waterer (W), the feeders (F) and rest areas (R) away from the feeders and waterer. Three samples (approximately 1 kg each) were taken from each location for a total of nine samples per room or 27 samples per treatment. This targeted sampling was done to assess effect of feeding and drinking activities on the moisture and nutrient content of the litter (Maguire et al., 2006; Patterson et al., 1998).

The litter samples were stored at 4 ^{o}C and analyzed for TAN within 48 hours of collection. Approximately two grams of litter, weighed using an analytical balance, were placed in an Erlenmeyer flask and 100ml of de-ionized water added. The flasks were sealed with parafilm and the contents mixed thoroughly on a rotary shaker at 175 rpm for one hour. The TAN concentration was determined using an ammonia selective electrode (Orion 9512, Themo Electron Corporation, Waltham, MA), Method 4500-NH_3D from Standard Methods for Examination of Water and Wastewater (APHA, 2012). The millivolt (mV) output from the meter is proportional to the $\log_{10}$ of the TAN concentration. Calibration curves were generated by plotting mV readings against concentration for standards ranging from 10 to 1000 mg/L on semi-log paper and used to determine the unknown litter TAN concentration. The electrode was checked for calibration twice daily and the membrane and filling solution were replaced weekly, as recommended by the manufacturer.

Litter moisture content was determined as the percentage change in weight after drying at 105 ^{o}C for 24 hours (Peters et al., 2003). Litter pH was determined using a combination pH meter (Orion 9512, Thermo Electron Corporation, Waltham, MA) for a 2:1 deionized water to litter ratio. The pH electrode was checked for calibration daily. TN and mineral content analysis was done on dry samples by a commercial laboratory using combustion method.

Statistical analysis

A completely randomized design with repeated measures was used for this study; with each room as an experimental unit and three replicates per treatment. The null hypotheses were that time-treatment interaction did not occur, and the mass of ammonia emitted from treatment and control was the same. The statistical model is shown in equation 3-2. Paired t tests were done using SAS JMP Version 9.0 Software (SAS Institute Inc., Cary, NC) to compare ammonia emitted from BLA and CTL at a significance level of 0.05.

$$y_{ijk} = \mu + \tau_i + d_{ij} + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \qquad 3\text{-}2$$

where:

μ = mean response

τ_i = i^{th} treatment effect

β_j = j^{th} time effect

$(\tau\beta)_{ij}$ = treatment-time interaction

$d_{ij} \sim N(0, \sigma_d^2)$

$\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon^2)$

Results and discussion

The weekly run time for both BLA and CTL exhaust fans during flocks 2 through 5 is shown in Table 3-1. Comparisons between BLA and CTL were made on a weekly basis for each flock. Differences in mean fan run time for BLA and CTL were statistically significant for week 6 of flock 4. However, on average, the exhaust fans in BLA rooms ran 7%, 9% and 22% less than the CTL during flocks 2, 3 and 4, respectively, to maintain the same set temperature. Fan run time generally increased with bird age but fluctuations in outdoor temperature had a direct effect on fan operation. During flock 2, a drop of 3°C in observed outdoor temperature between week 1 and week 2 caused the fan run times to decrease by 50% and 72% for BLA and CTL, respectively.

Table 3-1: Exhaust fan run time in hours (mean ± std. dev) during flocks 2 through 5

Flock		Wk1	Wk2	Wk3	Wk4	Wk5	Wk6	Total
2	BLA	56 ± 42^{a}	29 ± 9^{b}	43 ± 16^{c}	78 ± 17^{d}	142 ± 8^{e}	134 ± 9^{f}	482 ± 48^{h}
	CTL	76 ± 10^{a}	25 ± 5^{b}	53 ± 29^{c}	74 ± 8^{d}	144 ± 8^{e}	147 ± 8^{g}	531 ± 51^{h}
3	BLA	145 ± 24^{b}	75 ± 51^{c}	35 ± 4^{a}	136 ± 5^{e}	147 ± 2.4^{f}	158 ±10^{h}	697± 50^{g}
	CTL	162 ± 51^{b}	114 ± 45^{c}	40 ± 15^{a}	142 ± 11^{e}	153 ± 9^{f}	153 ±12^{h}	718 ± 44^{g}
4	BLA	112 ± 29^{c}	128 ± 30^{d}	70 ± 53^{e}	27 ± 32^{f}	18 ± 2^{h}	54 ± 5^{i}	68 ± 44^{i}
	CTL	115 ± 15^{c}	142± 19^{d}	113 ± 13^{e}	47 ± 33^{f}	35 ± 14^{h}	72 ± 20^{h}	87 ± 42^{i}
5	BLA	77 ± 20^{e}	75 ± 18^{e}	65 ± 20^{f}	102 ± 24^{a}	100 ± 33^{a}	116 ± 26^{a}	89 ± 20^{c}
	CTL	71 ± 39^{e}	63 ± 31^{e}	66 ± 38^{f}	89 ± 53^{a}	115 ± 53^{a}	98 ± 59^{a}	84 ± 21^{c}

A common superscript for BLA and CTL during a given week for any flock indicates means that are not significantly different ($p>0.05$).

The use of litter amendments for ammonia mitigation slows down microbial processes and, consequently, heat generation from the litter (Ritz et al., 2004; Shah et al., 2012). Cost savings from reduced ventilation requirements have been reported during use of commercial products such as alum and PLT for control of ammonia in broiler houses (Shah et al., 2012). However, dry amendments such as alum and BLA require water for activation and insufficient litter moisture content (less than 20%) coupled with residual ammonia from flock 4 necessitated an increase VR during flock 5, and exhaust fans for the BLA rooms ran approximately 6% more than the CTL.

The mass of ammonia emitted each week from BLA and CTL for flocks 2 through 5 is presented in Table 3-2. The ammonia emitted from the BLA rooms was significantly lower ($p<0.05$) than CTL during week 1 of flock 2, and weeks 4 and 5 of flock 4. Total ammonia emitted from the BLA rooms over flocks 2, 3 and 4 (6 weeks each) was 38%, 31% and 47%, respectively, lower than CTL. The BLA achieved 72% reduction in ammonia emitted during week 1 of flock 2, compared to only about 30% reduction during week 6. The mass of ammonia emitted from the BLA rooms during flock 3 was 30% to 45% lower than CTL. The greatest reduction in ammonia emitted (84%) by BLA was achieved during weeks 4 and 5 of flock 4. Ammonia emissions from BLA and CTL rooms generally increased with bird age and litter reuse as expected (Wheeler et al., 2008; Burns et al, 2007). This is due to increased VR, manure production and, consequently, ammonia generation, as the birds grow older.

Table 3-2: Weekly mass of ammonia emitted (mean ± std. dev) for flocks 2 through 5

Flock	Treatment	Wk1 (kg)	Wk2 (kg)	Wk3 (kg)	Wk4 (kg)	Wk5 (kg)	Wk6 (kg)	Total (kg)
2	BLA	0.06 ± 0.08^{a}	0.06 ± 0.03^{c}	0.15 ± 0.04^{d}	0.63 ± 0.16^{e}	0.86 ± 0.37^{f}	0.97 ± 0.30^{g}	2.72 ± 0.42^{h}
	CTL	0.21 ± 0.03^{b}	0.07 ± 0.01^{c}	0.43 ± 0.36^{d}	0.87 ± 0.26^{e}	1.28 ± 0.41^{f}	1.54 ± 0.69^{g}	4.38 ± 0.60^{h}
	% reduction	72.6	15.3	65.1	27.3	33.0	38.04	38.0
3	BLA	0.42 ± 0.50^{c}	0.25 ± 0.16^{d}	0.17 ± 0.06^{e}	0.70 ± 0.44^{f}	0.71 ± 0.58^{g}	1.80 ± 0.41^{h}	4.04 ± 0.60^{i}
	CTL	0.62 ± 0.50^{c}	0.44 ± 0.15^{d}	0.25 ± 0.10^{e}	1.20 ± 0.68^{f}	1.22 ± 0.88^{g}	2.14 ± 0.95^{h}	5.87 ± 0.69^{i}
	% reduction	32.3	43.6	33.2	42.0	42.0	15.7	31.1
4	BLA	1.15 ± 0.75^{d}	0.68 ± 0.74^{e}	0.23 ± 0.19^{f}	0.11 ± 0.14^{g}	0.09 ± 0.02^{i}	0.84 ± 0.42^{k}	3.10 ± 0.44^{l}
	CTL	1.23 ± 0.25^{d}	1.06 ± 0.14^{e}	0.69 ± 0.24^{f}	0.68 ± 0.15^{h}	0.57 ± 0.38^{j}	1.63 ± 0.54^{k}	5.87 ± 0.41^{m}
	% reduction	6.7	36.2	67.1	83.8	83.6	48.6	47.1
5	BLA	0.53 ± 0.39^{e}	1.04 ± 0.81^{f}	1.58 ± 1.06^{g}	0.68 ± 0.60^{h}	0.47 ± 0.25^{i}	0.41 ± 0.17^{j}	0.79 ± 0.45^{k}
	CTL	0.21 ± 0.15^{e}	0.68 ± 0.58^{f}	0.91 ± 0.72^{g}	0.61 ± 0.40^{h}	0.22 ± 0.14^{i}	0.36 ± 0.27^{j}	0.50 ± 0.28^{k}
	% reduction	-153	-54.0	-73.6	-11.3	-111.3	-11.8	-57.5

A common superscript for BLA and CTL during a given week for any flock indicates means that are not significantly different ($p>0.05$).

More ammonia (not significantly higher) was emitted from the BLA rooms than CTL during flock 5, which might be the combined effect to low relative humidity and litter moisture content. The average relative humidity for flock 5 was only 44%, compared to 59%, 66% and 67% for flocks 2, 3 and 4, respectively. During weeks 1 and 5 of flock 5, when ammonia emitted from the treated rooms was more than double that of CTL, RH was below 40%. It has been observed that the ideal range for relative humidity in a broiler house is 60% to 70% (REM, 2010). When RH is above 70%, there is a possibility of moisture buildup in the litter and a subsequent increase in ammonia emitted (REM, 2010). However, when the RH drops below 50%, dry and dusty conditions develop and could result in increased release of ammonia bound to dust particles (Ritz et al., 2006; REM, 2010). The overall litter moisture content for both BLA and CTL decreased with reuse, and was significantly lower ($p<0.05$) during flock 5 compared to flock 2. Since dry litter amendments require water for activation, there was probably inadequate water to support the acid-base reaction between BLA and ammonia.

The start and end dates, outdoor temperature range, room temperature, litter moisture content, total ammonia nitrogen (TAN) and total nitrogen (TN) concentration for each flock are shown in Table 3-3. Mean room temperature was highest ($30 \pm 1.5\ ^{o}$C) for flocks 2 and 3, grown during summer. Flock 4, which was grown during the fall, had a mean room temperature of $25 \pm 1.0\ ^{o}$C; while flock 5 was a winter flock with a mean room temperature of $20.5 \pm 0.5\ ^{o}$C.

Table 3-3: Environmental conditions and litter characteristics during the study

	Treatment	Flock 1	Flock 2	Flock 3	Flock 4	Flock 5
Start Date		March 30	June 7	August 3	October 6	December 1
End Date		May 12	July 18	Sep 15	November 16	January 10
Outdoor Temp. (^{o}C)						
High		19.2 ± 6.4	28.1 ± 2.8	27.9 ± 3.4	17.0 ± 5.2	9.0 ± 5.0
Low		5.5 ± 4.4	15.5 ± 2.8	14.9 ± 3.1	2.7 ± 5.2	-3.1 ± 4.5
Room Temp. (^{o}C)	BLA	NA	30.4 ± 0.3^{b}	30.6 ± 0.3^{b}	24.6 ± 0.6^{c}	20.3 ± 0.3^{d}
	CTL		30.6 ± 0.6^{b}	31.1 ± 0.8^{b}	24.9 ± 0.6^{c}	20.7 ± 1.1^{d}
Litter Temp. (^{o}C)	BLA	NA	26.0 ± 0.35^{a}	26.9 ± 0.33^{b}	24.4 ± 0.45^{c}	21.0 ± 0.05^{d}
	CTL		25.6 ± 0.38^{a}	26. 6 ± 0.53^{b}	24.4 ± 0.38^{c}	21.6 ± 0.17^{d}
TAN (g/kg)	BLA	NA	5.34 ± 0.25^{c}	4.41 ± 0.22^{d}	6.99 ± 0.37^{e}	3.80 ± 0.20^{f}
	CTL		5.84 ± 0.25^{c}	4.48 ± 0.22^{d}	7.10 ± 0.38^{e}	3.98 ± 0.20^{f}
TN (g/kg)	BLA	NA	32.9 ± 1.70^{g}	31.4 ± 1.79^{g}	32.7 ± 1.70^{g}	36.4 ± 1.00^{h}
	CTL		31.0 ± 1.70^{g}	31.3 ± 1.79^{g}	33.0 ± 1.70^{g}	37.2 ± 1.00^{h}
Litter Moisture Content (%)	BLA	NA	27.7 ± 1.54^{d}	24.0 ± 1.42^{d}	20.7 ± 1.45^{e}	18.8 ± 1.00^{e}
	CTL		26.0 ± 1.54^{d}	24.9 ± 1.42^{d}	21.1 ± 1.45^{e}	18.0 ± 1.00^{e}
Litter pH	BLA	NA	8.07 ± 0.11^{e}	7.90 ± 0.12^{e}	8.04 ± 0.10^{e}	7.30 ± 0.12^{f}
	CTL		8.22 ± 0.11^{e}	8.10 ± 0.12^{e}	8.04 ± 0.10^{e}	7.40 ± 0.12^{f}

NA = Not applicable. A common superscript for BLA and CTL for any flock indicates means that are not significantly different ($p>0.05$). Also applies to comparisons between flocks within treatments.

Differences in moisture, TAN and TN between BLA and CTL were not statistically significant for any given flock. For both BLA and CTL, litter from flock 4 had significantly higher TAN compared to other flocks. There was condensation of water vapor in the rooms as outdoor temperatures dropped. The effect of the condensation on litter moisture content and, consequently, the significantly higher litter TAN and ammonia emitted during flock 4 compared to other flocks was not determined since litter samples were only analyzed at the end of the flock.

For both BLA and CTL, litter temperature was significantly lower during flock 5 (winter) compared to previous flocks. The amount of ammonia emitted from the CTL rooms was significantly lower than previous flocks because ammonia generation and emission from broiler litter decreases with litter temperature. The significantly higher ammonia emitted from the BLA rooms during flock 5 was because low litter moisture content rendered the amendment ineffective. Litter temperature increased with flock age and the amount of ammonia emitted was significantly higher during week 6 compared to week 1.

Example 48-hr litter and room temperature profiles taken during flock 2, which had the largest variation in room temperature, showed that diurnal changes in litter temperature were not as large as for room temperature (Figure 3-5). Temperatures in the BLA and CTL rooms increased by approximately 6^{o}C over 12 hours but litter temperature remained fairly constant around 25.0 ^{o}C.

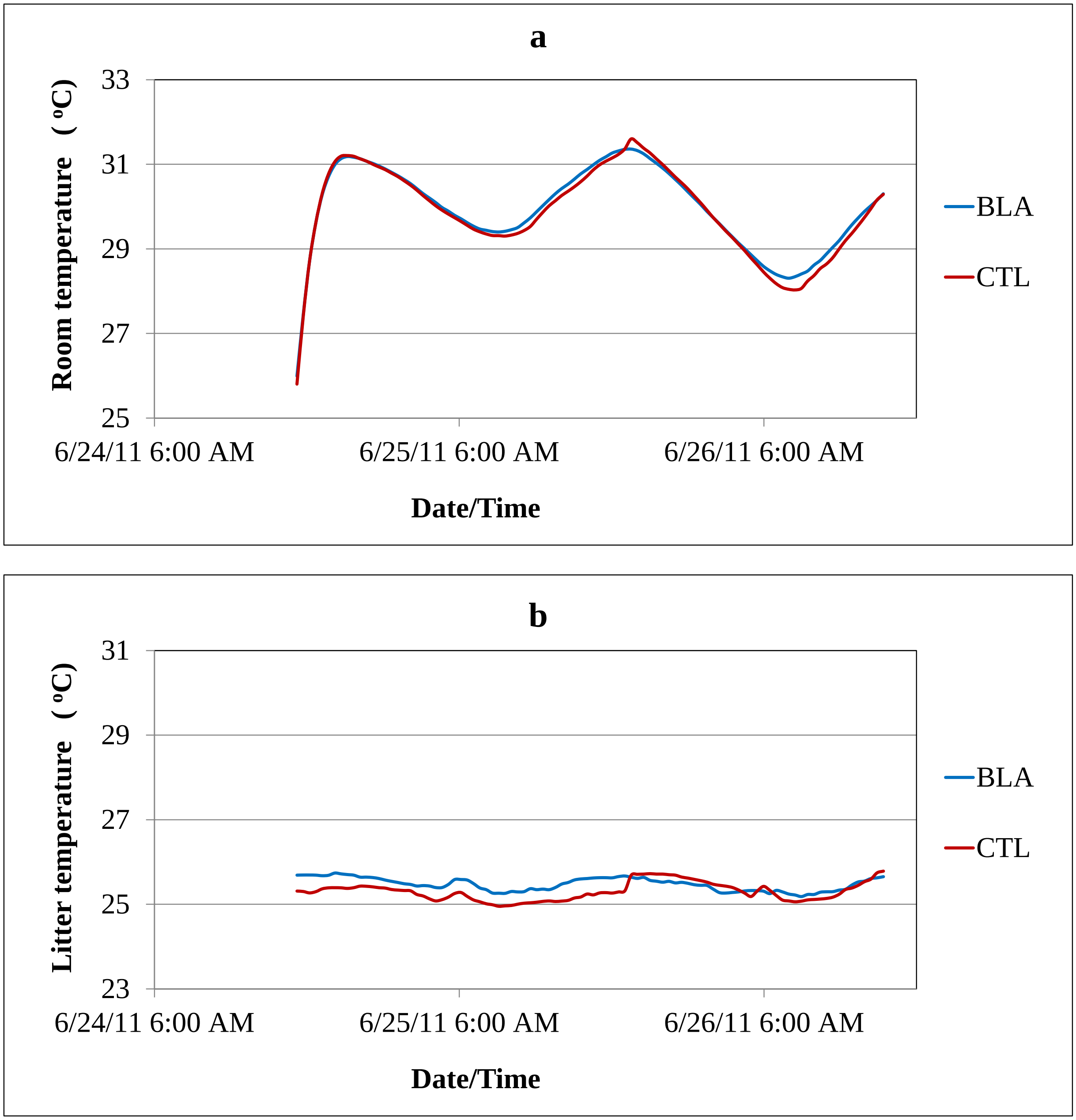


Figure 3-5: Diurnal changes in room temperature (a) and litter temperature (b) during flock 2 (summer)

Differences in room and litter temperature between BLA and CTL were not statistically significant for any flock. This is of importance because the amount of ammonia emitted from broiler house increases with increasing air and litter temperature. Since conditions within the BLA and CTL rooms were not significantly different, the differences in ammonia emitted can be attributed to the use of BLA.

The ERs (g/bird^{-}day) from this study are compared to published data in Table 3-4.

Table 3-4: Mean daily ammonia emission rate from this study vs. published data

Source		**BLA** (g/bird-day)	**CTL** (g/bird-day)	**Stocking density** (birds/m^2)	**Flock duration** (days)	**Bird weight** (kg)
This Study	Flock 2	0.64 ± 0.39	1.01 ± 0.52	13.2	42	2.80
	Flock 3	0.83 ± 0.43	1.20 ± 0.52	13.2	42	2.95
	Flock 4	1.19 ± 0.74	2.04 ± 0.69	13.2	42	2.80
	Flock 5	1.26 ± 0.69	1.14 ± 0.36	13.2	42	2.62
Burns et al., 2007		NA	0.62	12.3	54	NR
Wheeler et al., 2006		NA	0.65	14.7	42	2.20
Burns et al., 2003		NA	0.92	16.1	42	2.30
Lacey et al., 2003		NA	0.63	13.5	49	1.03
Siefert et al., 2004		NA	1.18	20.0	42	NR

NR = Not Reported, NA = Not applicable

Different assessment methods were used to determine ER in different studies but the recommended best practice and most accurate method is to continuously monitor ammonia emitted from the facility over an extended duration, including downtime when houses are empty, and attribute the emissions to the number of birds grown (Gates et al., 2002). This approach, used by Burns et al. (2007), is not always practical. In this study, for example, the assessment period was determined by equipment limitations and no measurements were taken during downtime.

