INTRODUCTION

Broiler chicken production in the United States in 2011 totaled more than 8.6 billion chickens. Approximately 58% of broilers were produced in Georgia, Arkansas, Alabama, North Carolina, and Mississippi (National Agricultural Statistics Service, 2012). Optimal delivery of water and feed to broiler chickens and a myriad of other factors interrelate and contribute to grower and industry profitability. One such factor is the litter covering broiler house floors; its quality and management are prime contributors to bird well-being. Because growers are challenged by natural processes that generate ammonia (NH$_3$) from accumulated fecal matter as litter ages, a better understanding of NH$_3$ volatilization relative to specific locations (i.e., around feeders and waterers) within houses can provide useful insights for more effective management.

Complications from NH$_3$ exposure in animal rearing facilities have long been recognized. These include respiratory disease (exposure 200 ppm, Anderson et al., 1964), eye damage (exposure 50 and 75 ppm, Miles et al., 2006a), inefficient feed conversion (exposure 100 ppm, Charles and Payne, 1966), and decreased BW (exposure 50 and 75 ppm, Miles et al., 2004; exposure 50 ppm, Reece et al., 1981). More recently, environmental issues relative to gaseous emissions from houses are becoming a concern for the animal production industry (Moore et al., 2011) due to the possibilities of compromising terrestrial bio-diversity, inducing aquatic nutrient enrichment, and diminishing air quality (Asman et al., 1998; Council for Agricultural Science and Technology, 2002; Mukhtar et al., 2003). One method of reducing NH$_3$ concentrations in houses is using chemical litter treatments, which generally act by lowering litter pH. Compared with no litter treatment, reductions of 36 to 90% can be achieved using chemical treatments (Shah et al., 2006). However, chemical effectiveness varies with type and application rate and, generally, may become ineffective after a few days to a few weeks. Animal nutrition research is being conducted to re-
duce excess N excretion and thereby reduce NH$_3$ emissions (Council for Agricultural Science and Technology, 2002) as another mitigation strategy. In addition, NH$_3$ scrubbers are emerging in the United States to treat exhaust air from broiler houses (Lahav et al., 2008). Use of scrubbers would satisfy environmental concerns, but would not address the house interior atmosphere. As with most new technologies, widespread implementation will not be immediate, and most of the industry will need to hone existing technology and house management for the best NH$_3$ control.

Factors pertinent to litter and NH$_3$ generation include physical and chemical litter properties (temperature, moisture, pH, and N content), type of original bedding material, between flock management such as windrowing and decaking, effects and frequency of top dressing, and spatial characteristics of gas evolution within houses. Elliott and Collins (1982) indicated an increase in NH$_3$ with temperature, moisture, and pH. Coufal et al. (2006b) cited moisture and pH as more readily manipulated in houses than temperature, which is controlled for bird comfort. Separately, for reducing N volatilization when reusing litter (rice hull base and top dressing), Coufal et al. (2006a) recommended that top dressing not be used. A comparative laboratory study of organic vs. inorganic bedding materials reported that wood shavings and rice hulls produced less NH$_3$ than sand and vermiculite and increases in litter moisture increased NH$_3$ produced for all materials (Miles et al., 2011b). Spatial characterization of litter relative to NH$_3$ volatilization has shown higher litter moisture content near waterers (Tasistro et al., 2004), increased NH$_3$ volatilization just outside water lines (Brewer and Costello, 1999), and that litter between feeders and waterers can be consistently differentiated from surrounding samples from mid to late growout, but the magnitude of moisture is not reliably higher or lower between winter and summer (Miles et al., 2011a). The present study is more similar to Tasistro et al. (2004) in that NH$_3$ measurements were conducted on litter samples removed from the houses rather than performed in houses on undisturbed litter such as Brewer and Costello (1999) and Miles et al. (2011a). The current research is explicitly differentiated from Tasistro et al. (2004) by having tunnel ventilation from 11 (1.3 m) fans vs. cross-flow ventilation from 4 (91 cm) fans; being conducted in 3 larger commercial houses with footprint 15.2 × 152 m vs. a single house with dimensions of 10.5 × 120 m; reusing rice hulls over 6 flocks; conducting measurements at mid-flock over different seasons vs. at the end of a winter flock; and using 100-g litter samples in an acid trap system vs. 0.5-g litter samples suspended in 50-mL water with an ion selective probe.

