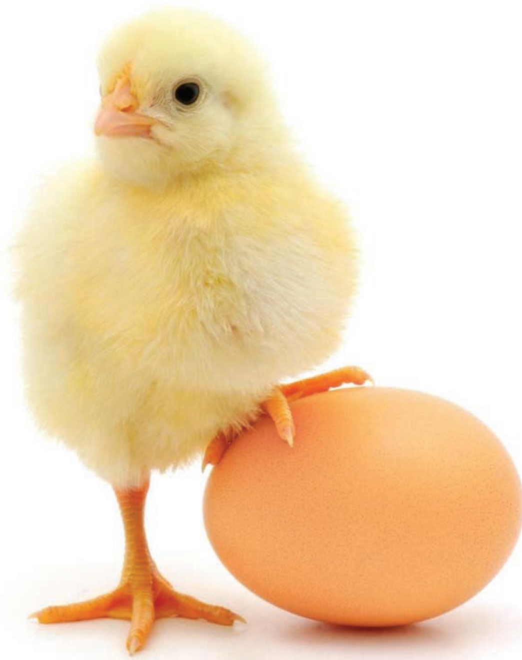
ISSN 1682-8356
ansinet.com/ijps



INTERNATIONAL JOURNAL OF POULTRY SCIENCE

Science Alert
scialert.net

ANSInet
an open access publisher
http://ansinet.com

OPEN ACCESS International Journal of Poultry Science

ISSN 1682-8356
DOI: 10.3923/ijps.2022.129.135

Research Article
Broiler Litter Ammonia: Caked, Surface and Base Moisture Effects on Emissions

[1]D.M. Miles, [1]J.P. Brooks, [1]A. Adeli and [2]P.A. Moore, Jr.

[1]Genetics and Sustainable Agriculture Research, USDA-ARS, 150 Twelve Lane, Mississippi, MS 39762, United States
[2]Poultry Production and Product Safety Research, USDA-ARS, Fayetteville, AR 72701, United States

Abstract

Background and Objective: Relating ammonia (NH_3) generation from broiler house bedding to specific management activities is fundamental to developing solutions for NH_3 control. Though it is known that increasing litter moisture accelerates NH_3 loss, management scenarios specifically for caked litter, litter surface or base moisture have not been considered. The objective of the current study was to determine the variation in NH_3 release for caked litter based on bedding age/reuse, to compare sample sizes and surface area of caked litter, as well as evaluate surface and base moisture additions to the litter column. **Materials and Methods:** A series of laboratory tests were conducted evaluating the caked litter and litter column moisture separately. Daily and cumulative NH_3 volatilization was assessed using a chamber acid trap system. Statistical assessments were performed using a mixed linear model to accommodate both the fixed- and random-effects parameters. **Results:** Caked litter from 0.5 year bedding reuse emitted the most NH_3 (new cake), followed by cake formed after more than 3 years of bedding reuse (old cake samples-intact or fragments). Smaller cake samples emitted less than large cake samples. For the litter column, surface misting of litter twice daily emitted the most NH_3, followed by surface misting once daily and then the high rate of base moisture addition. Finally, the low rate of base moisture to the litter column and the control with no moisture added were similar. **Conclusion:** Minimizing cake formation within broiler houses will reduce NH_3 emissions once the cake is stored. Management scenarios that prevent litter surface or base wetting, such as proper cooling pad operation and outside drainage away from houses, will reduce NH_3 released from litter within broiler facilities. Moisture control in broiler litter and cake can be accomplished with attentive flock management and can reduce NH_3 emissions.

Key words: Ammonia, broiler, cake, litter, moisture

Citation: Miles, D.M., J.P. Brooks, A. Adeli and P.A. Moore, Jr., 2022. Broiler litter ammonia: Caked, surface and base moisture effects on emissions. Int. J. Poult. Sci., 21: 129-135.

Corresponding Author: D.M. Miles, Genetics and Sustainable Agriculture Research, USDA-ARS, 150 Twelve Lane, Mississippi, MS 39762, United States Tel: 662-320-2024

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Daily, efficient operation is essential to broiler production profits which are influenced by as little as a single ten-thousandths of a dollar in the U.S. Aside from sustaining profit margins, neither small family farms nor large capacity facilities are immune to mounting environmental concerns regarding soil, water and air quality protection. Air quality can be improved by minimizing ammonia (NH_3) emissions from broiler operations. For soil and water, environmental concerns resulting from NH_3 deposition include soil acidification, reduced ecosystem diversity and eutrophication of surface waters[1,2].