With the exception of flock 2 (BLA), the calculated ERs from this study are at least 30% higher than reported values for birds growing on reused litter, for the same duration at similar stocking density. This could be due to differences in barn environment, type, size, and even activity level of the birds being grown. However, the amount of ammonia emitted also increases when birds are raised to greater weights on built-up litter (Wheeler et al., 2008); and the birds in this study were approximately 34% and 190% larger at the end of each flock compared to those in the studies by Wheeler et al. (2006) and Lacey et al. (2003), respectively.

The ER, VR (m^3/hr), ammonia concentration (mg/m^3) and total ammonia emitted (kg) during flock 3 (Aug. to Sept. 2011) are shown in Figure 3-6. A decrease of 10°C in observed outdoor temperature during weeks 2 and 3 resulted in 80% decrease in VR and 35% decrease in ammonia emitted. However, there was a five-fold increase in room ammonia concentrations because reducing VR causes a buildup of ammonia in the house. The highest ammonia concentration for flock 3 was recorded during this period. Similar observations were made by Gates et al. (2004) who reported 19% reduction in VR and 11% decrease in NH_3 emitted for a drop of 3°C in average outdoor temperature between monitoring periods.

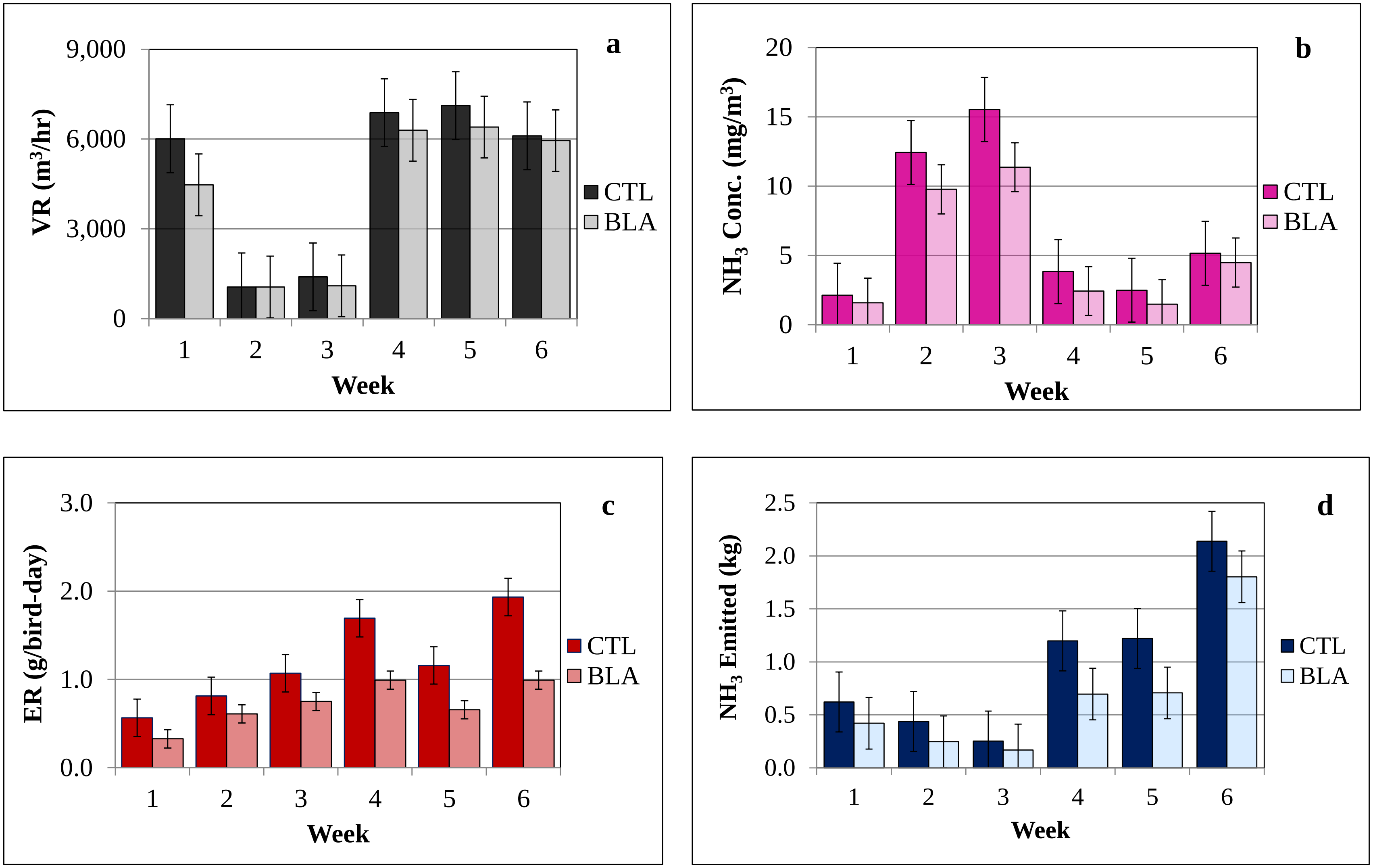


Figure 3-6: Ventilation rate (VR), room NH_3 concentration, emission rate (ER) and NH_3 emitted during flock 3 (Aug to Sep. 2011)

The ER increased from the start of the flock to week 4, dropped during week 5 and increased again during 6; a trend that was also observed by Burns et al. (2007). These observations demonstrate the effect of outdoor conditions on VR and, consequently, room ammonia concentrations and the amount of ammonia emitted, and illustrate why using room ammonia concentrations without taking VR into consideration would be an inaccurate approach to assessing the effectiveness of ammonia mitigation methods.

The mean VR, NH_3 concentration, ER and total ammonia emitted, for BLA and CTL rooms during flocks 2 through 5 are shown in Figure 3-7. Total ammonia emitted from the BLA rooms was 36%, 31% and 47% lower than CTL for flocks 2, 3 and 4, respectively. The mean ER for CTL during flock 4 was significantly higher than for other flocks. The significantly higher mean ER for flock 4 could be due to residual ammonia from flock 3. However, flock 4 also had significantly higher litter TAN concentration compared to other flocks, which could be another explanation for the observed ERs. Elevated ammonia concentrations were observed during flock 5 (winter), which necessitated an increase in VR for both BLA and CTL. The BLA rooms had significantly higher VR than CTL and 57% more ammonia was emitted from the BLA rooms. The mean daily ER for the BLA rooms during flock 5 was also 10% higher than CTL.

The NH_3 emitted per kg live bird weight (LW) at different growth stages during four flocks is shown in Table 3-5. Ammonia emission per kilogram of live weight generally decreased from beginning to the end of the flock and increased with litter reuse. The BLA had lower ammonia emitted per kg of live weight at all stages during flocks 2 to 4 and the final stage of flock 5. The BLA had 37%, 33%, and 44 % less ammonia emitted per kg of harvested bird weight than CTL during flocks 2, 3, and 4, respectively.

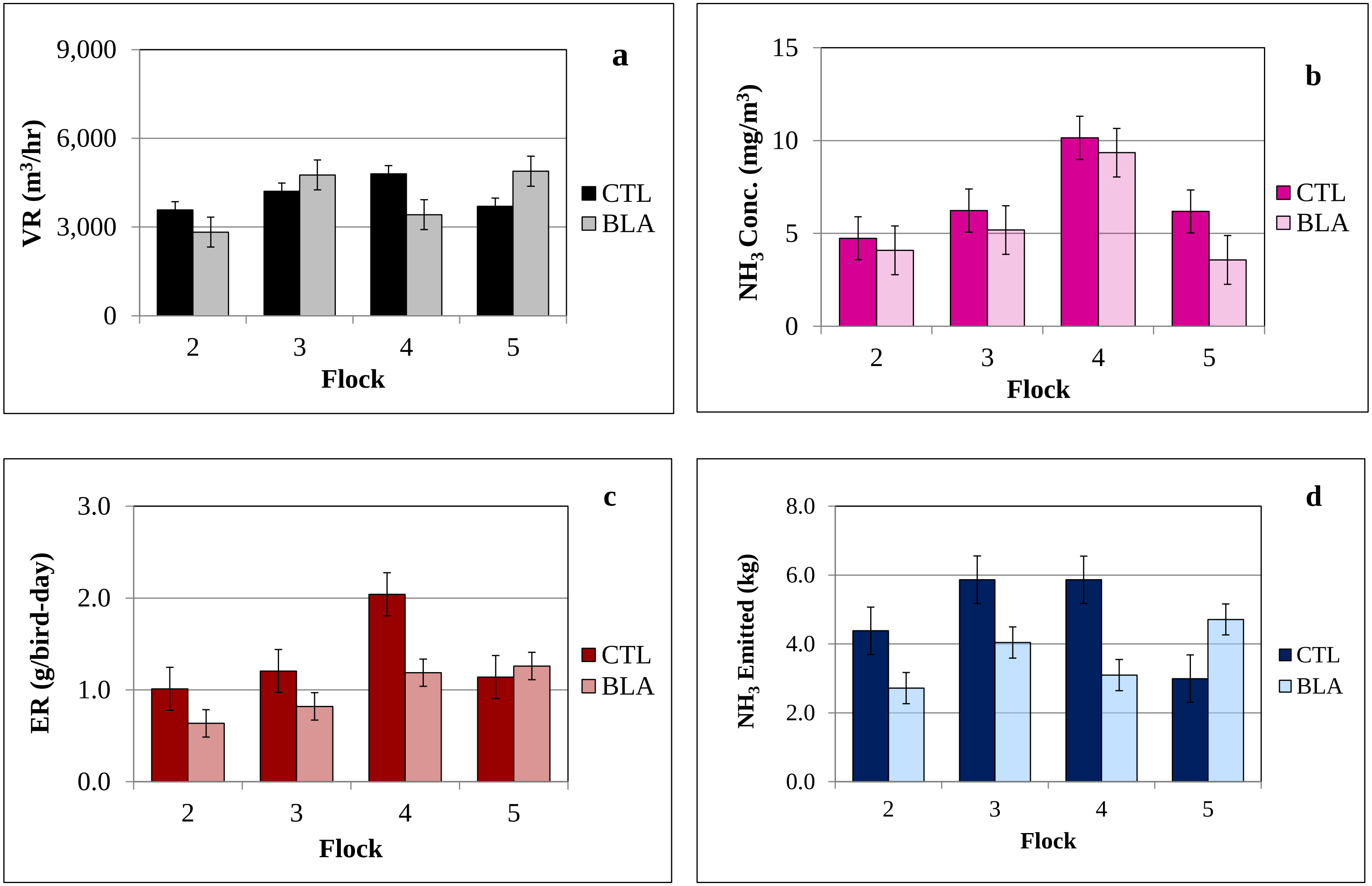


Figure 3-7: Ventilation rate (VR), NH_3 concentration, emission rate (ER) and NH_3 emitted during flocks 2 through 5 (Jun. 2011 to Jan. 2011)

Table 3-5: Ammonia emission rate (ER) per kg of live flock weight (LW) at different growth stages during flocks 2 through 5

Flock	Treatment	Weigh 1 (Day 1)		Weigh 2 (Day 15 – 17)		Weigh 3 (Day 33-35)		Weigh 4 (Day 41-43)	
		ER (g/kg)	LW (kg)	ER (g/kg)	LW (kg)	ER (g/kg)	LW (kg)	ER (g/kg)	LW (kg)
2	BLA	1.08 ± 0.81^{a}	23.5 ± 0.2^{h}	0.71 ± 0.26^{c}	135 ± 2^{d}	0.52 ± 0.18^{e}	315 ± 19^{f}	0.34 ± 0.11^{g}	459 ± 21^{i}
	CTL	3.22 ± 0.56^{b}	23.5 ± 0.1^{h}	1.17 ± 0.43^{c}	133 ± 2^{d}	0.78 ± 0.29^{e}	316 ± 19^{f}	0.46 ± 0.23^{g}	462 ± 21^{i}
3	BLA	2.53 ± 2.9^{c}	25.2 ± 0.1^{d}	1.02 ± 0.41^{e}	132 ± 1^{f}	0.38 ± 0.31^{g}	322 ± 2^{h}	0.33 ± 0.11^{a}	508 ± 15^{b}
	CTL	4.13 ± 3.2^{c}	25.3 ± 0.2^{d}	1.51 ± 0.58^{e}	132 ± 1^{f}	0.67 ± 0.53^{g}	319 ± 3^{h}	0.57 ± 0.21^{a}	501 ± 5^{b}
4	BLA	13.9 ± 7.7^{d}	23.5 ± 0.1^{e}	0.49 ± 0.41^{f}	138 ± 3^{g}	1.56 ± 0.73^{h}	323 ± 11^{a}	1.02 ± 0.41^{b}	440 ± 18^{c}
	CTL	16.9 ± 2.7^{d}	23.5 ± 0.3^{e}	1.45 ± 0.72^{f}	142 ± 3^{g}	1.98 ± 0.50^{h}	333 ± 6^{a}	1.54 ± 0.31^{b}	459 ± 10^{c}
5	BLA	18.2 ± 10.1^{e}	23.5 ± 0.3^{f}	2.99 ± 1.4^{h}	124 ± 2^{i}	0.42 ± 0.33^{a}	287 ± 24^{b}	0.30 ± 0.10^{c}	390 ± 26^{d}
	CTL	12.8 ± 5.6^{e}	21.6 ± 0.1^{g}	$2.25 \pm 0.\,8^{h}$	124 ± 3^{i}	0.35 ± 0.12^{a}	296 ± 5^{b}	0.45 ± 0.24^{c}	402 ± 10^{h}

A common superscript for BLA and CTL at a given stage of any flock indicates means that are not significantly different ($p>0.05$)

The ammonia emitted per kg of live weight during flocks 2, 3 and 4 was not significantly different for BLA or CTL. During flock 5, the BLA rooms had significantly higher ammonia emitted per kg of live weight than previous flocks but ammonia emitted from the CTL rooms was significantly lower.

The ER at different stages (flock/bird age) during this study are compared to published data as shown in Table 3-6. With the exception of flock 5, the 20 day ERs for BLA compare well with values reported by Wheeler et al. (2008). There are no 60-day ERs for comparison but it is notable that the ammonia emitted per bird at 42 days during flock 3 is comparable to the 60-day values reported by Wheeler et al. (2008). A possible explanation is that the birds used for this study were approximately 21% larger at the end of the flock compared to those used in the study by Wheeler et al. (2008).

Table 3-6: Comparison of daily NH_3 emission rates (g/bird): this study vs. published data

	Ammonia ER (g/bird-day)						
Bird age (day)	**7**		**20**		**42**		**60**
This Study	**BLA**	**CTL**	**BLA**	**CTL**	**BLA**	**CTL**	
Flock 2	0.13	0.39	0.51	1.05	0.93	1.27	NA
Flock 3	0.32	0.57	0.75	1.07	1.60	1.93	NA
Flock 4	1.87	2.28	0.45	0.95	0.99	1.06	NA
Flock 5	2.02	1.45	2.00	1.47	0.22	0.59	NA
Wheeler et al. (2008)							
Treated litter	0.22		0.60		1.25		1.78
Built-up litter	0.30		0.70		1.39		1.95

Time had a significant effect on the total ammonia emitted, which is not surprising because the amount of ammonia emitted increases as the birds grow and produce more manure, and as the litter is reused to grow more flocks. The interaction between time and treatments was not significant ($p>0.05$) meaning that there is insufficient evidence to suggest that the effect of the treatments depends on time.

The reductions in ammonia concentrations, amendment application rates, and conditions for this study are compared to three amendments (alum, PLT and Poultry Guard^{TM}) commonly used for mitigation of ammonia from broiler houses in Table 3-7. Application rates range from 0.25 to 1.5 kg/m^2, depending on expected quantity and N concentration of manure. The reduction in room ammonia concentration and mass emitted is generally highest immediately after amendment application and reduces towards the end of the grow-out. However, the reduction in ammonia concentration achieved by BLA was generally highest towards the end of each flock (weeks 5 and 6). This would be a hindrance for the intended application since young chicks are more susceptible to elevated ammonia concentrations. However, room ammonia concentrations only exceeded the 17.4 mg/m^3 concentration required for optimal broiler performance once (week 4 of flock 4) during the entire study.

The maximum reduction in ammonia achieved by BLA was about 25% less than values reported for alum and PLT, which could be the result of differences in application method [whole house (BLA) vs. brood area (PLT)] or mitigation mechanisms [weak acid (Korbieh et al., 2011) vs. strong acid (Moore et al., 1995)]. Since the amount of ammonia produced and, consequently, emitted from broiler litter decreases with decreasing litter pH, amendments such as alum, made using strong inorganic acids, which achieve a more significant reduction in litter pH tend to be more effective for mitigation (Moore et al., 1995).

Table 3-7: Comparison of reduction of ammonia emitted: BLA vs. common litter amendments

Treatment	Application Rate kg/m^2	Ammonia Reduction	House Management/Testing conditions
BLA (This Study)	0.66	~ 30% in weeks 1 to 2 ~ 40% in week 3 to 4 ~ 55% in weeks 5 to 6	–6 pens separated by full height partition and ventilated separately –Stocking density of 0.065 m^2/bird –First flock grown on fresh wood shavings; litter reused for 4 more flocks –Emissions used to evaluate effectiveness of amendment
Dry alum (Moore et al., 2000)	0.69 – 1.38	80% in weeks 1 to 2 50% in week 3 < 30% after week 3	–Two commercial broiler farms –Fresh wood shavings at start, reused for 6 flocks –House ammonia concentrations used to evaluate the effectiveness of the amendment
Sodium Bisulfate (PLT) (Pope and Cherry, 2000)	0.25 – 0.50	90% in week 1 50% in week 2 < 30% after week 3	–Twelve commercial broiler farms –Two complete flocks on two farms and one flock on 10 farms –Birds grown on built-up litter; house ammonia concentrations used to evaluate the effectiveness of the amendment
Granulated Sulfuric acid (Poultry Guard) (McWard and Taylor, 2000)	0.54 – 1.08	78% in weeks 1 to 4 30% after week 4	–40 pens separated by full height partition and ventilated separately – Stocking density of 0.065 m^2/bird –Two flocks on built-up litter that had been reused for 4 flocks prior to study –House ammonia concentrations used to evaluate the effectiveness of the amendment

Conclusion

The BLA achieved 31% to 47% reduction in total ammonia emitted compared to CTL over 3 subsequent flocks. Ammonia emitted during flock 5 for BLA was 57% higher than CTL. The litter was relatively dry with less than 20% moisture by weight during flock 5. Since dry litter amendments require water for activation, there was probably inadequate water to support the acid-base reaction between BLA and ammonia.

The reduction in room ammonia concentrations achieved by BLA was generally highest towards the end of each flock (weeks 5 and 6), which would be a disadvantage for the intended application, since young chicks are more susceptible to elevated ammonia concentrations. The maximum reduction in ammonia by BLA was about 25% less than values reported for alum and PLT, which is probably the result of differences in application method or mitigation mechanisms. The amount of ammonia emitted also decreases with decreasing litter pH and inorganic amendments tend to achieve a more significant reduction in litter pH.

During three subsequent flocks, the exhaust fans in BLA rooms ran 7% to 22%, respectively, less to maintain the same set temperature as CTL, which shows energy savings from using the amendment. However, insufficient litter moisture content to support the reaction between BLA and ammonia resulted in elevated ammonia concentrations during flock 5 and, consequently, the fans to BLA rooms ran approximately 6% more than CTL. Further research is required to determine the minimum litter moisture content necessary for BLA to work effectively.