The objective of the current research was to determine the temporal changes in NH$_3$ generation from rice hull litter located specifically in proximity to broiler house sidewalls, feeders, and waterers at mid-growout during 6 flocks on reused litter. The research began in pristine houses where birds had never been placed, providing an opportunity to test background soils and fresh bedding materials for NH$_3$ generation. No other works were found in the literature that have studied the influence of these house attributes for modern tunnel-ventilated houses through this extended period of litter reuse. The goal was to provide integrators with a decision-making tool for managing reused litter within houses relative to NH$_3$ emissions.

**MATERIALS AND METHODS**

**Experimental Design**

To compare NH$_3$ generation of rice hull litter relative to location and half house brooding effects, a factorial arrangement of treatments was tested in 3 houses. Six trials (flocks 2, 3, 4, 5, 7, and 9) evaluated litter sampled at 3 locations (sidewalls, feeders, and waterers) in the brood half and nonbrood half in each of the broiler houses, yielding a balanced factorial design of 6 treatments. For each treatment, 2 duplicate samples were tested for NH$_3$ volatilization during each trial. The average of the duplicate samples was statistically analyzed.

**Litter Sampling and Analyses**

Access to a new commercial farm in Mississippi afforded a unique opportunity to investigate the progression of NH$_3$ volatilization at selected locations within new houses where birds had never been grown. Construction on the 6-house broiler farm was completed in 2009. Each 15.2 × 152.4 m (50 × 500 ft), solid-side wall house had the following components: 3 automated feeder lines with nipple waterer lines on both sides of the feeders, an insulated drop ceiling, box inlets near the ceiling, brood heaters down the center of the entire house, evaporative cooling pads on each side at the front of the house (brood half, west end), two 0.91-m (36 in) fans in the east end for minimum ventilation, eleven 1.3-m (52 in) fans on the east end (nonbrood half), capacity for up to 30,000 chicks at placement, rice hull bedding, and migration fencing (division of the house into quarters, lengthwise). The houses were operated in all-in/all-out mode, and each growout was approximately 53 d. For each house and after each flock, decaking followed by top dressing with rice hulls was performed during a 2- to 3-wk layout. At the beginning of each flock, chicks were placed in the west end or brood half of the house for variable time periods determined by the grower’s preference.

Litter samples were collected at the northern sidewall, waterer line, and feeder line in 3 of the 6 broiler houses (Figure 1). Five samples for each treatment were obtained at equally spaced intervals along a 45.7-m (150 ft) lengthwise section of both the brood and nonbrood halves of each house. At each interval, samples were picked up by a gloved hand from approxi-
mately the upper 5 cm (2 in) from a 930 cm² (1 ft²)
area. Gloves were changed between treatments. These
5 samples were combined to create the brood-sidewall,
brood-waterer, brood-feeder, nonbrood-sidewall, non-
brood-waterer, and nonbrood-feeder treatments. Each
treatment from each house was placed in a 1-gallon
(3.79 L) plastic bag. The bags were sealed, transported
to the laboratory via cooler, and then refriger-
ated at 4.4°C (40°F) for 3 d. Just before NH₃ mea-
surement, the contents within each bag were mixed by
gloved hand. Friable samples were mixed by stirring
the entire contents of the bag. Where the bags contained
small pieces of cake (1–98 cm³) as well as friable litter,
the contents were turned carefully so that the cake was
not unnecessarily broken down. Samples taken from the
bag for NH₃ characterization (described below) were
selected in portions of friable litter and pieces of cake
(if present) to visually represent the entire treatment at
the time of collection.

Samples were collected at the end of flocks 1, 2, and
3 (data not shown) and at 3 wk into the growout for
flocks 2, 3, 4, 5, 7, and 9. Those flocks corresponded
to sampling dates in June, August, and December of
2009 and February, June, and November of 2010. The
mid-flock (3 wk) time was chosen to ascertain the po-
tential of NH₃ release during this phase of the growout
as well as to avoid the greater degree of cake expected
near feeders and waterers later in the flock. Qualitative
descriptions of litter condition were made before NH₃
measurements. Litter moisture content was determined
by loss in weight after oven drying for 48 h at 65°C
and pH was measured using a deionized water to litter
ratio of 5:1 (wt:wt). Litter ammonium (NH₄⁺) was
determined by extracting 2 g of litter with 20 mL of 2
M potassium chloride (KCl), followed by shaking for 1
h (Keeney and Nelson, 1982), then filtering through a
funnel containing Whatman No. 1 paper. Extract was
analyzed by flow injection analysis (QuikChem 8000,
Lachat Instruments, Milwaukee, WI).