Ammonia is emitted during the natural breakdown of fecal material and litter bedding (which includes compacted or caked litter). Ammonia concentrations within houses vary due to many interrelated house management factors, in addition to litter moisture, temperature and pH[3,4]. Examples of reported NH_3 concentrations in commercial broiler houses range from: 2-75 ppm[5], 85-129 ppm[6], 2-80 ppm[7], 12-24 ppm[8], 0.2-45 ppm[9] and 11-100 ppm[10]. Inside the house, NH_3 is a health concern for birds and caretakers. For birds, respiratory and ocular problems have long been reported in the literature[11-13]. In addition, depressed body weight attributed to NH_3 reduces production efficiency[11,14-16].

Litter properties and gas flux vary with time during the flock as well as spatially in broiler houses[17,18], suggesting prospects exist to develop new best management practices to reduce NH_3 emissions. Elliot and Collins[3] reported the primary factors influencing NH_3 volatilization as litter pH, temperature and moisture, in order of declining significance. Others have observed increases in NH_3 generation as pH, temperature, moisture, wind speed and litter ammonium concentration rise[4,19]. Chemical litter treatments usually decrease litter pH and reduce house NH_3 for a limited time during the beginning of the flock but are later overwhelmed as birds grow and excrete more waste. Litter temperature is at least partially a consequence of house temperature which is controlled for bird comfort. Birds appear to insulate the litter, especially later in the flock, to maintain its temperature above house air temperature[18]. Greater temperatures encourage bacterial activity (conversion of waste N compounds to NH_3) and increase the rate of NH_3 transfer into the air[20]. Reducing NH_3 generation by providing cooler litter temperatures seems unlikely but managing litter moisture may be a target for realizing lower NH_3 generation. Researchers have deduced that microbial activity degrading uric acid in litter is greater at higher litter moisture[21]. It is known that water is required in four of the five reactions for the pathway of degrading uric acid aerobically[22,23]. Also, the upper moisture level at which NH_3 emissions decrease has been reported to range from 37-51% and is temperature dependent[24].

Areas where birds cluster tend to have a greater accumulation of excreta. Greater moisture levels and concentration of the manure in these locations form a compacted layer over the litter, known as "cake"[25]. The cake is compressed by the birds walking over it. Depending on house conditions, cake may have a relatively dry or wet surface; it may barely compress when walked on or have a spongy texture. Heavy bird traffic and fecal deposition are observed predominantly near feeder/water lines in commercial broiler houses. Another area prone to develop cake is near the exhaust fans of tunnel ventilated houses where light infiltration through the fans likely increases bird concentration. Presence of cake may be unavoidable and undesirable from a bird health perspective (sustaining diseases and creating a slippery surface).

In commercial houses the ratio of cake to friable litter and consequent effects on NH_3 flux from litter has not been quantified[18]. Research has shown that NH_3 volatilization from caked surfaces is less than friable litter while the cake remains undisturbed as part of the house bedding[10,18]. A common U. S. commercial broiler management practice between flocks is to decake, removing the compacted litter from the bedding surface using specialized screening equipment pulled by a tractor[26]. As the cake is conveyed up the screen and deposited into a hopper, it breaks into pieces of variable size, exposing moisture laden surfaces. The practice of only decaking between flocks (rather than performing a total house clean out) reduces the quantity of waste material to be used as fertilizer or to be stored until needed. Sistani *et al.*[26] characterized the rate of cake vs. litter production for one year on three commercial farms, finding approximately 57% of litter remains in houses after decaking between flocks. Average litter moisture for the study was 26-30%, with cake having 44-48% moisture.