References

Agblevor, F. A., J. A. Ogejo, S. W. Gay 2008. Patent Application Publication No. US 2008/0050273 A1.

Amaral, M. F. P., R. S. Gates, E. G. Wilkerson, D. G. Overhults, I. F. F. Tinôco, H. Li, R. T. Burns, H. Xin and J. W. Earnest. Comparison Between Two Systems for Ammonia Emission Monitoring in Broiler Houses. Paper presented at International Symposium on Air Quality and Waste Management for Agriculture, Broomfield, Colorado, 16-19 September 2007.

American Society of Agricultural & Biological Engineers (ASABE). 2010. Manure Production and Characteristics. In ASAE D384.2.

Barthelmie, R. J., S. C. Pryor. 1998. Implications of Ammonia Emissions for Fine Aerosol Formation and Visibility Degradation: A Case Study from the Lower Fraser Valley, British Columbia Atmos. Environ. 32: 345-352.

Beker, A., S. L. Vanhooser, J. H. Swartzlander and R. G. Teeter. 2004. Atmospheric Ammonia Concentration Effects on Broiler Growth and Performance. J. Appl. Poultry. Res. 13(1): 5-9.

Burns, R. T., K. A. Armstrong, F. R. Walker, C. J. Richards and D. R. Raman. Ammonia Emissions from a Broiler Production Facility in The United States. Paper presented at International Symposium on Gaseous and Odor Emissions from Animal Production Facilities, Horsens, Denmark. June 2-4, 2003.

Burns, R. T., H. Xin, R. S. Gates, H. Li, D. G. Overhults, L. Moody and J. W. Earnest. Ammonia Emissions from Broiler Houses in the Southeastern United States. Paper presented at International Symposium on Air Quality and Waste Management for Agriculture, Broomfield, CO. September 16-19, 2007.

Carlile, F. S. 1984. Ammonia in Poultry Houses: A Literature Review. Worlds Poult. Sci. J 40(2):99-113.

Dräger Safety AG & Co. 2007. XSEC Sensor Data Sheet. Available at http://www.draeger.com/media/10/02/45/10024547/draegersensor_xs_ec_co2_ds_9023376_de_en.pdf. Accessed April 09, 2013.

EPA (United States Envionmental Protection Agency). 2004. National Emission Inventory - Ammonia Emissions from Animal Husbandry Operations. Available at http://www.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf. Accessed June 30, 2012.

EPA (United States Envionmental Protection Agency). 2009. CERCLA/EPCRA Administrative Reporting Exemption for Air Releases of Hazardous Substances from Animal Waste at Farms. Final Rule. Available at http://www.epa.gov/emergencies/docs/chem/CAFO_rule_fact_sheet.pdf. Accessed February 27, 2013.

Gates, R. S., H. Xin, K. D. Casey, Y. Liang and E. F. Wheeler. 2005. Method for Measuring Ammonia Emissions from Poultry Houses. J. Appl. Poultry. Res. 14(3): 622-634.

Gates, R. S., K. D. Casey, E. F. Wheeler, H. Xin and A. J. Pescatore. 2008. U.S. Broiler Housing Ammonia Emissions Inventory. Atmos. Environ. 42(14): 3342-3350.

Gates, R. S., K. D. Casey, E. F. Wheeler, H. Xin, A. J. Pescatore, J. L. Zajaczkowski, J. R. Bicudo, P. A. Topper, Y. Liang and M. Ford. Broiler House Ammonia Emissions: US Baseline Data. Paper presented at Multi-State Poultry Feeding and Nutrition and Health and Management Conference and Degussa Corporation's Technical Symposium, Indianapolis, IN, May 25-27, 2004.

Gates, R. S., H. Xin and E. F. Wheeler. Ammonia Losses, Evaluations and Solutions for Poultry Systems. Paper presented at National Poultry Waste Management Symposium, Birmingham, AL, October 28-30, 2002.

Jaworski, N. A., R. W. Howarth and L. J. Hetling. 1997. Atmospheric Deposition of Nitrogen Oxides onto the Landscape Contributes to Coastal Eutrophication in the Northeast United States. J. Environ. Sci. Technol. 31(7): 1995-2004.

Kim, J. H., D. H. Lim, J. K. Kim, S. J. Jeong and B. K. Son. 2005. Effects of Particulate Matter (PM10) on the Pulmonary Function of Middle-School Children. J. Korean Med. Sci. 20(1): 42-45.

Kling, H. F., C .L. Quarles. 1974. Effect of Atmospheric Ammonia and the Stress of Infectious Bronchitis Vaccination on Leghorn Males. Poultry Sci. 53(3): 1161-1167.

Korbieh, T. N. and Z. Bo. Production of Bio-degradable Poultry Litter Amendment Material for Ammonia Control in Poultry Houses. Paper Number: 1111012. Paper presented at ASABE Annual Meeting, Louisville, Kentucky, Aug 7-10, 2011.

Lacey, R. E., J. S. Redwine, C. B. Parnell Jr. 2003. Particulate Matter and Ammonia Emission Factors for Tunnel-Ventilated Broiler Production Barns in The Southern U.S Trans. ASAE 46(4): 1203-1214.

MacDonald, J. M. 2008. The Economic Organization of U.S. Broiler Production. USDA - ERS. Economic Information Bulletin No. 38. Available at: http://www.ers.usda.gov/media/205671/eib38_1_.pdf. Accessed: February 17, 2013.

Maguire, R. O., P. W. Plumstead, and J. Brake. 2006. Impact of diet, moisture, location and storage on soluble phosphorus in broiler breeder manure. J. Environ. Qual. 35:858-865.

McWard, G. W. and D. R. Taylor. 2000. Acidified Clay Litter Amendment. J. Appl. Poult. Res. 9(4): 518-529.

Moody, L. B., H. Li, R. T. Burns, H. Xin, R. S. Gates, S. J. Hoff and D. G. Overhults. 2008. Southeastern Broiler Gaseous and Particulate Matter Emissions Monitoring Quality Assurance Project Plan. Special ASABE Peer Reviewed Publication.

Moore, P. A., T. C. Daniel and D. R. Edwards. 2000. Reducing Phosphorus Runoff and Inhibiting Ammonia Loss From Poultry Manure With Aluminum Sulfate. J. Environ. Qual. 29(1):37-49.

NCC (National Chicken Council). 2012. U.S. Broiler Production Statistics. Available at http://www.nationalchickencouncil.org/about-the-industry/statistics/u-s-broiler-production/ Accessed January 31, 2013.

Patterson, P. H., E. S. Lorenz, W. D. Weaver, Jr., and J. H. Schwartz. 1998. Litter production and nutrients from commercial broiler chickens. J. Appl. Poult. Res. 7:247–252.

Pescatore, A. J. and Harter-Dennis, J. M. 1989. Effects of ferrous sulfate consumption on the performance of broiler chicks. Poult Sci. 68(8):1063-1067.

Peters, J., S. M. Combs, S. Hoskins, J. Jarman, J. L. Kovar, M. E. Watson, A. M. Wolf. and N. Wolf. 2003. Recommended Methods of Manure Analysis. Univeristy of Wisconsin Extension Publication No. A3769.

Pope, M. J. and T. E. Cherry. 2000. An Evaluation of the Presence of Pathogens on Broilers Raised on Poultry Litter Treatment-Treated Litter. Poultry Sci. 79(9):1351-1355.

REM (Ross Environmental Management). 2010. Environmental Management in the Broiler House. Available at: http://en.aviagen.com/assets/Tech_Center/Ross_Broiler/Ross_Environmntal_Management_in_the_Broiler_House.pdf. Accessed January 23, 2013.

Ritz, C. W., B. W. Mitchell, B. D. Fairchild, M. Czarick III and J. W. Worley. 2006. Improving in-house air quality in broiler production facilities using an electrostatic space charge system. J. Appl. Poultry. Res. 15:333–340.

Shah, S., P. Westerman and J. Parsons. 2012. Pair quality education in animal agriculture - Poultry litter amendments. Available at: http://www.extension.org/sites/default/files/Litter%20Amendments%20FINAL.pdf. Accessed August 31, 2012.

USDA (United States Department of Agriculture). 2012. Poultry - Production and Value 2011 Summary. Available at http://usda.mannlib.cornell.edu/usda/current/PoulProdVa/PoulProdVa-04-26-2012.pdf. Accessed November 30, 2012.

Van Breemen, N., P. A. Burrough, E. J. Velthorst, H. F. Van Dobben, T. de Wit, T. B. Ridder and H. F. R. Reijnders. 1982. Soil Acidification from Atmospheric Ammonium Sulphate in Forest Canopy Throughfall. Nature 299:548-550.

Watts, D. B., K. E. Smith and H. A. Torbert. 2012. Impact of Poultry Litter Cake, Cleanout, and Bedding following Chemical Amendments on Soil C and N Mineralization. Int. J. Agron. Article 204629.

Wheeler, E. F., K. D. Casey, R. S. Gates, H. Xin, P. A. Topper and Y. Liang. 2008. Ammonia Emissions from USA Broiler Chicken Barns Managed with New Bedding, Built-up Litter, or Acid-Treated Litter. ASABE Publication Number 701P0408. In Mitigation of Air Emissions from Animal Feeding Operations, Iowa State University, Ames, IA.

Wheeler, E. F., K. D. Casey, R. S. Gates, H. Xin, J. L. Zajaczkowski, P. A. Topper, Y. Liang and A. J. Pescatore. 2006. Ammonia Emissions from Twelve US Broiler Chicken Houses. Trans. ASABE 49(5): 1495-1512.

Xin, H., A. Tanaka, T. Wang, R. S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Ni and T. Lim. A Portable System for Continuous Ammonia Measurement in the Field. Paper No. 024168. Paper presented at ASABE Annual Meeting, Chicago, IL July 28-31, 2002.

CHAPTER 4: THE EFFECT OF USING A BIODEGRADABLE LITTER AMENDMENT TO CONTROL AMMONIA EMISSIONS ON BIRD WEIGHT, FEED EFFICIENCY, FOOTPAD DERMATITIS AND LITTER CHARACTERISTICS

Abstract: Broilers are raised on litter, which is often reused due to economic reasons. Ammonia produced by microbial decomposition of uric acid from broiler manure in the litter reduces the growth rate and feed efficiency of the birds, and may aggravate the development of footpad dermatitis (FPD). Litter amendments are used to minimize the impact of ammonia on flocks grown on reused litter. Commercially available litter amendments include inorganic and organic products. Inorganic litter amendments are corrosive to structures and may be harmful to handlers but organic amendments can be used for ammonia mitigation without the adverse effects of inorganic amendments. A novel biodegradable litter amendment made from corn cobs effectively reduced the emission of ammonia and other odorous gases from broiler litter in laboratory studies.

The objective of this study was to determine the effects using BLA to control ammonia emissions on bird weight, feed conversion, development of footpad dermatitis and litter characteristics. Four flocks of straight run, Cobb-Hubbard cross broilers were grown on top-dressed reused litter treated with BLA and untreated litter. The birds were raised at a stocking density of 0.07 m^2 per bird, fed a standard commercial, corn and soybean meal based diet and weighed four times during each flock. Bird mortality was monitored daily. Litter samples were collected from target locations around the feeders, waterers and rest areas after harvesting and used to compare moisture content, total ammonia nitrogen, pH and total nitrogen for treated (BLA) and untreated litter (CTL).

The mean bird weight at 42 days for flocks 2, 3, 4 and 5 was 50, 70, 60 and 25 g, respectively higher for BLA compared to CTL. The BLA birds also consumed 30 to 90 g less feed per kilogram of weight gain during flocks 2 through 5. Increased growth rate was linked to higher mortality from “flip-over” disease among the BLA birds during flocks 4 and 5. For both BLA and CTL, there was a significant decrease (~ 300 g) in mean bird weight and a significant increase (~ 0.2 g/kg) in feed conversion ratio (FCR) for flock 5 compared to flock 2. The BLA treatment had no effect on development of footpad dermatitis (FPD).

Litter pH, water TAN and TN were not significantly different for BLA and CTL for any of the flocks. However, litter collected from around the waterer had significantly higher moisture, pH and TAN, and significantly lower TN compared to other locations, which shows that ammonia formation and N loss are most significant in wet litter.

Keywords: Biodegradable litter amendment, ammonia, broiler performance

Introduction

Commercial broiler farms in the U.S. raise birds in confinement and use litter as part of manure management. The litter is reused for several flocks to minimize production costs associated with buying fresh bedding and disposing of old litter, which leads to buildup of manure nutrients in the litter (Shah et al., 2102). Ammonia released as manure in the litter decomposes may have adverse effects on broiler performance including weight gain, feed efficiency and mortality (Carlile, 1984) and footpad dermatitis (De Jong and van Harn, 2012). Decreased growth rate and feed efficiency and increased mortality have been linked to ammonia concentrations above 17.4 mg/m^3 (Beker et al. 2004; Miles et al., 2004; Al Homidan et al., 2003; Johnson et al, 1991; Al-Mashhadani and Beck, 1985; Caveny et al., 1981; Anderson et al., 1964). Footpad dermatitis (FPD), which appears as lesions on the bottom of the birds' feet, has been linked to wet and sticky litter and may be aggravated by chemical irritants like ammonia in the litter (Abbott et al., 1969; Harms et al., 1977; Nairn and Watson, 1972).

Litter amendments are used to minimize the impact of ammonia on flocks grown on reused litter. Commercially available products include sodium bisulfate (PLT^{TM}), granulated sulfuric acid (Poultry $Guard^{TM}$) and aluminum sulfate ($Alum^+$ $Clear^{TM}$). These are acid-based amendments, which lower litter pH and slow the conversion of uric acid to ammonia and, consequently, N loss as NH_3 (Shah et al, 2012; Cook et al., 2011; Moore et al, 1996). Decreased house ammonia concentrations and improved bird performance have been reported for broilers raised on reused litter treated with amendments (Terzich et al, 1998a & b; Pope and Cherry, 2000; McWard and Taylor, 2000). Terzich et al. (1998a, 1998b) evaluated the effect of PLT on house ammonia concentrations, bird weight and mortality in broilers raised on reused litter and observed weight gains of 8% and 5% after 23 and 49 days, respectively, compared to the control. They also observed fewer lesions and incidences of respiratory tract damage among the birds grown on treated litter. McWard and Taylor (2000) reported 5% higher broiler weight, improved carcass quality, and reduced foot-pad dermatitis in birds growing on litter treated with Poultry Guard^{TM}, which they attributed to reduced ammonia concentrations in the house.

Inorganic litter amendments are corrosive to structures and may be harmful to handlers (Shah et al., 2012); however, organic litter amendments such as acetic acid (Roach et al., 2009) and Litter Life^{TM} (HRC, 2013), which are not as corrosive or toxic, can also reduce house ammonia concentrations and improve bird performance. The objective of this study was to determine the effects using BLA to control ammonia emissions on bird weight, feed conversion, development of footpad dermatitis and litter characteristics.

Materials and methods

Birds, diet and house management

Five flocks of straight run chicks (Cobb-Hubbard cross) broilers were grown to 42 days at a stocking density of 0.07 m^2 per bird between March 30, 2011 and January 10, 2012. The birds were grown in six adjacent rooms, each measuring 3.8 m long x 3.6 m wide and tapering in height from 3.3 m at the inner wall to 2.7 m at the external wall, selected from a building with 36 similar rooms at the Virginia Tech Turkey Farm. The chicks were randomly placed in the rooms to spread variability in bird performance due to hatching sequence among the rooms. The birds were fed a standard commercial corn and soybean meal based diet from three tube feeders using a 3-phase feeding program based on age for starters (0 to 18 days), growers (18 to 33 days) and finishers (33 to 42 days), with 24%, 18% and 20% protein respectively. Water was provided ad libitum via nipple drinkers. The birds were euthanized by manual cervical dislocation at 42 days.

Feed consumption, weight gain and mortality

The birds were weighed four times during each flock on days 1, 18, 33 and 42, which coincided with chick placement, change of feeding phases and harvesting. The first and second weighs were done in batches of 100 and 45 birds, respectively, while birds were weighed individually during the third and fourth weighs. Bird mortality was recorded daily. The feed input to each room was recorded. Feed leftover at the end of a feeding phase or flock was subtracted from the total input to obtain the feed intake. The feed conversion ratio (FCR) was estimated as the ratio of feed intake to weight total gain (including mortality) and does not account for spilled feed.

Footpad dermatitis (FPD)

Assessment of FPD was done during bird harvesting using the three-point scale described by Ekstrand et al. (1998). Each footpad was assigned a score of 0, 1 or 2 (Figure 4-1), depending on whether no lesions, mild lesions or severe lesions, respectively, were present. The same assessor was used for consistency. The FPD prevalence level for each flock/treatment was calculated as the percentage of the birds that showed any evidence of lesions. The Modified Ekstrand Score (MES) was calculated for each flock/treatment by multiplying each score by its frequency then summing the weighted scores (Pagazaurtundua and Warriss, 2006). Prevalence of FPD during each flock was also correlated with litter TAN and moisture content, which have been linked to development of the lesions (Mayne et al., 2007; Martland, 1984) .

Litter sampling and analysis

Litter samples were collected within 24 hours of harvesting the birds, from three locations in each room: around the waterer (W), the feeders (F) and rest areas (R) away from the feeders and waterer. Three samples (approximately 1 kg each) were taken from each location for a total of nine samples per room or 27 samples per treatment. This targeted sampling was done to assess effect of feeding and drinking activities on the moisture and nutrient content of the litter (Maguire et al., 2006; Patterson et al., 1998). Handling of samples and analysis for TAN, moisture, pH and TN was as described in chapter 3.

Class 0: Smooth, no lesions

Class 1: Superficial lesion, no lesions

Class 2: Ulcer covered by crust

Figure 4-1: Guide for scoring footpad dermatitis (De Jong and van Harn, 2012)

Results and discussion

Bird weights, feed consumption and mortality

The Modified Ekstrand Score (MES), FPD prevalence, mortality, feed conversion ratio (FCR), and mean weight for the birds from flocks 2 to 5 are shown Table 4-1. The mean bird weight for BLA at 42 days for flocks 2, 3, 4 and 5 was 25 to 70 g higher compared to CTL. The BLA birds also consumed 30 to 90 g less feed per kilogram of weight gain during flocks 2 through 5. The 60 g difference ($p<0.05$) in mean bird weight between BLA and CTL after flock 4 would translate to 1,170 kg for a house with 20,000 birds with 2% expected mortality. This represents a monetary equivalent of approximately $2,340 at the suggested retail price of $2 per kg (NCC, 2012).

The FCR and mean bird weight were significantly different for flock 5 compared to flock 2, for both BLA and CTL. The ammonia emitted from the litter also increased significantly from 8.37 and 13.11 g/d during flock 2, to 9.29 and 17.59 g/d during flock 4 for BLA and CTL, respectively. Since there were no changes in feed and management practices between flocks, the observed differences in bird weight and FCR are likely due to increased ammonia released from the litter.