Once cake is removed from broiler houses, it is usually stored under a roofed structure (pole barn), designated as a "litter shed" or dry-stack barn[25]. The litter shed protects the material within it from weather exposure so that nutrients are not lost during rain or by runoff. Outside the broiler industry, there is little designation in property differences between litter and cake as well as no distinction in terminology. Once the cake is in the "litter shed" and is transferred from the grower to others for crop or pasture fertilization, it is termed litter. In the case of a total house clean out, the cake is not separated from the litter before storage. An alternative management practice to decaking is chopping the cake and tilling it into the litter base so that it remains within houses. With either decaking or chopping/tilling, the exposure of moisture rich surfaces is likely to increase NH_3 release. Thus, the release of NH_3 occurs within the broiler house and during storage.

Preliminary studies revealed broiler cake emitted 2.5 times more NH_3 than litter which lead to these distinct research approaches for broiler cake and litter. The objective of this investigation was twofold. First, characterize broiler cake NH_3 emissions relative to age (i.e., the litter base having grown a few flocks or many consecutive flocks), mass and the condition of the sample (whether the cake was one piece or was broken into smaller pieces). Second, explore transient moisture effects on friable litter NH_3 volatilization by assessing the effects of surface and base moisture addition to the broiler litter column. The aim was achieved through a series of laboratory tests on broiler cake and litter that controlled the physical aspects of the samples while capturing all emitted NH_3. Results from the study should be used to produce additional guidelines for management of broiler cake and litter that result in lower NH_3 emissions.

MATERIALS AND METHODS

Ammonia measurement system: For both the broiler cake and the litter experiments, a chamber acid trap (CAT) system was used to quantify NH_3 loss from the respective samples. It was detailed in Miles *et al.*[27] Briefly, the system uses 1-L containers to house litter or cake samples. Periodic titration quantifies NH_3 lost in units of mg of N. Overall, continuous air flow was provided to each chamber at a rate of approximately 115 mL min^{-1}. Exhaust air and NH_3 were trapped in a series of flasks containing H_3BO_3 solution. The trap solution was titrated with 0.1 M HCl. For the cake experiments, titration occurred every 24 h for the first 4 days, then approximately every 3rd day. The duration of each trial was 10 days to simulate a time period with no additional fecal or moisture input, which could correspond to lay-out time between flocks as well as cake storage in the dry-stack barn. With the litter experiments (addition of water to the litter surface or base), each trial lasted 3 days and titration occurred each 24 hrs.

- **Phase 1: Characterization of broiler cake emissions**

Cake collection and sample preparation: Broiler cake was collected from two commercial broiler houses in Mississippi. The solid sidewall houses measure 12.8 m×152.4 m (42×500 ft). Four houses were built in 2003, four houses were built in 2005. Houses feature insulated drop ceilings with 54 box inlets near ceiling (27 along each sidewall with each inlet measuring 0.5×5 ft, spaced approximately 20 ft apart). Down the entire length of the center of each house, 22 infrared brooders (26,000 BTU h^{-1} rating) are spaced equally; there are no space heaters. In each house, about 28,000 birds are placed each flock (same for summer and winter). The brood period varies between placement and day 5-12, which depends on exterior climatic conditions (e.g. colder outside means heat needed longer for small birds). Brood area is front half (cooling pad end) of house. Automatic feeders and waterers run the length of the houses, two feeder lines are located near either sidewall and have a waterer line on both sides of each feeder line. The type of bird (e.g. Cobb-Cobb straight run) is not usually reported to farmer. Typical flock length is 42-45 days, operated in all-in/all-out model.

The houses belong to a single grower on one farm but the houses were located approximately 0.4 km (0.25 mi) apart. Cake was collected from the older house during the 20th and 21st consecutive flocks grown on the litter and the 2nd and 3rd flocks from the newer house. All samples were gathered when birds were about 6 weeks old. Within the houses, cake was collected 0.2 m (8 in) from the waterers, towards the center of each house and lengthwise approximately 38 m (125 ft) from the exhaust fans. The collection area was about 0.36 m by 1 m long (14 in by 40 in). The cake thickness ranged from 3.8-5 cm (1.5-2 in). Samples were transported to the laboratory in sealed tubs.

At the laboratory, cake samples were prepared by breaking larger chunks and randomly eliminating fragments at the edges to reach 25 g and 50 g for the individual samples. Gloved hands carefully broke 50 g samples into four pieces to produce the fragmented condition. After reaching the desired size and condition (fragmented or intact), each sample was placed in a 1-L container in the NH_3 measurement system described above. Moisture content (oven dried for 48 h at 65°C) and pH (5:1 mixture of deionized water: cake) were determined for the bulk cake samples, (Table 1).