Table 4-1: Bird Performance (FPD, FCR and Mean Weight) during flocks 2, 3, 4 and 5

Flock		MES	FPD Prevalence (%)	Mortality (%)	FCR (kg/kg)	Mean weight (kg)
2	BLA	218 ±133$^{a\,f}$	41.6±27.2$^{a\,f}$	8.1±5.5$^{a\,g}$	1.72±0.01$^{a\,m}$	2.82±0.01$^{a\,g}$
	CTL	315 ± 67$^{a\,g}$	55.6±13.7$^{a\,g}$	8.7±5.5$^{a\,m}$	1.76±0.05$^{a\,f}$	2.77±0.01$^{a\,c}$
3	BLA	436±74$^{b\,f}$	77.1±12.5$^{b\,f}$	5.4±1.2$^{a\,b}$	1.64±0.04$^{a\,m}$	2.99±0.03^{b}
	CTL	463±73$^{b\,g}$	81.9±11.2$^{b\,g}$	6.7±0.6$^{b\,m}$	1.67±0.06$^{a\,f}$	2.92±0.03^{b}
4	BLA	429±41$^{c\,e}$	74.3±7.8$^{c\,e}$	14.1±2.6$^{f\,g}$	1.72±0.05^{c}	2.84±0.01^{g}
	CTL	358±177$^{c\,g}$	59.0±27.q$^{c\,g}$	7.6±1.7^{m}	1.81±0.09^{f}	2.78±0.01^{c}
5	BLA	313±16$^{d\,e\,f}$	58.4±7.5$^{d\,f}$	18.3±5.8$^{e\,f}$	1.92±0.06^{e}	2.63±0.03^{e}
	CTL	327±161$^{d\,g}$	57.6±25.9$^{d\,g}$	12. 8±2.4$^{e\,k}$	1.99±0.14^{e}	2.60±0.03^{e}

Column means with at least one superscript in common are not statistically different ($p>0.05$)

The lowest mortality rate of 5.4% and 6.7% for BLA and CTL, respectively, was during flock 3, which also had the highest bird weights and lowest feed conversion ratio. Mortality for BLA was not statistically different from the CTL during flocks 2 and 3. During flocks 4 and 5 mortality among the BLA was significantly higher than CTL. All the dead birds showed the signs of “flip-over” disease suggested by Collett (2011); they often died suddenly after brief convulsions during weighing or were found dead on their backs during daily inspections. “Flip-over” disease usually occurs when broilers take less than 8 weeks to reach 2 kg and feed conversion ratio is less 2.5 at 6 weeks (Collett, 2011). The FCR at 6 weeks for both BLA and CTL during flocks 2 through 5 was less than 2.0 and the birds generally achieved the 2 kg weight by 5 weeks of age, implying that the birds were generally susceptible to the disease.

FPD prevalence

The prevalence of FPD was not significantly different between the BLA and CTL during the four grow out periods. There was insufficient evidence to suggest that BLA had any effect on the development of FPD. Correlations between FPD prevalence and litter TAN and moisture content are shown in Table 4-2. The highest prevalence of FPD for both CTL and BLA was observed during flock 3, which also showed higher correlation coefficients between FPD and litter characteristics compared to other flocks.

Table 4-2: Correlation between prevalence of footpad dermatitis and litter characteristics

Flock	Prevalence vs. moisture content	Prevalence vs. TAN
2	-0.07	0.14
3	0.75	0.66
4	-0.83	-0.28
5	0.65	0.08

The lowest FPD prevalence for both BLA and CTL was observed during flock 2 (summer flock). It is reported that ventilation rates in summer often result in lower litter moisture content and lower prevalence of FPD compared to cool weather flocks (Folegatti et al., 2012). The drying effect of VR on litter during flock 2 cannot be established using data from the study; however, Wu and Hocking (2011) observed a linear relationship between FPD severity and moisture content and reported that FPD prevalence and severity was minimal in litter with less than 30% moisture. Litter moisture content during flocks 2 to 5 was below 30% and decreased with litter reuse. The role of moisture content could be implied by decreasing FPD prevalence in subsequent flocks. There was insufficient evidence from the study to link FPD prevalence to litter TAN concentration and similar observations were made by Youssef et al. (2011).

Litter characteristics

Litter TAN, TN, pH and moisture content at the end of flocks 2, 3, 4 and 5 are shown in Table 4-3. Differences in TN, TAN, moisture content and pH between BLA and CTL were not statistically significant for any of the flocks. For both BLA and CTL, litter pH and TAN were lowest and TN was highest at the end of flock 5. The significantly higher TN after flock 5 shows that the concentration of litter nutrients generally increases with reuse.

Litter TAN concentration was highest after flock 4, which might be the result of condensation of water vapor as outdoor temperatures decreased during the flock. However, the effect of condensation on litter moisture content and, consequently, TAN concentration was not established since litter characteristics were not analyzed until the end of the flock. It was necessary to increase VR during flock 5 to decrease room ammonia concentrations. Increasing VR keeps the litter drier and slows the formation of ammonia in the litter, which probably resulted in the significantly lower litter TAN concentration after flock 5.

Table 4-3: Litter TAN, TN, moisture content and pH during 4 flocks grown on reused litter

		Flock 2	**Flock 3**	**Flock 4**	**Flock 5**
TAN (g/kg)	BLA	5.34 ± 0.25^{d}	$4.41 \pm 0.22^{c\ p}$	6.99 ± 0.37^{b}	$3.80 \pm 0.20^{a\ p}$
	CTL	5.84 ± 0.25^{d}	4.89 ± 0.22^{c}	7.10 ± 0.38^{b}	3.98 ± 0.20^{a}
TN (g/kg)	BLA	$32.9 \pm 1.70^{a\ r\ q}$	$31.4 \pm 1.79^{d\ q}$	$32.7 \pm 1.70^{c\ r\ q}$	$36.4 \pm 1.00^{b\ r}$
	CTL	$31.9 \pm 1.70^{a\ t}$	$31.3 \pm 1.79^{d\ t}$	$33.0 \pm 1.70^{c\ p\ t}$	$37.2 \pm 1.00^{b\ p}$
Litter Moisture content (%)	BLA	$23.8 \pm 1.54^{b\ e}$	$24.0 \pm 1.42^{a\ e}$	$20.7 \pm 1.45^{d\ e\ f}$	$18.8 \pm 1.00^{c\ f}$
	CTL	$26.0 \pm 1.54^{b\ g}$	$24.9 \pm 1.42^{a\ g\ h}$	$21.1 \pm 1.45^{d\ h\ k}$	$18.0 \pm 1.00^{c\ k}$
pH	BLA	$8.07 \pm 0.11^{c\ m}$	$7.90 \pm 0.12^{b\ m}$	$8.04 \pm 0.10^{a\ m}$	7.33 ± 0.12^{d}
	CTL	$8.22 \pm 0.11^{c\ n}$	$8.10 \pm 0.12^{b\ n}$	$8.04 \pm 0.10^{a\ n}$	7.43 ± 0.12^{d}

Means with at least one superscript in common are not significantly different ($p>0.05$)

The mean pH for both BLA and CTL during the four flocks remained within the typical values of 7.5 to 8.5 reported by Ritz et al. (2004), but was significantly lower after flock 5 compared to flock 2. Litter moisture content was also significantly lower at the end of flock 5 compared to flock 2. Since ammonia formation from uric acid decreases with decreasing moisture content, the lower litter pH during flock 5 is likely due to non-mineralized uric acid.

The effect of location within room on litter moisture content, pH, TAN and TN during a flock 2 are shown in Figure 4-2. Data from flock 2 was used for illustration but similar observations were made with the other flocks (Appendices E, F and G). The moisture content for BLA and CTL from similar locations was not significantly different. However, litter from beneath the waterer had significantly ($p<0.0001$) more water by weight (typically about 10%) compared to the other areas. The moisture content of litter around the feeders and rest areas were not significantly different. Litter moisture content in all three locations decreased with reuse for both BLA and CTL, and was significantly lower after flock 5 compared to flock 2.

Over the four flocks (2 to 5) when litter was treated with BLA, moisture content around the waterer for both BLA and CTL decreased by approximately 12%, compared to a reduction of 3% to 5% around the feeders and rest areas. Litter from underneath the waterer for both BLA and CTL had significantly higher ($p<0.0001$). The litter around the waterer had significantly higher pH, moisture and TAN but significantly ($p<0.0001$) lower TN compared to litter around the feeders and the rest areas for all 4 flocks. This observation is not unusual because, if all areas received approximately the same amount of manure, higher moisture around the waterer would provide more conducive conditions for growth of microbes that convert uric acid in the manure to ammonia, resulting in a higher TAN concentration and, consequently, higher pH. Ammonia volatilization (N loss) from this litter would likely be higher due to elevated litter pH, resulting lower litter TN content at the end of the flock. Similar observations were made by Maguire et al. (2006) and Patterson et al. (1998) and are indicative of water spillage from the drinkers, which can be addressed by proper adjustment of waterer height and water pressure as birds grow, to meet bird requirements while minimizing spillage and wastage (Ritz et al, 2004).

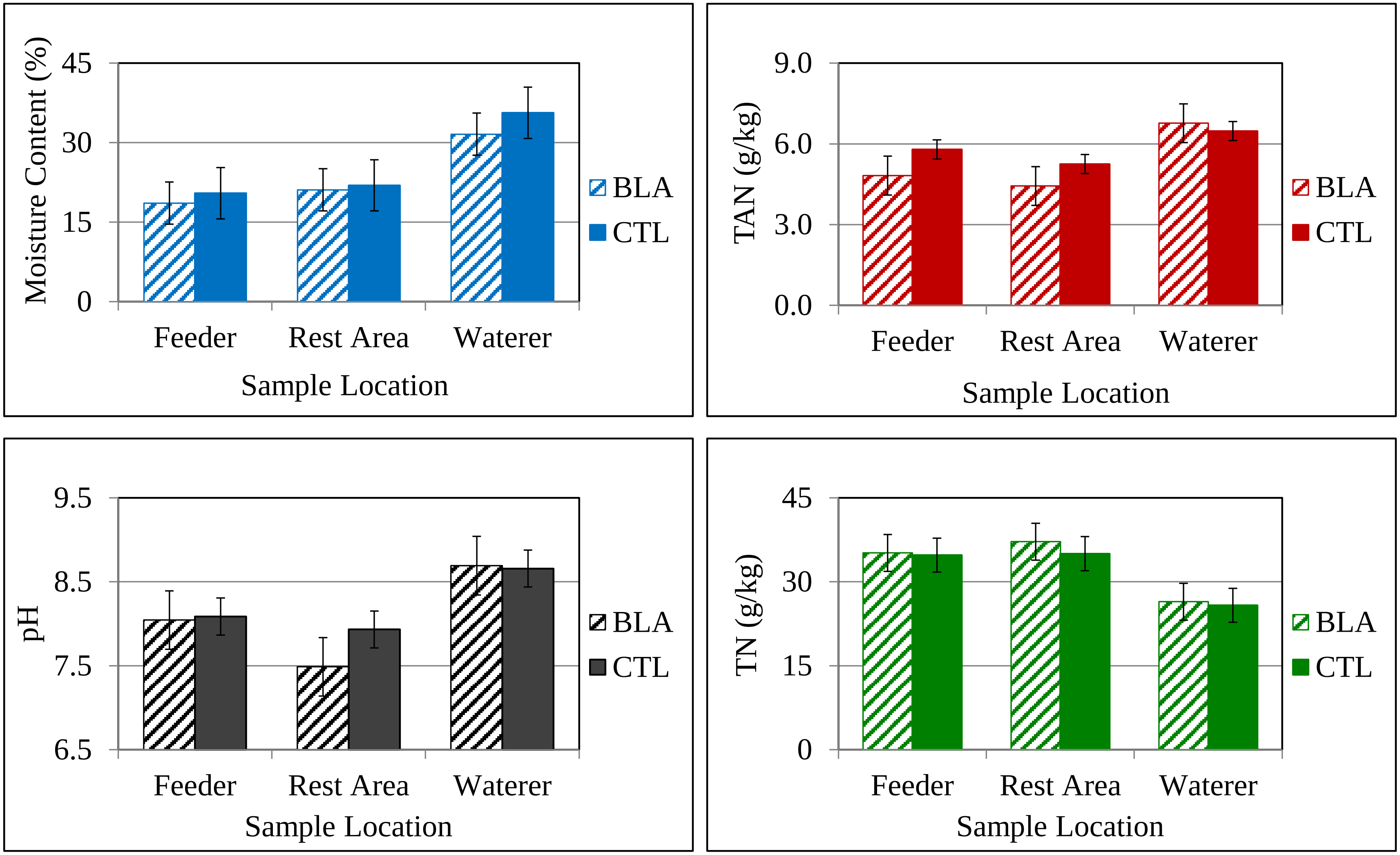


Figure 4-2: Effect of location on litter moisture, TAN, pH and TN during Flock 2

Litter from flocks 2 and 5 was analyzed (in a commercial laboratory) to assess mineral accumulation because it has consequences for the intended use (fertilizer, power generation) of the litter after cleanout. The results are compared to published values in Table 4-5. Differences in mineral concentration between BLA and CTL were not statistically significant for flock 2 or flock 5. The mineral concentration of BLA did not change significantly between flocks 2 and 5; however, CTL had significantly higher concentrations of P, sulfur (S), calcium (Ca), magnesium (Mg), manganese (Mn) and iron (Fe) after flock 5 compared to flock 2.

The average P concentration (15 g/kg) for litter from this study was within the range of 6 to 38 g/kg reported in the studies used for comparison. The concentration of K was closer to the value reported by Dick et al. (1990) but almost double the amount reported by Bolan et al. (2010). The concentration of Zn (0.75 g/kg) was more than double the values reported by Dick et al., (1990) and Zublena et al., (1997), and more than four times as high as reported by Bolan et al. (2010). Broiler litter is a source of nutrients and can be incorporated into fertilizer programs. However, nutrients and trace elements can vary significantly as shown and successful fertilizer management requires litter characteristics to be matched with the nutritional requirements of the crops (Zublena et al., 1997). For instance, litter with elevated P concentration would not be suitable for fertilizer in P-rich soils.

Table 4-4: Comparison of litter mineral concentration from this study to published data

Source		P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	S (g/kg)	Zn (g/kg)	Cu (g/kg)	Mn (g/kg)	Fe (g/kg)	Na (g/kg)	Al (g/kg)
Flock 2	BLA	14.8$^{a, c}$ ± 0.5	24.8^{d} ± 0.7	15.7$^{a, b}$ ± 0.6	5.3$^{a, c}$ ± 0.2	3.9$^{a, c}$ ± 0.1	0.73$^{a, c}$ ± 0.03	0.09$^{a, c}$ ± 0	0.49 $^{a, c}$ ± 0.02	1.10$^{a, c}$ ± 0.04	3.71 $^{a, c}$ ± 0.15	1.01 $^{a, c}$ ± 0.05
	CTL	13.9^{a} ± 0.5	25.0^{d} ± 0.7	15.0^{a} ± 0.6	5.1^{a} ± 0.2	3.9^{a} ± 0.1	0.69$^{a, d}$ ± 0.04	0.09^{a} ± 0	0.46$^{a, d}$ ± 0.02	1.04^{a} ± 0.04	3.92$^{a, d}$ ± 0.15	0.96$^{a, d}$ ± 0.05
Flock 5	BLA	15.8^{c} ± 0.7	25.7^{d} ± 1.0	17.6$^{c, b}$ ± 0.8	6.2$^{b, c}$ ± 0.3	4.3$^{b, c}$ ± 0.2	0.77$^{b, c}$ ± 0.03	0.10$^{b, c}$ ±0	0.53$^{b, c}$ ± 0.03	1.18$^{b, c}$ ± 0.04	4.37$^{b, c}$ ± 0.18	1.02$^{b, c}$ ± 0.07
	CTL	16.0^{c} ± 0.6	26.0^{d} ± 0.8	17.6^{c} ± 0.7	6.1^{b} ± 0.2	4.2^{b} ± 0.1	0.76$^{b, d}$ ± 0.02	0.10$^{b, d}$ ± 0	0.54^{b} ± 0.03	1.20$^{b, d}$ ± 0.03	4.38$^{b, d}$ ± 0.15	1.00$^{b, d}$ ± 0.06
Bolan et al. (2010)		6.7	10.1	16.2	3.5	5.2	0.16	0.03	0.16	NR	NR	NR
Dick et al. (1990)		21.0	27.0	40.0	7.3	7.0	0.38	0.16	0.44	3.25	NR	NR
Zublena et al. (1997)		37.5	NR	20.5	4.0	7.5	0.32	0.23	0.34	0.65	NR	NR

Column means with at least one common subscript are not statistically different

Health risks from handling the litter and, surface-water and groundwater contamination can be valid concerns depending on concentration of presence of trace elements such as As, Cd, Cu, Mn, Pb, and Zn (Zublena et al., 1997). With land application, trace elements contained in broiler litter may accumulate in the soil or plants, can be transported as run-off to surface water, or leached into groundwater (Gupta and Charles, 1999). Oxides of sulfur (regulated pollutants) are produced during power generation, and lower concentrations of S would be advantageous for air pollution control if the litter were to be used as a fuel source.

Conclusion

The mean bird weight for BLA at 42 days was consistently higher and the birds consumed less feed per kilogram of weight gain compared to CTL. At the current wholesale price for broiler meat, the 60 g significant difference in mean weight between BLA and CTL would translate to a monetary equivalent of approximately $2,350 for a house with 20,000 birds with 2% expected mortality.

Increased growth rate is likely linked to higher mortality among the BLA birds during flocks 4 and 5. The birds generally achieved the market weight of 2 kg by 5 weeks of age, and FCR at six weeks was less than 2.5, implying that they were more susceptible to the disease. However, losses from bird mortality can be overcome by marketing the birds as soon as they reach market age, which would also result in savings in feed costs.

There was insufficient evidence from this study to suggest that the use of BLA had any effect on FPD prevalence and severity. No link was established between FPD prevalence to litter TAN concentration. However, the general decrease in FPD prevalence and litter moisture with subsequent flocks suggests a link between moisture content and FPD prevalence.

There was insufficient evidence from this study to suggest that the use of BLA had a significant effect on litter characteristics. However, litter from underneath the waterers had significantly higher pH, moisture and TAN but significantly lower TN than litter from the rest areas and around the feeders, which shows that ammonia formation and N loss are most significant in wet litter. Therefore house management and amendment application practices for ammonia mitigation should place emphasis on litter around the waterer.

References

Abbott, W. W., J. R. Couch, and R. L. Atkinson. 1969. The incidence of foot-pad dermatitis in young turkeys fed high levels of soybean meal. Poultry. Sci. 48(6): 2186-2188.

Al Homidan, A., Robertson, J. F., and Petchey, A. M. 2003. Review of the effect of ammonia and dust concentrations on broiler performance. World Poult. Sci. J. 59: 340-349.

Al-Mashhadani, E. H., and M. M. Beck. 1985. Effect of atmospheric ammonia on the surface ultrastructure of the lung and trachea of broiler chicks. Poult. Sci. 64:2056–2061.

American Public Health Association (APHA). Standard methods for the examination of water and wastewater. 22 ed., Water Environment Federation: London, UK, 2012.

Anderson, D. P., C. W. Beard, and R. P. Hanson. 1964. Adverse effects of ammonia on chickens including resistance to infection with Newcastle disease virus. Avian Dis. 8:369–378.

Beker, A., S. L. Vanhooser, J. H. Swartzlander, and R. G. Teeter. 2004. Atmospheric ammonia concentration effects on broiler growth and performance. J. Appl. Poult. Res. 13:5–9.

Bolan, N. S., A .A. Szogi, T. Chuasavathi, B. Seshadri, M. J. Rothrock Jr. and P. Anneerselvam. 2010. Uses and management of poultry litter. World Poult. Sci. J. 66: 673-698.

Carlile, F. S. 1984. Ammonia in poultry houses: a literature review. World Poult. Sci. J. 40:99–113.

Caveny, D. D., C. L. Quarles, and G. A. Greathouse. 1981. Atmospheric ammonia and broiler cockerel performance. Poult. Sci. 60:513–516. Charles, D. R., and C. G. Payne. 1966. The influence of graded levels of atmospheric ammonia on chickens: 1. Effects on respiration and on the performance of broilers and replacement growing stock. Br. Poult. Sci. 7:177–187.

Collett, S. R. 2011. Flip-over Disease. Available at: http://www.merckmanuals.com/vet/poultry/sudden_death_syndrome_of_broiler_chickens

/overview_of_sudden_death_syndrome_of_broiler_chickens.html?qt=flip%20over&alt=sh. Accessed January 23, 2013.

Cook, K. L., M. J. Rothrock Jr., M. A. Eiteman, N. Lovanh, and K. Sistani. 2011. Evaluation of nitrogen retention and microbial populations in poultry litter, treated with chemical, biological or adsorbent amendments. J. Environ. Manage. 92: 1760-1766.

De Jong, I. and J. van Harn. 2012. Management Tools to Reduce Footpad Dermatitis in Broilers. Available at: http://en.aviagen.com/assets/Tech_Center/Broiler_Breeder_Tech_Articles/English/AviaTech-FoodpadDermatitisSept2012.pdf. Accessed January 17, 2013.

Dick, W. A., J. W. Johnson and D. J. Eckert. 1990. Land Application of Poultry Litter. Ohio State University Publication No. ANR-4-98. Available at http://ohioline.osu.edu/anr-fact/0004.html. Accessed April 12, 2013.

Ekstrand, C., T. E. Carpenter, I. Andersson and B. Algers. 1998. Prevalence and control of foot pad dermatitis in Sweden. Br. Poult. Sci. 39: 318-324.

Folegatti, E., F. Sirri, A. Meluzzi and T. Toscani. Prevalence of foot pad lesions and carcass injuries as indicators of broiler welfare conditions in Italy http://www.cabi.org/animalscience/Uploads/File/AnimalScience/additionalFiles/WPSAVerona/10803.pdf. Accessed January 18, 2013.

Gupta, G. and S. Charles. 1999. Trace Elements in Soils Fertilized with Poultry Litter. Poult. Sci. 78:1695–1698.

Harms, R. H., B. L. Damron and C. F. Simpson. 1977. Effect of wet litter and supplemental biotin and/or whey on the production of foot pad dermatitis in broilers. Poultry. Sci. 56(1): 291-296.

HRC. (Highlander Research & Consulting LLC). 2013. Commercial Broilers: A study of the effects of litter treatments. Available at: http://www.litterlife.com/commercial-broilers. Accessed March 09, 2013.

Johnson, R. W., S. E. Curtis, and R. D. Shanks. 1991. Effects on chick performance of ammonia and heat stressors in various combination sequences. Poult. Sci. 70:1132.

Maguire, R. O., P. W. Plumstead, and J. Brake. 2006. Impact of diet, moisture, location and storage on soluble phosphorus in broiler breeder manure. J. Environ. Qual. 35:858-865.

Martland, M. F. 1984. Wet litter as a cause of plantar pododermatitis, leading to foot ulceration and lameness in fattening turkeys. Avian Pathology. 13: 241-252.

Mayne, R. K., R.W. Else and P.M. Hocking. 2007. High litter moisture alone is sufficient to cause footpad dermatitis in growing turkeys. Br. Poult. Sci. 48 (5): 538-545.

Miles, D. M., S. L. Branton, and B. D. Lott. 2004. Atmospheric Ammonia is Detrimental to the Performance of Modern Commercial Broilers. Poult. Sci. 83:1650 -1654.

Nairn, M. E. and A. R. A. Watson. 1972. Leg weakness of poultry: A clinical and pathological characterisation. Aust. Vet. J. 48(12): 645-656.

National Chicken Council (NCC). 2012. U.S. Broiler Production Statistics. Available at http://www.nationalchickencouncil.org/about-the-industry/statistics/u-s-broiler-production/ Accessed January 31, 2013.

Pagazaurtundua, A. and P. D. Warriss. 2006. Measurements of footpad dermatitis in broiler chickens at processing plants. Vet. Rec. 158: 679-682.

Patterson, P. H., E. S. Lorenz, W. D. Weaver, Jr., and J. H. Schwartz. 1998. Litter production and nutrients from commercial broiler chickens. J. Appl. Poult. Res. 7:247–252.

Peters, J., S. M. Combs, S. Hoskins, J. Jarman, J. L. Kovar, M. E. Watson, A. M. Wolf. and N. Wolf. 2003. Recommended Methods of Manure Analysis. Univeristy of Wisconsin Extension Publication No. A3769.

Pope, M. J., and T. E. Cherry. 2000. An evaluation of the presence of pathogens on broilers raised on Poultry Litter Treatment-treated litter. Poult. Sci. 79:1351-1355.

Ritz, C. W., B. D. Fairchild and M. P. Lacy. 2004. Implications of ammonia production and emissions from commercial poultry facilities: A review. J. Appl. Poult. Res. 13:684-692.

Roach, S., L. Isenhart, L. McKenna and M. Cunningham. 2009. Filthy feed: The risky and unregulated practice of feeding poultry litter to cattle. Available at: http://www.foodanimalconcerns.org/PDF/filthy_feed_report.pdf accessed March, 09, 2013.

Terzich, M., C. Quarles, J. Brown, and M. A. Goodwin. 1998a. Effect of Poultry Litter Treatment (PLT) on the development of respiratory tract lesions in broilers. Avian Pathol. 27:566-569.

Terzich, M., C. Quarles, M. A. Goodwin, and J. Brown. 1998b. Effect of Poultry Litter Treatment (PLT) on death due to ascites in broilers (research note). Avian Dis. 42:385-387.

Wu, K. and P. M. Hocking . 2011. Turkeys are equally susceptible to foot pad dermatitis from 1 to 10 weeks of age and foot pad scores were minimized when litter moisture was less than 30%.Poult Sci. 90(6):1170-8.

Youssef, I. M., A. Beineke , K. Rohn and J. Kamphues J. 2011. Effects of litter quality (moisture, ammonia, uric acid) on development and severity of foot pad dermatitis in growing turkeys. Avian Dis. 55(1):51-58.

Zublena, J. P., J. C. Barker and T. A. Carter. 1997. Soil Facts Poultry Manure as a Fertilizer Source. North Carolina Cooperative Extension Service. Publication AG-439-5. Available at: http://www.soil.ncsu.edu/publications/Soilfacts/AG-439-05/ accessed April 12, 2013

CHAPTER 5: EMPIRICAL MODELS FOR ESTIMATING AMMONIA EMISSIONS FROM BROILER HOUSES

Abstract. Determining the quantity of ammonia emitted is the first step towards developing best management practices and technology to mitigate ammonia from broiler houses. The challenges to quantifying ammonia emitted from broiler production include high equipment costs, complexity of setup and the requirement for continuous monitoring at individual facilities. The amount of ammonia emitted from a broiler house is a function of the ventilation rate, which depends on outdoor temperature and desired room temperature. The objective of this study was to develop empirical models to estimate ammonia emitted from broiler houses based on ammonia flux from litter treated with BLA and untreated broiler litter (CTL).

A convective emissions chamber was used to determine the effect of air temperature and ventilation rate on ammonia fluxes from BLA and CTL litter. Three air temperatures and three air flow rates were used in the chamber to mimic the minimum ventilation requirements for broiler houses during different seasons. Ammonia released from the litter was captured in an acid trap and the flux of ammonia from the litter was calculated.

Empirical models developed using the flux data explained over 95% of the variability in observed flux and demonstrate that ventilation rate and supply air temperature have a significant effect on ammonia flux from broiler litter. Model output for both BLA and CTL was more sensitive to change in ventilation rate than air temperature. Model estimates for ammonia flux from broiler houses based on temperature and ventilation rate were within ± 25% of observed values during flocks 2 and 3 (summer). However, the models were not used to estimate ammonia flux during flocks 4 and 5 (winter) because this would involve extrapolation of testing conditions, making predictions highly unreliable. These models provide a simple method for generating initial estimates of the amount of ammonia emitted from a broiler house using ventilation rate and outdoor temperature, which can be easily determined.

Keywords: Broiler litter, amendment, ammonia, emissions, model

Introduction

Ammonia volatilization from broiler houses depends on litter temperature, pH and TAN concentration, as well as the temperature and flow rate of surrounding air (Carr and Nicholson, 1990; Elliott and Collins; 1982; Miles et al., 2011). However, the amount of ammonia released from a broiler house to the environment is dependent mostly on the ventilation rate and house ammonia concentration, and varies depending on geography, house design and management systems (Gates et al., 2002).

It is often necessary to determine the amount of ammonia released during broiler production, litter storage and land application, for testing emissions models, and evaluating the effectiveness of mitigation techniques. Quantification of ammonia emitted from different sources can be achieved through emission factors, emission models or direct measurements. Variations in ammonia emitted from each broiler house necessitate continuous monitoring of building ventilation rate and ammonia concentration for reliable quantification, which is expensive and not always feasible (Gates et al., 2002).

Emission factors (EF) are designed to relate the quantity of pollutant emitted to the atmosphere with the activities responsible for the release (EPA, 2011). For instance, ammonia emitted from animal buildings is related to the confined animal species. The ammonia EF for broilers based on the U.S. emission inventory is 0.22 kg/bird per year (EPA, 2004). Emission factors are representative of long-term averages for a particular category (EPA, 2011), but are not necessarily accurate representations of ammonia emitted from each facility. In contrast, emission models relate ammonia emitted to specific conditions including litter characteristics (pH, TAN, temperature, moisture content) and management factors (VR, RH, temperature), and allow users to obtain realistic estimates of ammonia emitted under varying conditions (Liu, 2009).

Understanding the release mechanism and factors that affect ammonia volatilization is important for modeling the emission of ammonia from broiler litter. Ammonia partitions between the water in the litter (liquid) and the air (gas) above the litter surface (Thakre et al., 2008). The rate of mass transfer across the gas-liquid interface is influenced by the physical properties of the gas and liquid, gas flow characteristics and can be described using models (Thakre et al., 2008). Ammonia volatilization from the liquid phase increases with air velocity at constant manure and air temperature (Arogo et al., 1999). Factors that affect the solubility of the gas in the liquid, such as temperature, the presence of other solutes, and turbulence will also affect the rate of mass transfer (Dutta, 2007). Ammonia volatilization increases with liquid temperature because the diffusivity of solutes in liquids increases with temperature and results in a corresponding increase in mass transfer rate (Arogo et al., 1999). The solubility of ammonia in water also decreases with increasing temperature resulting in a larger mass transfer rate (Dutta, 2007). Interrelations between the many factors that affect ammonia mass transfer present significant challenges to modeling ammonia emitted from broiler litter. Therefore, laboratory studies only correlate ammonia flux to some of these factors within a range of conditions, typically set by experimental limits (Dutta, 2007).

Dynamic emission chambers provide controlled environments that are useful for measuring fluxes of ammonia from animal manure in laboratory studies (Ndegwa et al., 2009; Burns et al., 2003). They can be operated year round at desired conditions regardless of changes in outdoor conditions, and provide a reliable, cost effective and replicable method for comparing treatments (Burns et al., 2003). Convective emission chambers, which are used to determine the effect of environmental variables such as temperature, ventilation rate (VR), and humidity on emission rate (ASTM, 1996) find common application in measuring ammonia volatilization from animal manures in laboratory studies (Ndegwa et al., 2009). The NH_3 source is placed in a chamber and air is forced through the chamber. Ammonia in the air leaving the chamber can be determined using analytical instruments or captured in an acid trap (Ndegwa et al., 2009). Ammonia that is bubbled through an acid trap reacts with the acid according to equation 5-1, and can be determined using an ammonia selective electrode, titration or calorimetric methods. Using the flow rate, volume of acid and the NH_4^+ concentration, a time averaged flux of ammonia from the litter can be determined.

$$NH_3 + H^+ \longleftrightarrow NH_4^+ \tag{5-1}$$

The flux of ammonia from a broiler house is a function of the ventilation rate, which depends on outdoor temperature and desired room temperature. The ventilation rate can be expressed as air flow (Lpm, m^3/hr) or the number of volume exchanges per minute (vcm) achieved at the given air flow rate. Since the ventilation rate and outdoor temperature at any facility can be easily determined, flux models based on these parameters would provide a simple method for generating initial estimates of the amount of ammonia emitted from the facility. The objective of this study was to develop empirical models to estimate ammonia emitted from broiler houses based on ammonia flux from litter treated with BLA and untreated broiler litter (CTL).

Materials and methods

Litter sampling

Litter used for the experiments was from six rooms (three BLA and three CTL), collected within 24 hours of harvesting, for four flocks of broilers. Nine samples comprising the full depth of the litter (approximately 10 cm) were obtained from each room. The samples were placed in zipper bags, sealed and stored in sealed plastic tubs at approximately $22^{o}C$ for several months. Two composite mixtures (BLA and CTL) were prepared for the study by combining litter from all four flocks.

Experimental setup

The study was conducted using a convective emission chamber made from a 190 x 190 x 105 mm (l x w x h) PVC box partitioned with 2.5 mm thick plexiglass sheets to create two chambers each measuring 190 x 85 x 105 mm (Figure 5-1). Acid scrubbers were used to capture the ammonia emitted. Each chamber had an access port with a removable cover to enable addition/removal of litter, and was sealed during the experiments. Air was supplied to the chambers by a vacuum pump (Model DOA-P707-AA, GAST Manufacturing Inc., Benton Harbor, MI). The supply air was passed through sulfuric acid and deionized water traps to remove ammonia and acid fumes, respectively, before delivery to the chamber. The exhaust from each chamber was run through an acid trap (a vented 500 ml Erlenmeyer flask with 300 ml of 0.1M H_2SO_4).

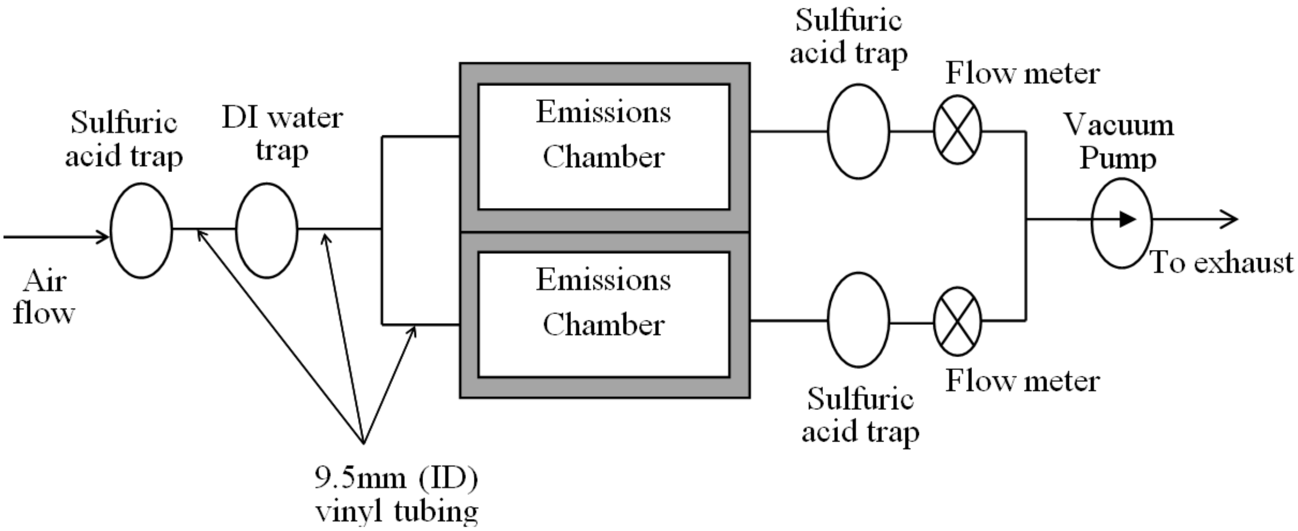


Figure 5-1: Experimental setup for determining ammonia flux from broiler litter

The experiments were performed in a room where temperature was controlled. Three air temperatures (10, 23, and 31 ^{o}C) and three air flow rates (0.1, 0.58, and 1.02 liters per minute) were used in a 3 x 3-factorial design with 4 replicates for both BLA and CTL. The air flows were selected to give 0.13, 0.75 and 1.33 volume changes per minute in the chamber to mimic the minimum ventilation requirements for broiler houses during winter, spring and summer, respectively (Barnwell and Wilson, 2006). Air flow rate through the chambers was controlled using volume flow control rotameters (Model PMR1-016360, Cole-Parmer Inc., Vernon Hills, IL). Air temperature during the experiments was monitored using Hobo TMC6-HD air/water/soil temperature sensors **(**Onset Computer Corporation, Inc. Bourne, MA**)**. Litter temperature was measured at the beginning and end of each test.

Emissions tests

The amount of litter was used for each replicate was 100 g. The litter depth in the chamber was approximately 3 cm. In general, the top surface of the litter was about 2 cm below the inlet and exhaust air ports. Ammonia-free air was supplied to the chamber the at the temperature and flow rate to be tested. At the end of each test, the contents of the acid traps were analyzed for TAN concentration using an ammonia-selective electrode (Method 4500-NH_3, D APHA, 2012). The mass of ammonia (mg) captured during each test was calculated by multiplying the TAN concentration (mg/L) by volume of acid in the trap (L). The flux of ammonia (g/m^2hr) from the litter was then calculated by dividing the mass of ammonia captured (mg) by the surface area (m^2) of the litter in the chambers and the test duration (hr).

The litter was analyzed for pH, TAN and moisture content before and after the tests to determine if these parameters changed during the emissions test. The TAN concentration was determined using an ammonia selective electrode (Orion 9512, Themo Electron Corporation, Waltham, MA), Method 4500-NH_3D from Standard Methods for Examination of Water and Wastewater (APHA, 2012). Litter moisture content was determined as the percentage change in weight after drying at 105 ^oC for 24 hours (Peters et al., 2003) and pH was determined using a combination pH meter (Orion 9512, Thermo Electron Corporation, Waltham, MA) for a 2:1 deionized water to litter ratio. The experimental design did not include determining the effects of pH, TAN and moisture on ammonia flux from the litter because litter pH, TAN and moisture cannot be easily controlled under testing conditions and the expected range in the litter samples was not large enough to have a significant effect on ammonia flux from the litter.

Statistical analysis

Paired t tests were carried out using SAS JMP Software version 9.0 (SAS Institute Inc., Cary, NC) to compare mean ammonia fluxes and litter characteristics (TAN, pH and moisture) for BLA and CTL before and after the emissions tests. The model in equation 5-2 below was assumed.

Flux = f (VR, T) 5-2

where

Flux = ammonia flux (g/m^{2}hr)

VR = ventilation rate (vcm)

T = air temperature (^{o}C)

f = function of

Stepwise regression was performed using SAS JMP Software version 9.0 (SAS Institute Inc., Cary, NC) to fit ammonia flux data to equation 5-2. The JMP software was used to construct flux equations for BLA and CTL using laboratory data. The software selects the most important model effects and fits the responses to the model using standard least squares. The forward selection approach was used and significance of model parameters and improvement in the model was tested (F-test) with the addition of each variable or combination of variables (terms). This was repeated until addition of terms did not improve the model.

Sensitivity analysis

Sensitivity analysis was performed to determine the relative change in ammonia flux with respect to changes in air temperature and VR. The relative sensitivity index (SI) was calculated as shown in equation 5-3.

$$\mathrm{SI} = \frac{\Delta y/y}{\Delta x/x} = \frac{(y - y_1)/y}{(x - x_1)/x} \qquad 5\text{-}3$$

where

x = input parameter value

y = model output for x

x_1 = new value of x (higher or lower)

y_1 = model output for x_1

The value of SI can be negative, positive or zero indicating negative correlation, positive correlation or no correlation respectively. The larger the absolute values of SI, the more sensitive the model output is to a particular parameter (White and Chaubey, 2005).

Model evaluation

The empirical models were used to estimate the mean ammonia flux from a broiler house. The VR and actual ammonia flux had been previously determined by continuous monitoring from the rooms (chapter 3). The input VR (vcm) for the models was determined by dividing the VR (m^3/min) by the volume of the room (m^3). The observed outdoor temperature for Blacksburg, VA (NCDC, 2013) on the days of monitoring was used for supply air temperature.

Results and discussion

Litter characteristics

The mean litter pH, moisture, and TAN before and after the tests are shown in Table 5-1. The mean pH and moisture content of CTL before and after the tests were significantly higher than BLA litter. However, the TAN concentration was not significantly different ($p>0.05$).