Experimental design and statistical methods: Ammonia evolution based on cake age, sample size and condition was analyzed using procedures of Statistical Analysis Systems

Table 1: Characteristics of broiler cake

	NEW*		OLD	
	Flock 2	Flock 3	Flock 20	Flock 21
Moisture content	42.6	26.2	33.3	32.5
pH	8.97	8.38	8.96	8.61

*Initial characterization of pine shavings placed on the NEW farm before flock 1: Moisture content = 64.1%, pH = 6.83

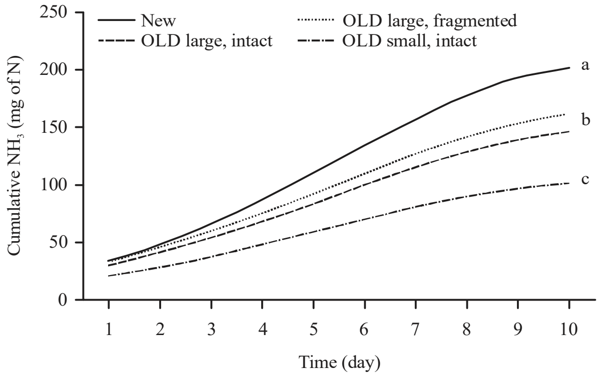


Fig. 1: Expected cumulative NH_3 generation from caked broiler litter

NEW cake samples were obtained during flocks 2 and 3, OLD cake samples were obtained during flocks 20 and 21. Day 10 data differ at $\alpha = 0.05$ when indicated by different letters (a-c)

(SAS)[28]. The experimental design was a randomized complete block where two sequential trials compared old and new cake samples with the following sizes and conditions: 25 g (small, intact), 50 g (large, intact) and 50 g (large, fragmented). During each trial, there were four replications of each of the three treatments. The quantitative results given in Fig. 1 are subsequently discussed qualitatively as new cake vs. old cake and small, intact vs. large, fragmented vs. large, intact samples. The data distribution was found to be positively skewed using Proc Univariate. Log transformation reduced the skewness to an acceptable level near zero and was used in subsequent analyses. Final results were converted back to the original units (mg of N) for discussion. Proc Mixed was used to perform a repeated measures analysis of variance. Because of the wide range in moisture contents for the new cake, moisture was included as a covariant. Interactions among age, treatment and day of experimentation made it appropriate to either look at overall treatment effects or effect of age. The choice was made to present results based first on effect of cake age. Regression responses for each cake age and cumulative NH_3 volatilization were generated using Proc Mixed; each equation included an intercept, a linear "day" term and a quadratic "day" term. The responses are depicted in Fig. 1.

- **Phase 2: Litter emissions from surface or base moisture addition**

Litter collection and sample preparation: Broiler litter from a commercial farm in Mississippi was collected during the 10th flock of birds grown on the litter (originally pine shavings bedding). The commercial house characteristics are described above. Two experiments were performed where the collection for experiment 1 was at the beginning of the flock and the litter sampling for experiment 2 was on day 22 (mid-flock). The bulk litter samples were obtained from a 61 cm×91 cm (24 in by 36 in) area in the center/non-brood end of the house at a collection depth of 7.6 cm (3 in). No chemical litter treatment had been applied prior to the flock. After transport to the laboratory, the bulk samples were homogenized before experimentation and assessed for moisture and pH. Litter moisture was determined by loss in weight (65°C for 48 hrs) and pH by using a distilled deionized (DDI) water:litter sample ratio of 5:1.