Table 5-1: Litter characteristics (mean ± std. dev) before and after emissions tests

	CTL		**BLA**		**P value**
	Before	**After**	**Before**	**After**	
pH	8.67 (± 0.06)	8.58 (± 0.07)	8.52 (± 0.10)	8.42 (± 0.09)	< 0.0001
Moisture (%)	22.8 (± 3.5)	21.8 (± 3.3)	21.5 (± 1.3)	20.3(± 0.8)	< 0.0001
TAN (g/kg)	9.8 (± 2.9)	9.3 (± 3.0)	8.9 (± 1.4)	8.9 (± 1.4)	> 0.05

Litter pH decreased by 0.9 pH units for both BLA and CTL and the moisture content after the tests was lower by 1.2% and 1.0%, respectively. The decrease in moisture content is due to loss of water vapor, while the decrease in pH was due to loss of ammonia from the litter during the tests. The ammonia species in the litter exist in equilibrium according to equation 5-4

$$NH_4^+{}_{(aq)} \longleftrightarrow NH_{3\,(aq)} + H^+{}_{(aq)} \qquad 5\text{-}4$$

Loss of NH_3 from the litter causes the reaction in equation 5-4 to proceed to the right to maintain equilibrium between NH_4^+ and NH_3. The accumulation of H^+ from that reaction causes a decrease in pH.

Ammonia flux

Ammonia fluxes (mean ± std. dev) from BLA and CTL at the air flow rates used for the study are shown in Table 5-2 and mean fluxes at the three test temperatures are shown in Table 5-3. The mean ammonia flux from CTL (0.84 ± 0.53 g/m^{2}hr) was significantly higher than BLA (0.55 ± 0.45 g/m^{2}hr).

Table 5-2: Ammonia flux (mean ± std. dev) at 0.10, 0.58 and 1.02 Lpm

Air flow rate (Lpm)	CTL	BLA	p value
0.10	0.27 (± 0.10)	0.15 (± 0.08)	0.005
0.58	0.93 (± 0.30)	0.68 (± 0.38)	0.034
1.02	1.28 (± 0. 51)	0.81 (± 0.51)	0.082

Table 5-3: Ammonia flux (mean ± std. dev) at 10, 23 and 31 ^{o}C

Air temperature (^{o}C)	CTL	Treated	p value
10	0.46 (± 0.21)	0.16 (± 0.10)	0.0002
23	0.83 (± 0.47)	0.56 (± 0.31)	0.1260
31	1.19 (± 0.64)	0.90 (± 0.52)	0.2430

Ammonia fluxes for both BLA and CTL increased with increasing air temperature and air flow as shown in Figures 5-2 and 5-3. This is an expected result for soluble gases such as ammonia whose volatilization is controlled mainly a gas film (Arogo et al., 1999). Increasing air velocity increases turbulence intensity, which results in thinning of the boundary layer at the gas-liquid interface resulting in higher mass transfer from the litter (Arogo et al., 1999).

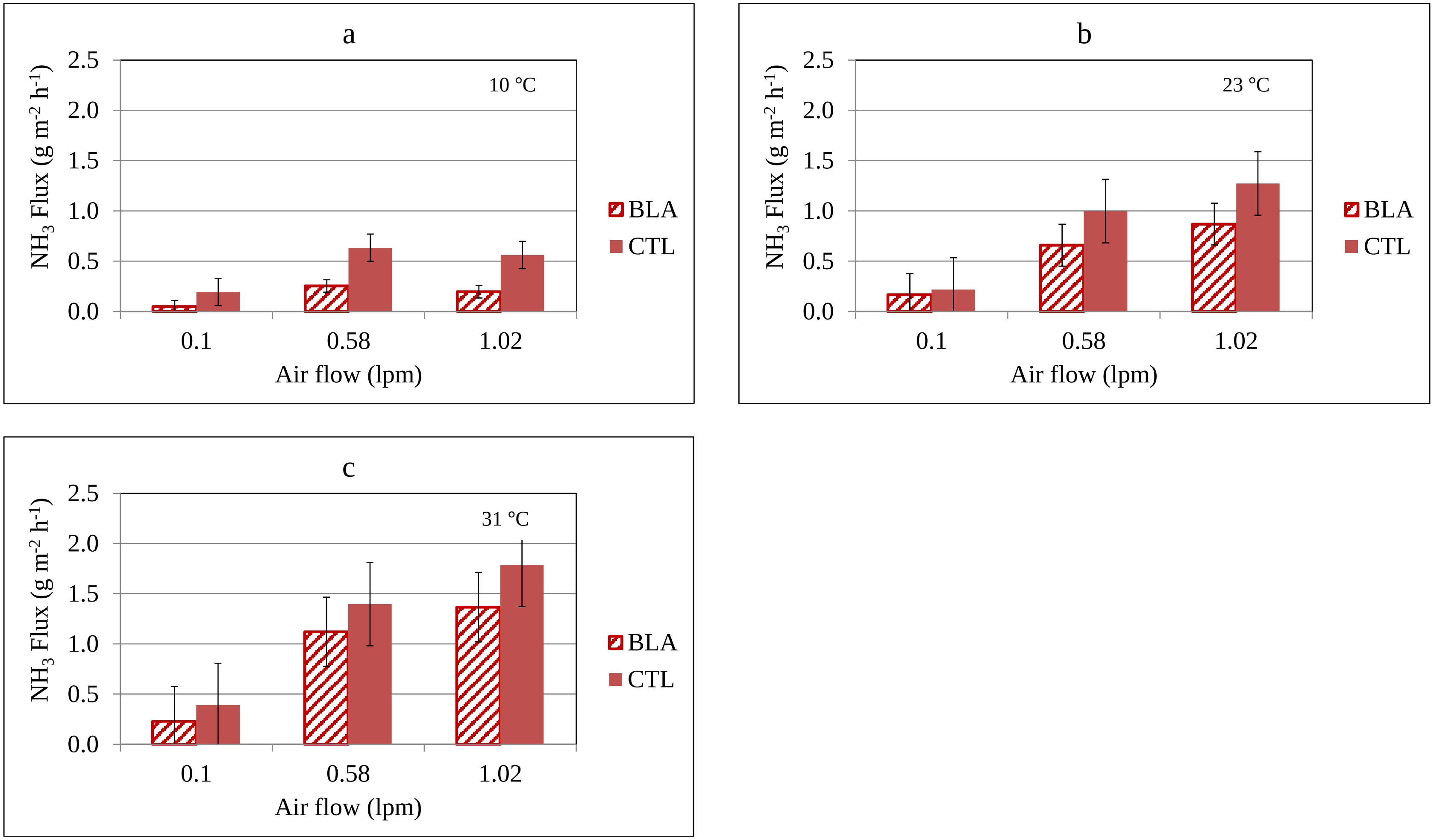


Figure 5-2: Ammonia flux from BLA and CTL at constant air temperature (a = 10 °C, b = 23 °C, c = 31 °C)

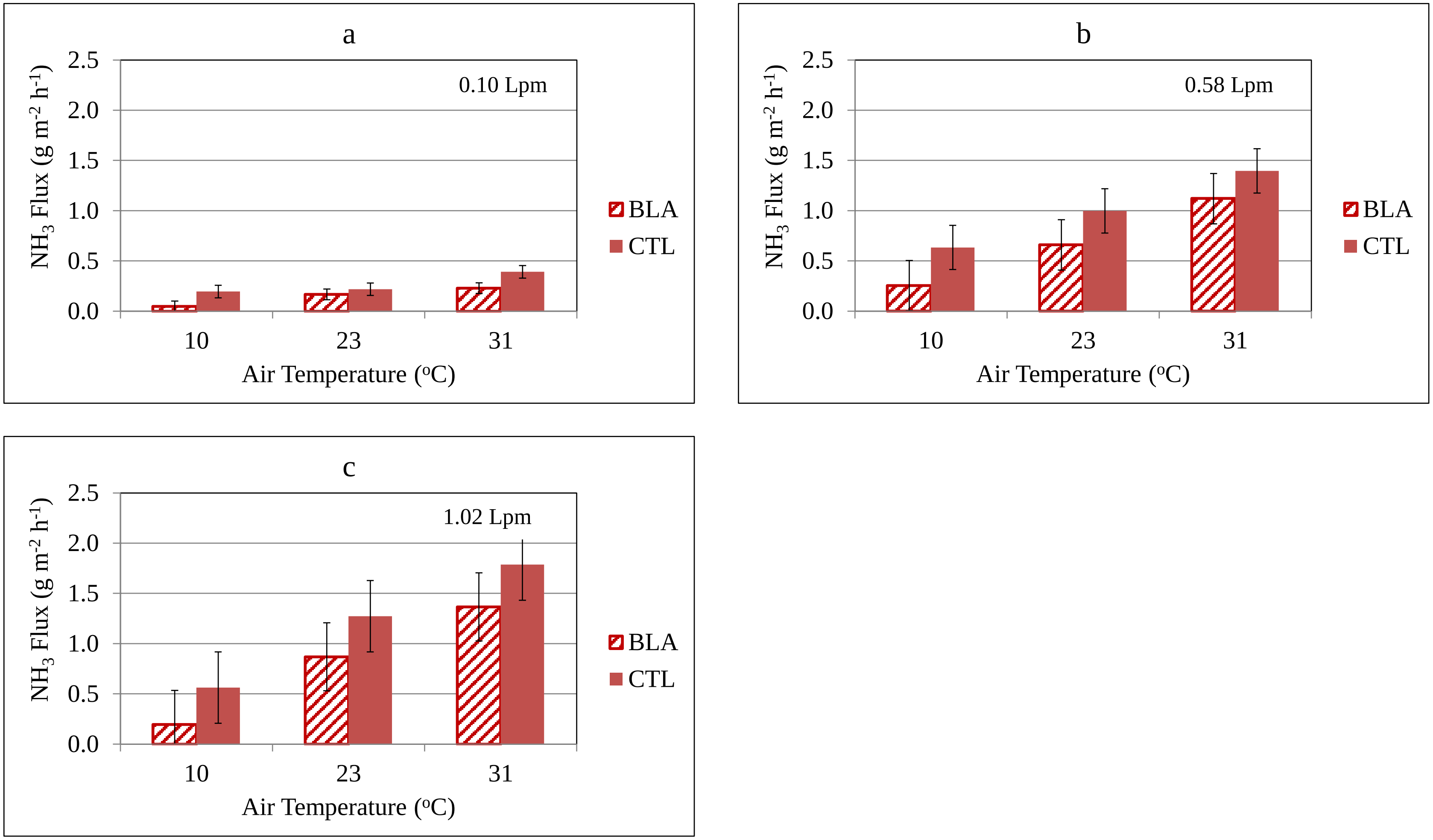


Figure 5-3: Ammonia flux from BLA and CTL at constant air flow (a = 0.10 Lpm, b = 0.58 Lpm, c = 1.02 Lpm)

Ammonia flux from CTL was significantly higher than BLA at 10 ^{o}C but not at 23 ^{o}C and 31 ^{o}C. Flux from CTL at 0.10 and 0.58 Lpm was significantly higher than BLA. There was a nearly four-fold increase in mean flux from both CTL and BLA when air flow was increased from 0.1 to 0.58 Lpm compared to an increase of 1.2 times when air flow was increased from 0.58 to 1.02 Lpm (Figure 5-3). Similar observations were made by Rong et al. (2010) and Liu (2009); the change from laminar to turbulent flow conditions as air velocity increases reduces the thickness of the boundary layer at gas-liquid interface and results in increased mass transfer from liquid to gas phase (Rong et al., 2010; Arogo et al., 1999). However, it is important to note that ammonia bound to particulates and gaseous ammonia captured by the acid trap cannot be differentiated and some of the ammonia captured at higher flow rates could be ammonia bound to particles swept from the chamber.

Model development

SAS JMP software was used to fit the models to the experimental data using the terms T, VR, T*VR and VR^2, which had significant effects on ammonia flux from both BLA and CTL. The software output for BLA and CTL are shown in Appendix A and Appendix C, respectively. The resulting equations, shown in Table 5-4 explain over 95% of the variability in ammonia fluxes from BLA and CTL as shown in Figure 5-4.

Table 5-4: Empirical models for estimating ammonia fluxes from broiler litter using temperature (°C) and ventilation rate (vcm)

Litter	Flux Equation	R^2
CTL	$F = -0.35 + 0.87 * VR + 0.034*T + 0.047*(VR-0.69)*(T-21.3) - 0.72*(VR-0.69)^2$	0.97
BLA	$F = -0.49 + 0.57 * VR + 0.036*T + 0.043*(VR-0.74)*(T-21.3) - 0.53*(VR-0.74)^2$	0.96

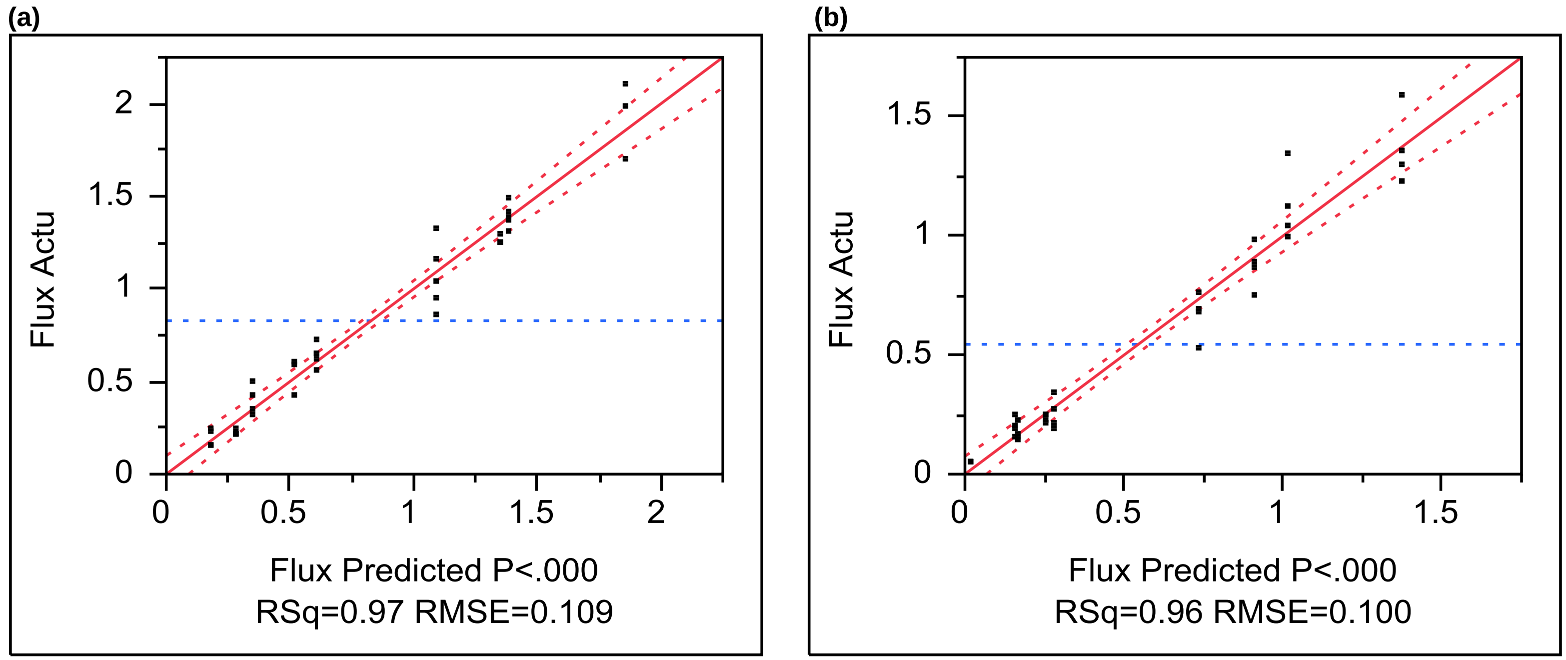


Figure 5-4: Predicted vs. actual flux from CTL (a) and BLA (b) – Lab data

Sensitivity analysis

Relative sensitivity indices for change in CTL and BLA model output for change in VR at constant T and change in T at constant VR are shown in Figures 5-5 and 5-6 respectively. For both BLA and CTL, the relative sensitivity of model output at constant VR did not change significantly with temperature. However, the sensitivity of model output at constant temperature decreased with increasing VR. Model output for BLA was most sensitive to change in VR at 10 ^{o}C; however relative sensitivity decreased with increasing VR. Similar observations were made by (Rong et al., 2010 and Arogo et al., 1999) and can be explained using the boundary theory of mass transfer. Mass transfer for soluble gases is more sensitive to changes in air velocity at low air flow because of decreasing boundary layer thickness and reduced resistance to mass transfer (Arogo et al., 1999). However, at high flow and under fully turbulent flow, the boundary layer is non-existent.

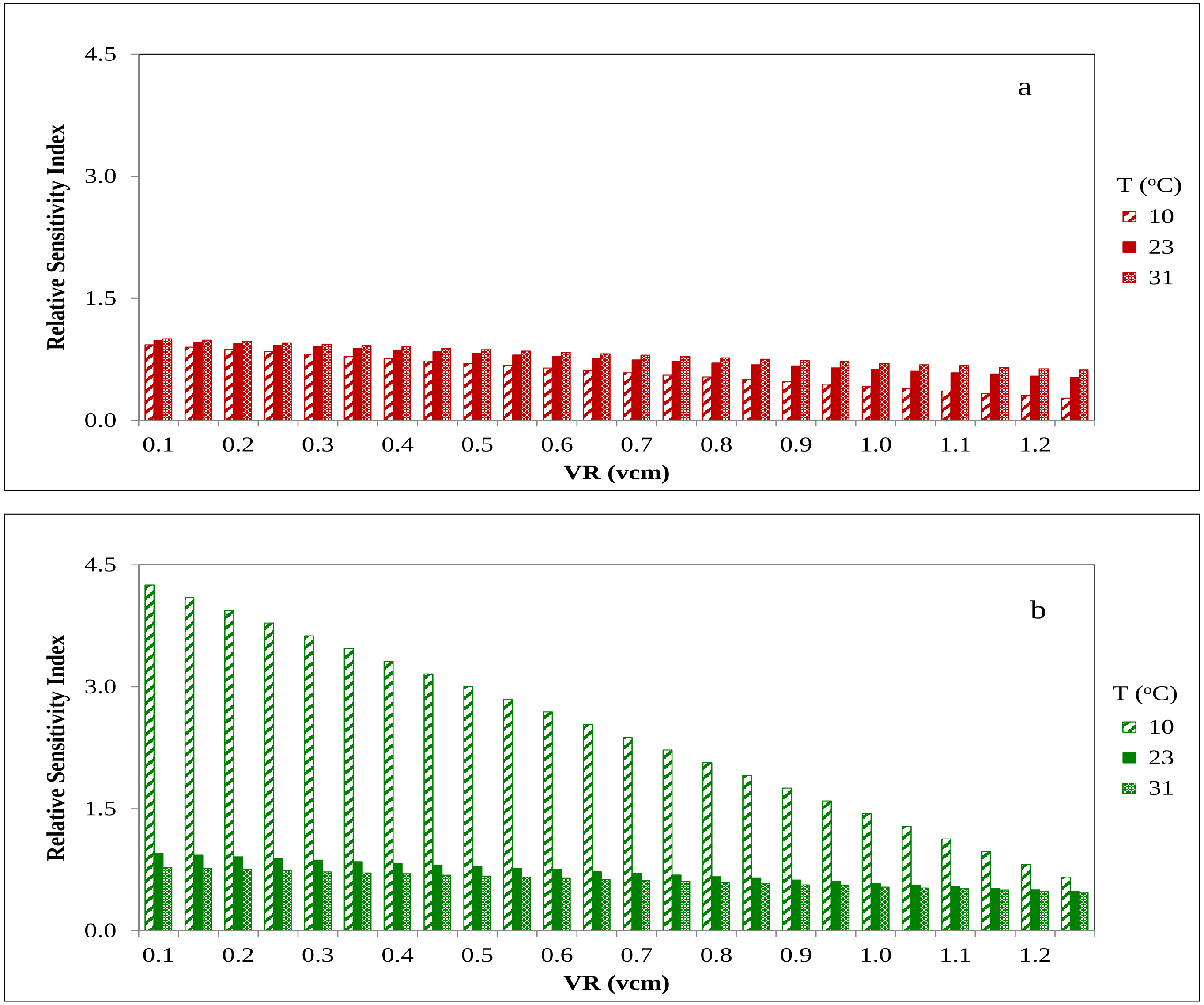


Figure 5-5: Relative Sensitivity of CTL (a) and BLA (b) Flux Model Output at Constant Temperature