Daily and cumulative NH_3 volatilization from litter was assessed using the chamber acid trap system[27] that was briefly described above. To accommodate moisture addition to the litter surface and to the base of the litter column while providing a uniform surface area of volatilization, column sets of inner and outer surface area adapters (SAA) were constructed. These consisted of close-fitting PVC cylinders where the outer SAA (7 cm tall×5.1 cm inside diameter) had a solid bottom to enable it to hold water. The inner SAA (4.3 cm inside diameter) had a mesh bottom to allow water infiltration and provided a common litter surface area of 14.4 cm^2. Approximately 43 g of litter was weighed into each inner SAA. For the base water treatments, 20 or 40 mL of DDI water was placed in the outer SAA. Inner SAA were lowered into the outer SAA to form the litter column sets that were placed in the 1-L chambers of the acid trap system. Each chamber received humidified air at approximately 115 mL min^{-1} which exhausted into a progression of two flasks (acid traps) each containing 30 mL of boric acid (H_3BO_3) indicator solution. At 24 hrs intervals for 3 days, the pair of acid trap contents were combined and titrated with hydrochloric acid (HCl) to determine mg N generated by the individual litter samples for each treatment replication. The daily mean N losses for each treatment and day were recorded. To arrive at cumulative N emitted, the mg N lost for each day was added to the previous day's result (Fig. 2).

Experimental design and statistical methods: Two experiments included these treatments: (1) Litter with no moisture addition (control), (2) surface misting 1 time daily (SM1), (3) Surface misting 2 times daily (SM2) and (4) Low rate base moisture addition of 20 mL DDI water (B20) and (5) High rate base moisture addition of 40 mL DDI water (B40). Misting was performed at the beginning of each experiment (day 0) and again just after titrating all samples on subsequent days. Specifically, for SM2, the second application followed the first misting by 5 hrs. The average mist was 2.358 g DDI water/spray.

Analysis of variance was performed for a randomized complete block design where the treatments were assigned

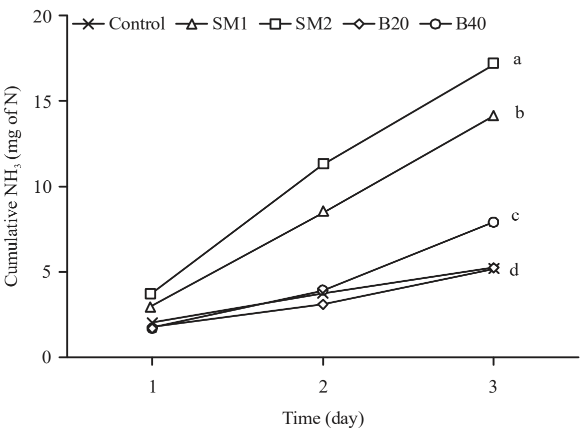


Fig. 2: Cumulative NH_3 emissions from broiler litter column
Moisture treatments: Control-no water addition; SM1-surface misting once per day, SM2-surface misting twice per day; B20-base absorption 20mL water; and B40-base absorption 40 mL water. Day 3 data differ at $\alpha = 0.05$ when indicated by different letters (a-d)

to chambers completely at random within each trial. In both experiments, there were three replications of each treatment. The Proc Mixed procedure of SAS[28] was used to evaluate day 3 mean cumulative (Fig. 2) and mean daily N emitted. Data points having different letters in Fig. 2 are significantly different at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Characterization of broiler cake emissions: Figure 1 depicts the expected cumulative NH_3 generated by new and old cake samples. Treatment effects of size and fragmented vs. intact were not significant for the new cake ($p = 0.41$), which is the solid line in Fig. 1. However, the new cake from only 2 and 3 grow outs produced more NH_3 ($p = 0.01$) than the old cake in any condition or size that had been harvested from flocks 20 and 21. This difference may be partly explained by the higher moisture content of the new cake in flock 2. Research has shown that increasing litter moisture increases NH_3 generation[3,4]. As noted in Table 1, the initial moisture of the shavings placed in the newer houses was quite high (64.1 %) which likely contributed to the high moisture content of the cake collected during flock 2 (42.6%). However, the new cake was much drier during the 3rd flock (26.2%). Simple additive moisture effects among the samples were taken into account in the statistical analyses by use of covariate but it is not effective if moisture effects are simply not additive. The cake moisture was nearly constant for the old samples (33.3 and 32.5%, in flocks 20 and 21). Beyond moisture content, increased litter pH also increases NH_3 released from litter[3,4] but the new vs. old pH values do not explain why the new cake would produce more NH_3 (Table 1).