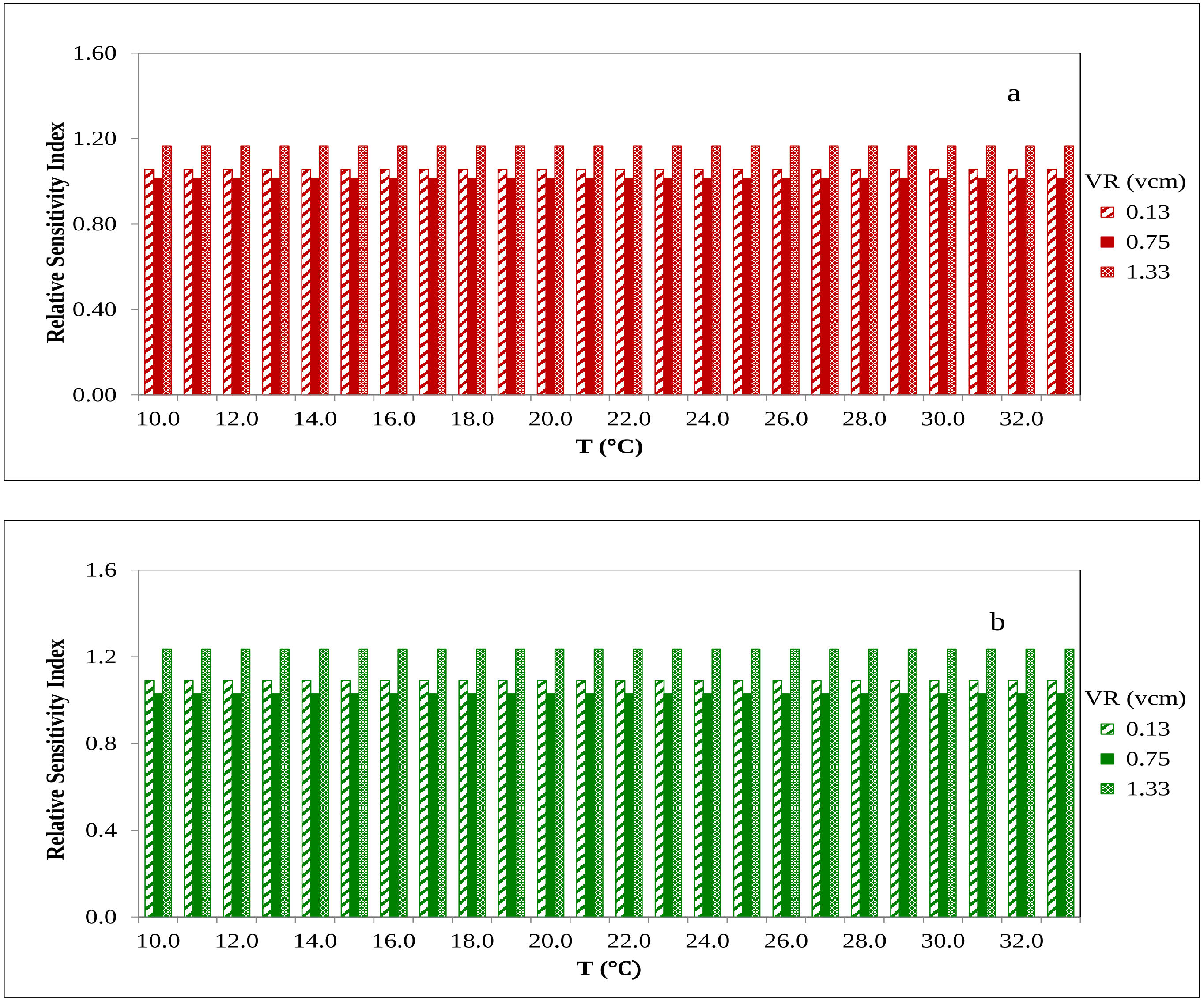


Figure 5-6: Relative sensitivity of CTL (a) and BLA (b) flux model output at constant VR

Model evaluation

Model estimates were compared to observed ammonia flux (g/m^2hr) from a broiler house as shown in Figure 5-7. Correlation between model estimated and observed ammonia flux from flock 2 was over 75% and the mean observed ammonia flux was less than estimated by approximately 21%. Model-estimated and observed ammonia flux from both BLA and CTL generally increased from the start to end of the observation period (as expected). However, the models overestimated ammonia fluxes at during week 1, when VR was controlled using a timer. Model estimates for both BLA and CTL were closest to observed ammonia flux during weeks 4 and 5. The estimates for mean ammonia during flocks 2 and 3 were within 25% of observed values for both BLA and CTL. The models were not used to estimate ammonia flux during flocks 4 and 5 because it would involve extrapolation of testing conditions, making predictions highly unreliable.

Although the models were a good fit to the lab study data, there are process-based factors that affect observed ammonia flux from broiler houses which were unaccounted for in model development. The litter used for the tests had been stored for several months and its characteristics including TAN, pH and moisture had changed significantly. The effect of change in litter characteristics during storage on model predictions can be investigated by studying ammonia flux from freshly collected litter. Multiple regression analysis of ammonia flux, air temperature and ventilation rate data recorded under field conditions also showed the model terms $VR*T$ and VR^2 that had a significant effect on ammonia flux in the laboratory tests were insignificant ($p>0.05$) under field conditions.

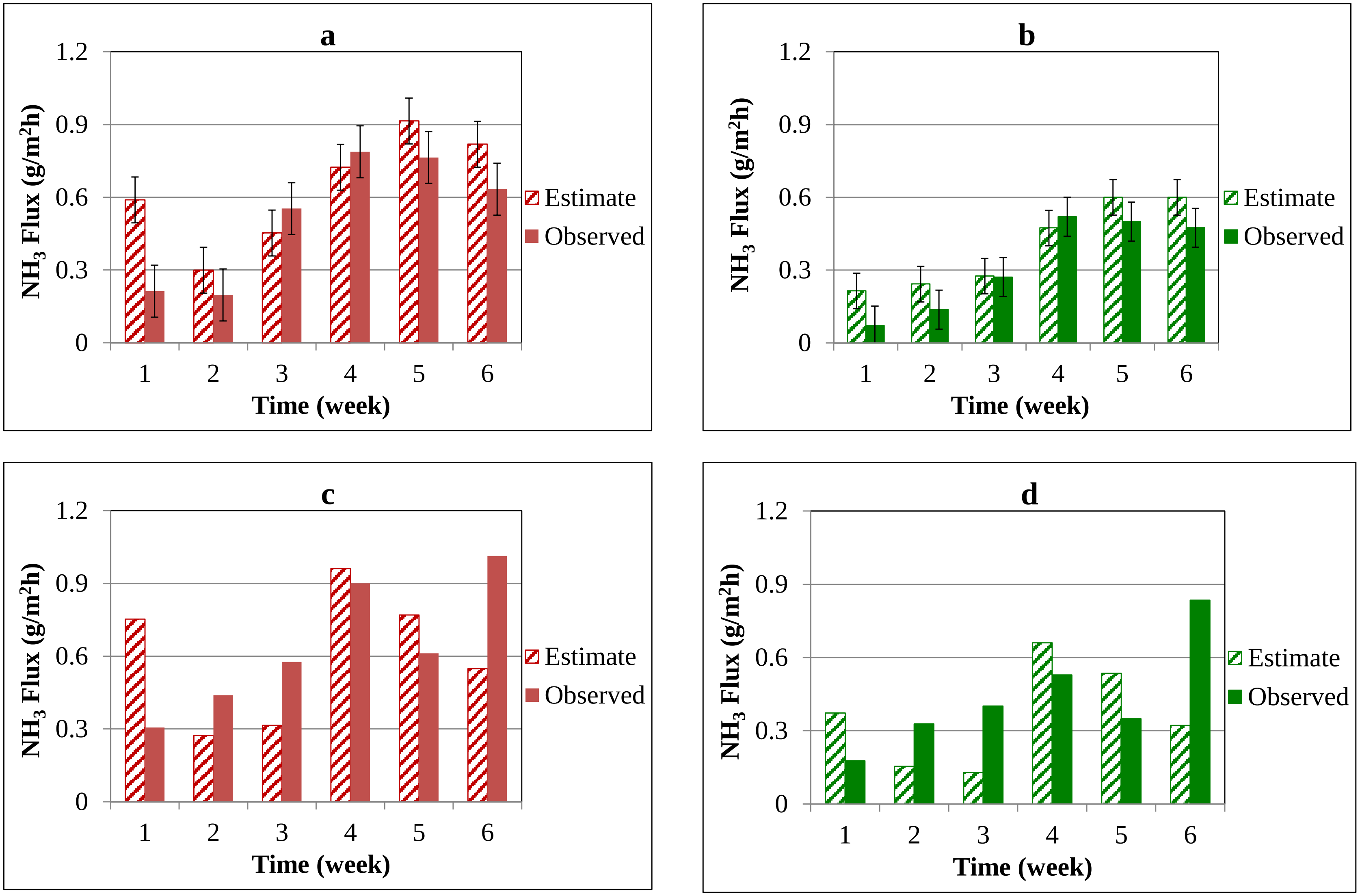


Figure 5-7: Estimated and observed ammonia flux from flocks 2 and 3 from CTL (a, c) and BLA (b, d)

Conclusion

Ventilation rate and supply air temperature have a significant effect on ammonia flux from broiler litter. Empirical models developed using ammonia flux data from broiler litter explained over 95% of the variability in observed flux using air temperature and ventilation rate.

Model estimates for ammonia flux from broiler houses based on temperature and ventilation rate were within ± 25% of observed values during summer conditions. The models were not used to estimate ammonia flux during the winter because it would involve extrapolation of testing conditions, making predictions highly unreliable.

The models can be used to provide preliminary estimates of ammonia emitted from boiler houses using temperature and ventilation rate within the range of conditions tested. However, there are process-based factors that affect observed ammonia flux from broiler houses that were not accounted for in model development, which could introduce considerable errors in model estimates.

References

American Public Health Association (APHA). Standard methods for the examination of water and wastewater. 22 ed., Water Environment Federation: London, UK, 2012.

Arogo, J., P. Westerman, A. Heber, W. Robarge and J. Classen. 2006. Ammonia emissionsfrom animal feeding operations. Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers. p. 41-88. J. M. Rice, D. F. Caldwell, F. J. Humenik, eds. Pub. Number 913C0306. St. Joseph, Michigan: ASABE.

Arogo, J., R. H. Zhang, G. L. Riskowski, L. L.Christianson and D. L. Day. 1999. Mass Transfer Coefficient of Ammonia in Liquid Swine Manure and Aqueous Solutions. Engng. Res. 73(1):10-10.

ASTM. 1996. D7706-11: Standard Practice for Rapid Screening of VOC Emissions from Products Using Micro-Scale Chambers. Available at: http://enterprise.astm.org/filtrexx40.cgi?+redline_pages/D7706.htm. Accessed March 17, 2013.

Barthelmie, R. J. and S.C. Pryor. 1998. Implications of Ammonia Emissions for Fine Aerosol Formation and Visibility Degradation: A Case Study from the Lower Fraser Valley, British Columbia. Atmos. Environ. 32: 345-352.

Beker, A., S. L. Vanhooser, J. H. Swartzlander, and R. G. Teeter. 2004. Atmospheric ammonia concentration effects on broiler growth and performance. J. Appl. Poult. Res. 13:5–9.

Burns, R. T., K. A. Armstrong, F. R. Walker, C. J. Richards and D. R. Raman. Ammonia Emissions from a Broiler Production Facility in The United States. Paper presented at International Symposium on Gaseous and Odor Emissions from Animal Production Facilities, Horsens, Denmark. June 2-4, 2003.

Carr, L. E. and J. Nicholson. 1990. Empirical Models to Determine Ammonia Concentrations from Broiler Chicken Litter. Trans. ASAE 33(4):1337-1342.

Dutta, B. K. Principles of mass Transfer and Separation Processes. Prentice Hall of India: New Delhi, India, 2007.

Elliott, H. A. and N. E. Collins. 1982. Factors Affecting Ammonia Release in Broiler Houses. Trans. ASAE 25(2):413 – 424.

EPA (U.S. Environmental Protection Agency). 2011. Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors. Available at http://www.epa.gov/ttnchie1/ap42/ Accessed: March 1, 2013.

EPA (U.S. Environmental Protection Agency). 2004. National Emission Inventory- Ammonia Emissions from Animal Husbandry Operations. Available at http://www.epa.gov/ttn/chief/ap42/ch09/related/nh3inventorydraft_jan2004.pdf Accessed: March 11, 2013.

Gates, R. S., H. Xin and E. F. Wheeler. Ammonia Losses, Evaluations and Solutions for Poultry Systems. Paper presented at National Poultry Waste Management Symposium, Birmingham, AL, October 28-30, 2002.

Jaworski, N. A., R.W. Howarth and L. J. Hetling. 1997. Atmospheric Deposition of Nitrogen Oxides onto the Landscape Contributes to Coastal Eutrophication in the Northeast United States. J. Environ. Sci.Technol. 31(7):1995-2004.

Kim, J.H., D.H. Lim, J.K. Kim, S.J. Jeong and B.K. Son. 2005. Effects of Particulate Matter (PM10) on the Pulmonary Function of Middle-School Children. J. Korean Med. Sci. 20(1):42-45.

Liu, Z. 2009. Measurement and Modeling Ammonia Emissions from Broiler Litter. PhD Dissertation. North Carolina State University. Available at: http://www.academia.edu/1549221/Measurement_and_modeling_ammonia_emissions_from_broiler_litter. Accessed March 2, 2013.

Miles, D. M., D. E. Rowe, and T. C. Cathcart. 2011. High litter moisture content suppresses litter ammonia volatilization. Poultry Sci. 90:1397-1405.

Miles, D. M., S. L. Branton, and B. D. Lott. 2004. Atmospheric Ammonia is Detrimental to the Performance of Modern Commercial Broilers. Poult. Sci. 83:1650 -1654.

NCDC (National Climatic Data Center). 2013. Quality Controlled Local Climatological Data. Available at: http://cdo.ncdc.noaa.gov/qclcd/QCLCD?prior=N. Accessed: February 07, 2013.

Ndegwa, P. M. , V. K. Vaddella, A. N. Hristov and H. S. Joo. 2009. Measuring Concentrations of Ammonia in Ambient Air or Exhaust Air Stream using Acid Traps. J. Environ. Qual. 38:648-653.

Ni, J. 1999. Mechanistic models of ammonia release from liquid manure: a review. J. Agric.Engng Res. 72: 1-17.

Rong, L., P. Nielsen, G. Zhang. 2010. Experimental and Numerical Study on Effects of Airflow and Aqueous Ammonium Solution Temperature on Ammonia Mass Transfer Coefficient. J. Air. Waste. Manage. 60(4):419-428.

Thakre, S.B., L.B. Bhuyar, S.J. Deshmukh. 2008. Mathematical models for overall gas transfer coefficient using different theories and evaluating their measurement accuracy. International Journal of Chemical and Biomolecular Engineering.(WASET) 1(4):203-207.

Van Breemen, N., P.A. Burrough, E.J. Velthorst, H.F. Van Dobben, T. de Wit, T.B. Ridder, H.F.R. Reijnders. 1982. Soil Acidification from Atmospheric Ammonium Sulphate in Forest Canopy Throughfall. Nature 299:548-550.

White, K. L. and I. Chaubey. 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable swat model. Journal of the American Water Resources Association (JAWRA) 41(5):1077-1089.

CHAPTER 6: GENERAL CONCLUSION AND RECOMMENDATIONS

Quantification and mitigation of ammonia emitted from broiler houses is important for addressing growing concerns regarding the effects of ammonia on bird welfare, human health and the environment. The primary focus of this work was quantifying ammonia emitted from broiler houses and determining the reduction in ammonia achieved by a biodegradable litter amendment. As reported in literature, wide variations in ammonia emitted, which could not be explained using measured parameters alone, were observed even among rooms with the same treatment and under similar environmental conditions. This remains a challenge to estimating ammonia emitted from broiler production facilities.

Models can provide estimates to simplify quantification of ammonia emitted from broiler houses to the atmosphere. However, formulation of models is complicated by the many factors that influence ammonia formation and release from broiler litter, including some like pH that cannot be controlled in the laboratory. Assumptions made to cover unknown factors during testing often limit the scope of application for models. Empirical relationships for estimating ammonia flux developed during this study can explain over 95% of the variability in the ammonia flux from litter in an emissions chamber. The models were developed using ammonia flux data from composite litter that had been stored for a considerable amount of time, and litter TAN and pH had increased during storage. Since ammonia flux from broiler litter increases with pH and TAN content, it would be insightful to compare these results with flux data from freshly collected litter, which was unavailable for the study.

The study corroborated the impact of elevated ammonia concentrations on broiler weights and feed efficiency, and the benefits of using litter amendments for ammonia mitigation but no correlation was established between litter TAN and development and severity of FPD. Established facts such as the effect of increasing air flow (VR) on ammonia flux and the effect of litter moisture on pH, TAN content and N retention were also affirmed. However, further research is required to clarify the significance and interrelations between these factors, and enable the development of more accurate models for ammonia emitted from broiler houses.

Moisture content is probably the single most important factor affecting ammonia production in broiler litter, and results from the study emphasize why moisture control is essential for ammonia mitigation. Litter around the drinkers had significantly higher moisture content, litter TAN and significantly lower TN at the end of each flock compared to other areas in the house. Waterer management is, therefore, crucial for ammonia mitigation and reducing the costs associated with spilled water. The current practice for amendment application does not place particular emphasis on litter around the drinkers might. However, the effect of increased amendment dose around the waterer should be investigated.

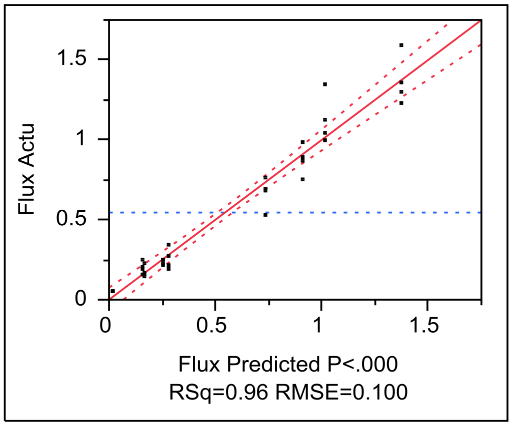
Increasing ventilation achieves reduction in ammonia house ammonia concentration but also increases ammonia emitted to the atmosphere. Given the increasing concerns regarding the effects of ammonia on the environment and human health, this option should be used in conjunction with other mechanisms (e.g. acid scrubbers) to trap and neutralize the ammonia leaving the building. Promising results for ammonia mitigation have been shown in studies using feed additives to control manure N and moisture content, which should be implemented on larger scale, if feasible.

The success of mitigation methods for ammonia from broiler houses lies in finding solutions that are effective, easy to implement and will not increase production costs. BLA provides a unique opportunity for achieving reduction in ammonia emitted and, consequently, increased bird weight and feed efficiency, and also showed potential for energy savings from reduced VR requirements. However, it is necessary to determine the minimum litter moisture content required for BLA to work effectively.

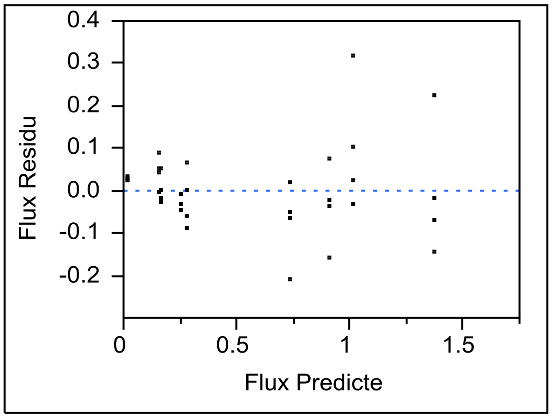
Since BLA is made from agricultural residues, it is non-toxic, non-corrosive and can provide a market for agricultural waste, creating extra revenues for farmers. Further research is required to increase BLA effectiveness to make it competitive against commercially available chemical products. Testing of BLA in a commercial broiler house is also required to ascertain performance under full scale production conditions. Process refinement to increase production rate and reduce costs, marketing to gauge public interest, and determination of the feasibility of BLA production on a commercial scale are all required.