Unlike the new cake, treatment differences were evident within the old cake samples (Fig. 1). The small sample of old cake, not surprisingly, produced the least NH_3 when compared to either of the large old cake samples. However, at only half the mass of the larger sample, the NH_3 generated by the small, intact sample was 70% of that of the large, intact sample after the 10 day experiment. Although the fragmented sample generated slightly more NH_3 numerically than the intact condition, the difference was not statistically significant ($p = 0.28$). Inconsistencies in the emitting surface area are likely responsible for the lack of significant difference. Research has shown that stockpiles of cake with lower surface area per unit volume have lower NH_3 emissions[29]. However, the cake surface area was not measured in the current study. A similar preliminary study (data not shown) investigated NH_3 volatilization relative to cake source (different farms), sample size and condition; it reported no difference in cake source between farms but significant differences for sample size and condition. The previous research used the same methods as the current study except that: (1) The samples were collected from different farms for flock ages 8 vs. 18, (2) The cake was collected from the center of the houses, not proximal to the waterer and (3) The test duration in the CAT system was 3 days. The cake moisture and pH characteristics in the previous study were very similar between the two farms which may partially explain why the sources did not appear different. The moisture content and pH of the cake were, respectively, 40.9% and 8.97 during flock 8 and 40.7% and 9.04 during flock 18. In the current study, the NH_3 emissions cannot be interpreted by simplistic comparison of cake moisture content and pH nor simply as a function of litter age from fewer or more flocks.

Currently, growers should know their litter nutrient content and litter production rate to develop nutrient management plans[30]. Potential new markets for litter/cake utilization will need to be aware of these characteristics and whether the material originates from decaking between flocks or a total house cleanout. The cost of replacing bedding material is commonly left to the individual grower, which discourages a total house clean out. The practice of decaking between flocks likely means that the material in the litter shed has different characteristics than that of friable litter within the houses. For the historically favored utilization as fertilizer, nutrient densities are critical. Reports differ as to whether cake has more[26,31] or less[32] nitrogen than litter. Cake location within the house may be an important factor. It has been noted that cake samples at feeder/waters have more total nitrogen than cake near the fan area[18]. Elevated nitrogen content of cake at these locations has also been reported to change based on season (summer vs. winter)[10]. Further studies will not likely benefit from including a larger comparison (e.g. more sampling) of cake and litter to be used by new markets. Rather, new markets must be developed that are able to adapt to the inherent variability of the product.

Litter emissions from surface or base moisture addition: In the first laboratory trial where litter was collected at the beginning of flock 10, the original bulk sample pH averaged 8.1 and the moisture was 14.2%. For the second experiment with litter collected at mid-flock, the litter pH was 7.8 and the moisture was 17.8%. Because the second samples were collected later in the growout, the increase in moisture and decrease in pH is reasonable as the mid-growout samples would contain more recently deposited excreta. An analogous trend has been previously observed in an intensive spatial sampling study of a broiler house[17].

The daily emission results indicated the magnitude of N emitted remained below 8 mg N for all treatments. Given the relatively low moisture for the bulk litter samples, a low emission level is expected. In other studies, escalated NH_3 concentration has been associated with litter moisture in beyond 30%[4]. By day 3, the misting treatments (SM1 and SM2) did not appear significantly different from one another and remained greater than all other treatments. The base moisture and control treatments were distinct from one another, ranking from greater to least as B40, B20 and control.

Assessing cumulative N emitted (Fig. 2) shows misting twice daily (SM2) produced the maximum NH_3 emissions = 17.1 mg N emitted. Once daily misting (SM1) followed with a mean of 14.1 mg N emitted. The next lower emissions were produced by the high rate base moisture treatment (B40) and the least cumulative emissions resulted from the control and low level of base moisture (B20). In previous work using the same acid trap system, cumulative emissions at day 3 for 50 g litter samples were just above 20 mg N[27]. Those samples would be comparable to the control samples in that they had not been exposed to moisture addition. The greater magnitude of emission may be explained in that they occupied the entire base of the 1000 ml chamber (93.8 cm^2, more than six times that of the inner SAA) and had greater initial moisture and pH, 23.1% and 8.67, respectively.

With increasing air quality regulations for animal production, the number of emissions research projects is rapidly increasing. Basic farm management practices have not been evaluated for potential effects on NH_3 emissions. Controlling litter moisture has historically been a management technique related to bird well-being but litter moisture also effects NH_3 volatilization. This work utilized a laboratory technique to characterize NH_3 generation from litter when subjected to surface and subsurface moisture addition, two conditions that could result from substandard house management. The laboratory method showed that adding surface moisture increased the emission rate by approximately 3 times the control (unamended) litter rate. Comparing the base water addition to the litter column in the cumulative NH_3 loss, only the higher rate of addition was significantly different than the control emission rate.

CONCLUSION

Greater cake mass produced more NH_3 emissions. Further, cake formed on litter reused for more than 3 year produced less NH_3 than cake formed over litter used for approximately 0.5 year. Whereas other research has shown litter reuse increases NH_3 within houses, litter reuse in older flocks did not increase NH_3 produced from cake. Emissions appear largely dependent on current moisture content. However, factors investigated in this study do not fully explain the variation in NH_3 volatilization that can be expected from broiler cake whether inside houses or during storage. Samples that mimic the industry practice of tilling the cake and litter bedding after each flock would likely show how cake breakup inside the house affects NH_3 emissions. Containment techniques should be investigated to minimize NH_3 generation from cake stockpiles.

Regarding the litter, the results demonstrate the impact of daily house management activities related to broiler litter, specifically that water addition to the litter on the surface or from below can increase NH_3 volatilization. Management scenarios that prevent these routes of entry, such as proper cooling pad operation and outside drainage away from houses, will reduce NH_3 released from litter within broiler facilities.

SIGNIFICANCE STATEMENT

This study discovered that moisture control in broiler cake and litter has many applications that can be beneficial for grower house management to reduce NH_3 emissions. The study will help the researcher to uncover the critical areas of cake physical properties, litter surface moisture and litter base moisture that many researchers were not able to explore. Thus, a new theory on managing broiler house litter and cake moisture may be arrived at.

REFERENCES

1. NRC., 2003. Air Emissions from Animal Feeding Operations Current Knowledge Future Needs. National Academy Press, Washington, DC., USA Page: 21.
2. Roadman, M.J., J.R. Scudlark, J.J. Meisinger and W.J. Ullman, 2003. Validation of Ogawa passive samplers for the determination of gaseous ammonia concentrations in agricultural settings. Atmos. Environ., 37: 2317-2325.