APPENDICES

Actual by Predicted Plot



Residual by Predicted Plot



Summary of Fit

RSquare	0.958575
RSquare Adj	0.95323
Root Mean Square Error	0.100162
Mean of Response	0.545111
Observations (or Sum Wgts)	36

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	7.1966370	1.79916	179.3359
Error	31	0.3110026	0.01003	**Prob > F**
C. Total	35	7.5076396		<.0001*

Lack of Fit

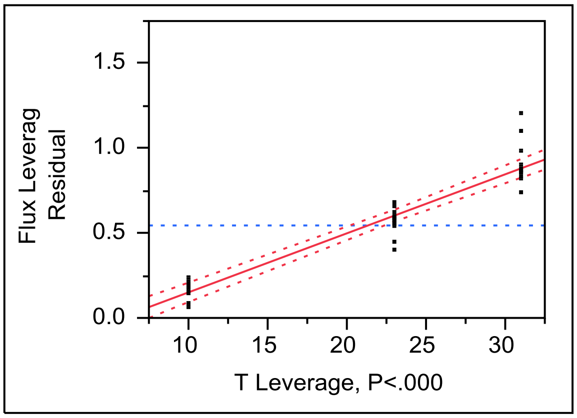
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Lack Of Fit	4	0.08559510	0.021399	2.5632
Pure Error	27	0.22540750	0.008348	**Prob > F**
Total Error	31	0.31100260		0.0611
				Max RSq

Parameter Estimates

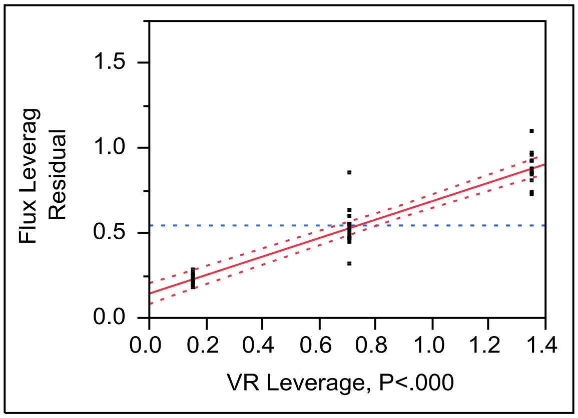
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	-0.47347	0.056851	-8.33	<.0001*
T	0.0347962	0.001929	18.04	<.0001*
VR	0.5449906	0.034126	15.97	<.0001*
(T-21.3333)*(VR-0.73667)	0.0390054	0.003937	9.91	<.0001*
(VR-0.73667)*(VR-0.73667)	-0.521536	0.098496	-5.30	<.0001*

Appendix A: BLA flux model parameter estimates

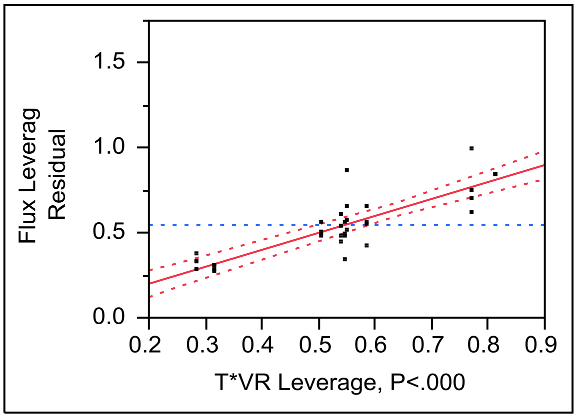
T



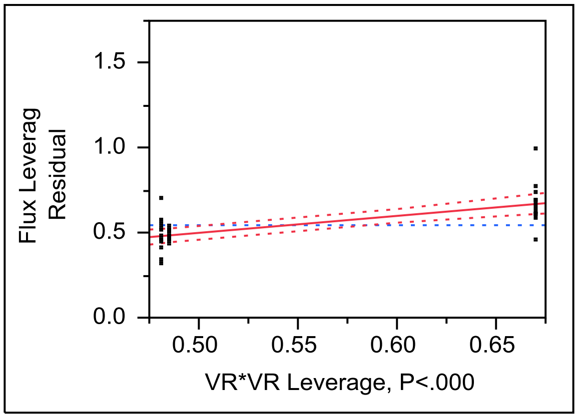
VR



T*VR

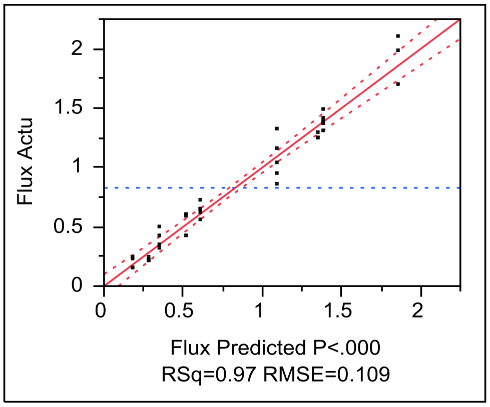


VR*VR

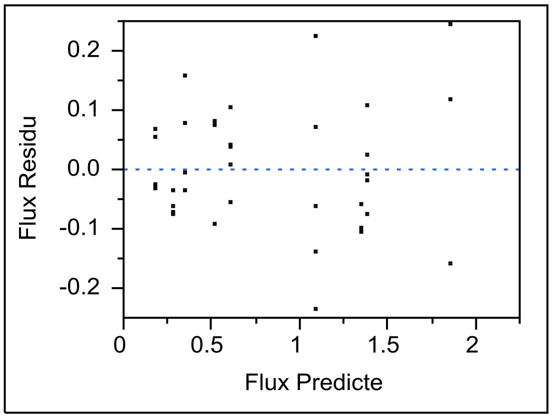


Appendix B: BLA flux model leverage plots

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	10.268415	2.56710	215.1278
Error	31	0.369921	0.01193	**Prob > F**
C. Total	35	10.638336		<.0001*

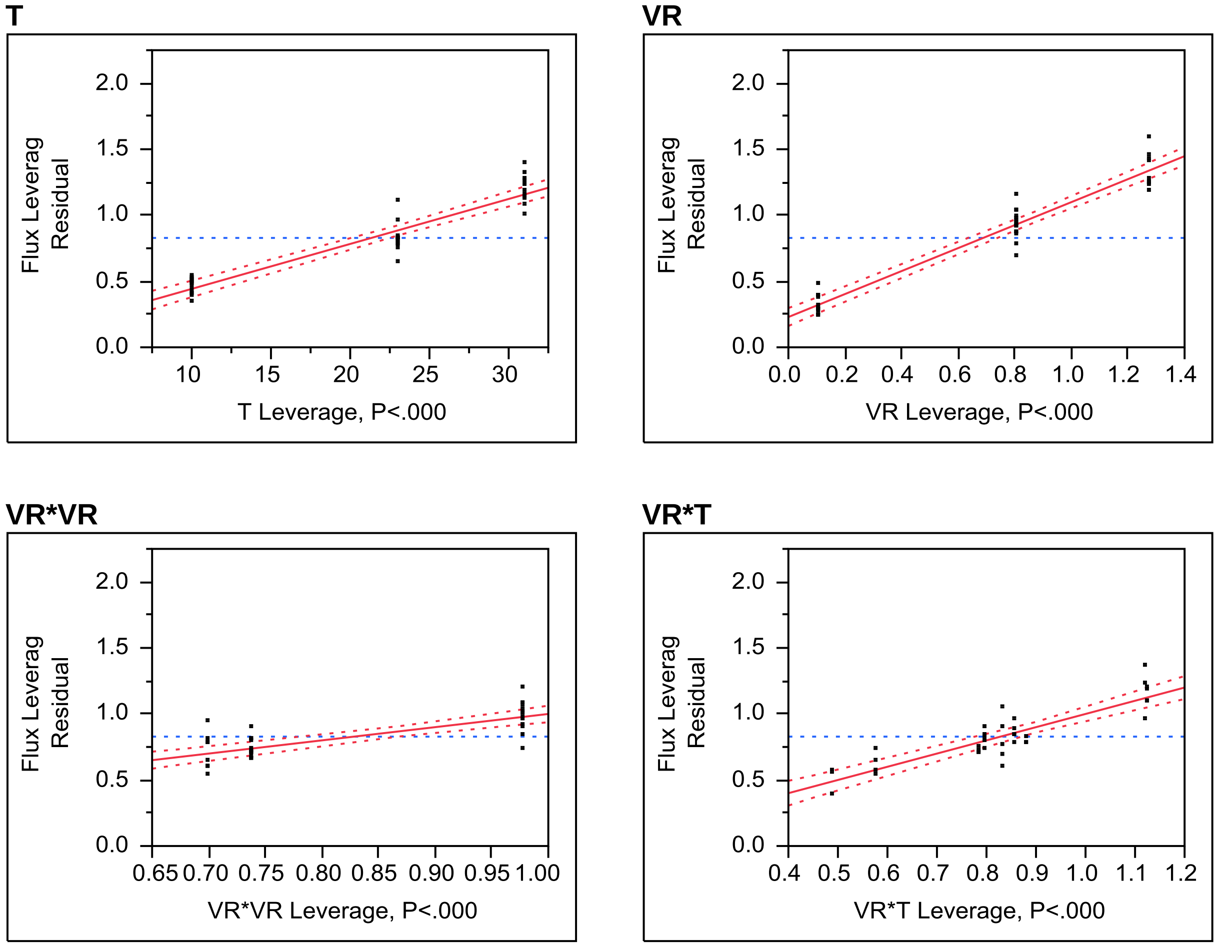
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	4	0.07200486	0.018001	1.6314
Pure Error	27	0.29791577	0.011034	**Prob > F**
Total Error	31	0.36992063		0.1952
				Max RSq

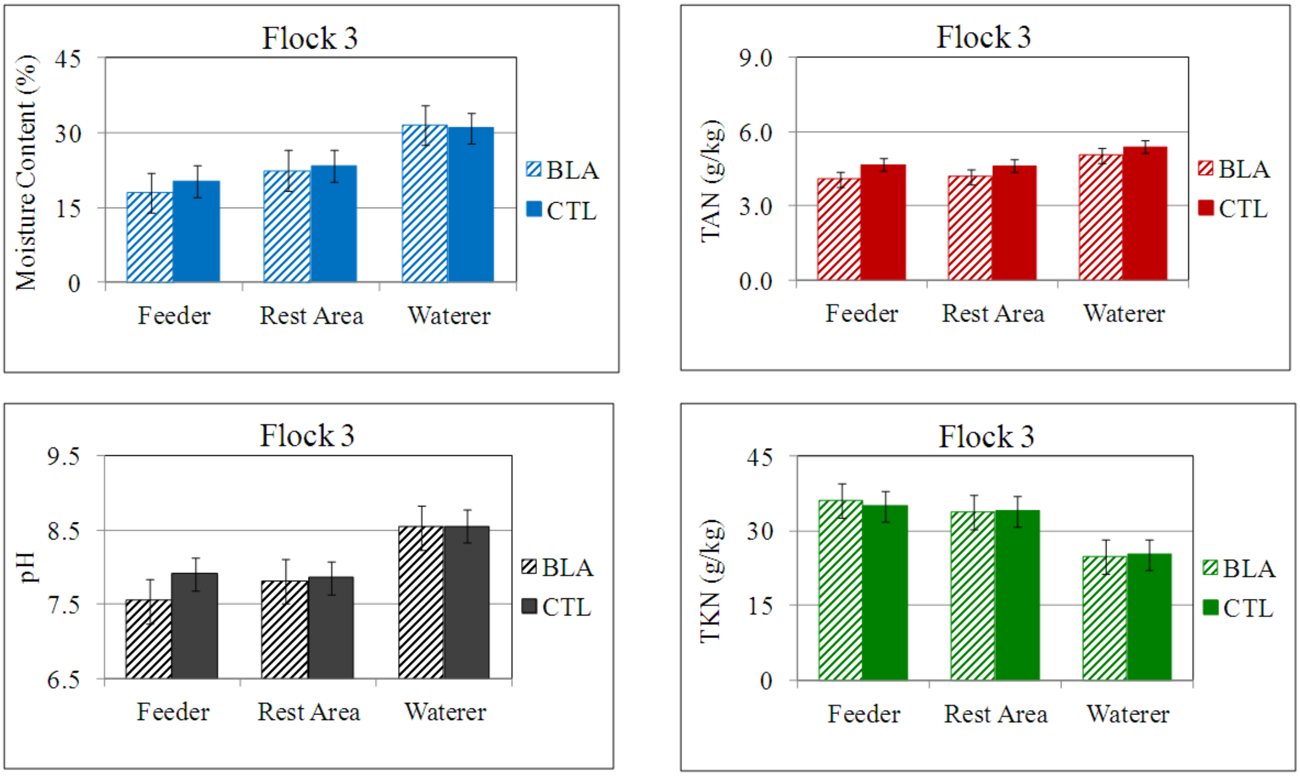
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.346796	0.058751	-5.90	<.0001*
T	0.0340464	0.002104	16.18	<.0001*
VR	0.8702408	0.040082	21.71	<.0001*
(VR-0.68833)*(VR-0.68833)	-0.720667	0.103371	-6.97	<.0001*
(VR-0.68833)*(T-21.3333)	0.0470125	0.004608	10.20	<.0001*

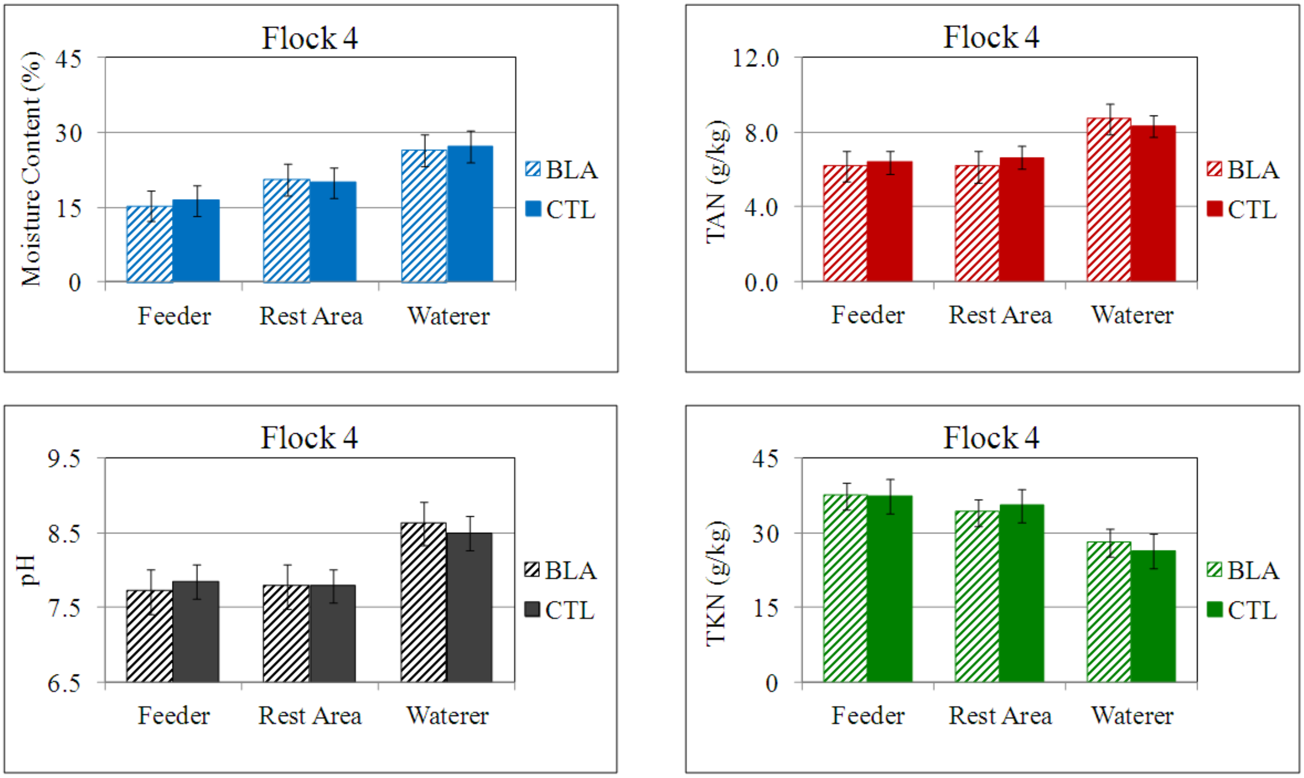
Appendix C: CTL flux model parameter estimates



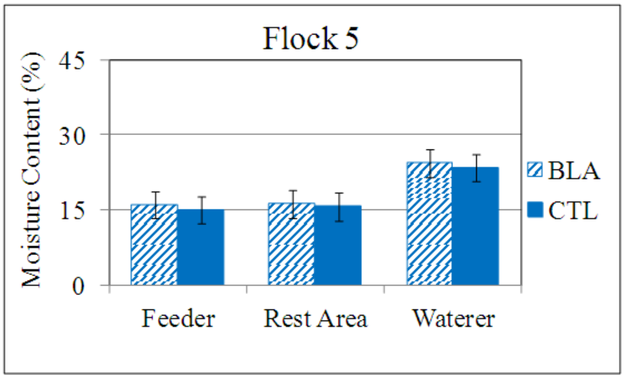
Appendix D: CTL flux model leverage plots

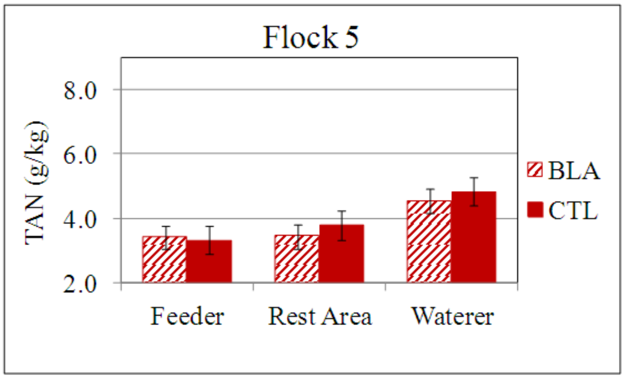


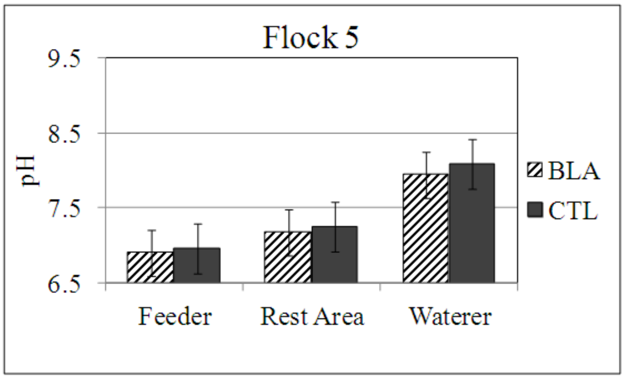
Appendix E: Litter Characteristics after Flock 3

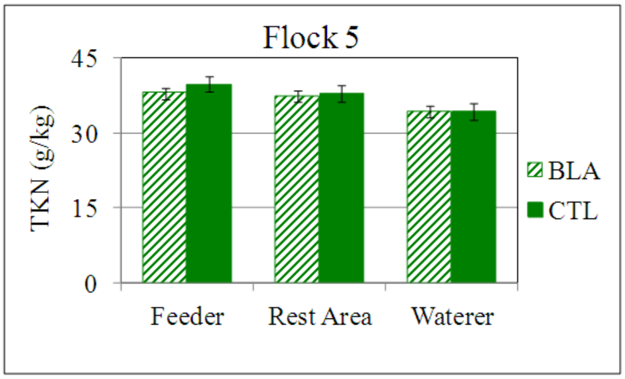


Appendix F: Litter Characteristics after Flock 4









Appendix G: Litter Characteristics after Flock 5