3. Elliott, H.A. and N.E. Collins, 1982. Factors affecting ammonia release in broiler houses. Trans. ASAE, 25: 413-424.
4. Carr, L.E., F.W. Wheaton and L.W. Douglas, 1990. Empirical models to determine ammonia concentrations from broiler chicken litter. Trans. ASAE, 33: 1337-1342.
5. Pickrell, J., 1991. Hazards in confinement housing--gases and dusts in confined animal houses for swine, poultry, horses and humans. Vet. Hum. Toxicol., 33: 32-39.
6. Wheeler, E.F., K.D. Casey, J.S. Zajaczkowski, P.A. Topper and R.S. Gates *et al*., 2003. Ammonia Emissions from U.S. Poultry Houses: Part III-Broiler Houses. Proceedings of the 3rd International Conference: Air Pollution from Agricultural Operations III. October 12, 2003 159-166.
7. Moore, P.A., D. Miles, R. Burns, D. Pote, K. Berg and I.H. Choi, 2011. Ammonia emission factors from broiler litter in barns, in storage and after land application. J. Environ. Qual., 40: 1395-1404.
8. Wathes, C.M., H.R. Holden, R.P. Sneath, R.P. White and V.R. Philips, 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer house. Br. Poult. Sci., 38: 14-28.
9. Redwine, J.S., R.E. Lacey, S. Mukhtar and J.B. Carey, 2002. Concentration and emissions of ammonia and particulate matter in tunnel ventilated broiler houses under summer conditions in Texas. Trans. ASAE, 45: 1101-1109.
10. Miles, D.M., J.P. Brooks and K. Sistani, 2011. Spatial contrasts of seasonal and intraflock broiler litter trace gas emissions, physical and chemical properties. J. Environ. Quality, 40: 176-187.
11. Charles, D.R. and C. Payne, 1966. The influence of graded levels of atmospheric ammonia on chickens. I. Effects on respiration and on the performance of broilers and replacement growing stock. Br. Poult. Sci., 7: 177-187.
12. Miles, D.M., W.W. Miller, S.L. Branton, W.R. Maslin and B.D. Lott, 2006. Ocular responses to ammonia in broiler chickens. Avian Dis., 50: 45-49.
13. Valentine, H., 1964. A study of the effect of different ventilation rates on the ammonia concentrations in the atmosphere of broiler houses. Br. Poult. Sci., 5: 149-159.
14. Anderson, D.P., C.W. Beard and R.P. Hanson, 1964. The adverse effects of ammonia on chickens including resistance to infection with Newcastle disease virus. Avian Dis., 8: 369-379.
15. 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.
16. Reece, F.N., B.D. Lott and J.W. Deaton, 1981. Low concentrations of ammonia during brooding decrease broiler weight. Poult. Sci., 60: 937-940.
17. Miles, D.M., P.R. Owens and D.E. Rowe, 2006. Spatial variability of litter gaseous flux within a commercial broiler house: Ammonia, nitrous oxide, carbon dioxide and methane. Poult. Sci., 85: 167-172.
18. Miles, D.M., D.E. Rowe and P.R. Owens, 2008. Winter broiler litter gases and nitrogen compounds: Temporal and spatial trends. Atmospheric Environ., 42: 3351-3363.
19. Reddy, K.R., R. Kaleel, M.R. Overcash and P.W. Westerman, 1979. A nonpoint source model for land areas receiving animal wastes: ammonia volatilization. Trans. ASAE, 22: 1398-1405.
20. Alhomidan, A., J.F. Robertson and A.M. Petchey, 2003. Review of the effect of ammonia and dust concentrations on broiler performance. Worlds Poul. Sci. J., 59: 340-349.
21. Carey, J.B., R.E. Lacey and S. Mukhtar, 2004. A review of literature concerning odors, ammonia and dust from broiler production facilities: 2. flock and house management factors. J. Appl. Poult. Res., 13: 509-513.
22. Carlile, F.S., 1984. Ammonia in poultry houses: A literature review. World's Poult. Sci. J., 40: 99-113.
23. Nahm, K.H., 2003. Evaluation of the nitrogen content in poultry manure. World Poult. Sci. J., 59: 77-88.
24. Miles, D.M., D.E. Rowe and T.C. Cathcart, 2011. High litter moisture content suppresses litter ammonia volatilization. Poult. Sci., 90: 1397-1405.
25. Moore, P.A., T.C. Daniel, A.N. Sharpley and C.W. Wood, 1998. Poultry Manure Management. In: Agricultural Uses of Municipal, Animal and Industrial Byproducts. Wright, R.J., W.D. Kemper, P.D. Millner, J.F. Power and R.F. Korcak, United States Department of Agriculture, United States pp: 66-77.
26. Sistani, K.R., G.E. Brink, S.L. McGowen, D.E. Rowe and J.L. Oldham, 2003. Characterization of broiler cake and broiler litter, the by-products of two management practices. Bioresour. Technol., 90: 27-32.
27. Miles, D.M., P.R. Owens, P.A. Moore and D.E. Rowe, 2008. Instrumentation for evaluating differences in ammonia volatilization from broiler litter and cake. J. Applied Poult. Res., 17: 340-347.
28. SAS., 2003. SAS System for Microsoft Windows, Version 9.1 (TSM1). SAS Institute Inc., Cary, NC., USA.
29. Yao, H., 2009. Ammonia Emission from Stored Broiler Cake. Master Thesis, North Carolina State University.
30. Coufal, C.D., C. Chavez, P.R. Niemeyer and J.B. Carey, 2006. Nitrogen emissions from broilers measured by mass balance over eighteen consecutive flocks. Poult. Sci., 85: 384-391.
31. Liang, Wei-Zhen, 2011. Mechanisms Controlling Ammonia/um Dynamics in Broiler Litter. Master Thesis, North Carolina State University.
32. Lory, J.A. and C. Fulhage, 1999. Sampling poultry litter for nutrient testing. https://extension.missouri.edu/g9340.

Mention of trade names or commercial products In this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.