**NH₃ Measurement**

Litter samples (2 duplicates from each treatment bag)
were placed in 1-L chambers receiving humidified air
that was exhausted into boric acid solution (H₃BO₃).
The laboratory system was designated the chamber
acid trap (CAT) system, and was described in greater
detail in a previous publication (Miles et al., 2008a).
Briefly, compressed, humidified air passed through the
1-L containers, which housed 100-g litter samples. For
each chamber, the air containing volatilized NH₃ ex-
hausted into a series of 2 flasks each containing 30 mL
of H₂BO₃ (Miles et al., 2008a). Each 24 h for 4 d, the
series trap solutions for a treatment were combined and
titrated with hydrochloric acid (HCl) to determine the
NH₃ captured (mg of N). The system has the capacity

![Figure 1. Schematic for sidewall, waterer, and feeder sampling in commercial broiler houses (not to scale). Color version available in the online PDF.](image)
to use 48 chambers during a trial. During this study, 36 chambers were used for litter samples (3 houses × 6 locations × 2 duplicate samples) and 3 chambers served as blanks (negative controls) to ensure no contamination of incoming supply air. During the 6 trials, the average flow rate to each chamber in the system was 112 mL/min (SD of 10 mL/min). House pad (soil) samples and fresh rice hull bedding were evaluated in the CAT system before the litter trials.

**Statistical Analyses**

The data were checked for normality followed by ANOVA using procedures of SAS (SAS Institute, Inc., 2003). PROC UNIVARIATE was used to determine if the responses for NH$_3$ generation were normally distributed. No abnormalities were associated with the distributions; thus, no transformations of the responses were needed for further evaluation of the data. Least significant difference (PROC GLIMMIX) means separation procedures were used to determine significance of NH$_3$ response, as well as to determine changes in litter NH$_4^+$, moisture and pH relative to flock, half of house (brood or nonbrood), and location (sidewalls, waterers, or feeders). House was treated as a random variable. The significance level declaration was $P = 0.05$. Both daily NH$_3$ volatilization and cumulative NH$_3$ (total volatilized during the 4 d experiment in the CAT system) were analyzed. Although simplified by analyzing by location, initially, 9 significant effects were present in the daily NH$_3$ volatilization. Because of the complexity and lack of utility of the quadratic responses to predict daily NH$_3$ for the sidewalls, waterers, or feeder locations, these equations are not reported.

**RESULTS AND DISCUSSION**

Mid-flock litter characteristics of 1) cumulative NH$_3$, reported as a flux of mass N per kg of litter per h (mg of N/kg of litter$^{-1}$·h$^{-1}$); 2) litter NH$_4^+$ (mg/kg of litter); 3) moisture content (%); and 4) pH are given in Table 1. Because the farm construction was recently completed and the broiler houses were new, a unique opportunity arose to test background levels of NH$_3$ in the house pad (soil) samples and unused rice hulls. House pad samples (13.3% moisture with pH = 7.67) emitted no NH$_3$ in the CAT system. Total generation of NH$_3$ from the unused rice hulls was 0.18 mg of N/kg of rice hulls$^{-1}$·h$^{-1}$, or between 1 and 6% of the mean overall litter-generated NH$_3$. Fresh rice hulls had a moisture content of 11% and a pH = 6.46. Mid-growout litter samples during 6 flocks gave the following overall results for litter moisture content and pH, respectively, of the reused rice hull litter: sidewalls, 25.8 ± 2.9% and 8.7 ± 0.4; waterers, 45.2 ± 8.8% and 8.3 ± 0.5; and feeders, 20 ± 3% and 8.4 ± 0.4.

During the mid-flock assessment, litter moisture content was significantly affected by location ($P < 0.0001$). Moisture contents during mid-flock at the sidewalls, waterers, or feeder locations are given in Table 1, where litter at waterers had the greatest moisture content, followed by sidewalls, then feeders. Analysis of litter pH indicated significant interaction of flock × location ($P = 0.0107$) as well as significant effects of sampling location ($P = 0.0002$), half of house ($P = 0.0169$), and flock ($P = 0.0008$). Separating by location and confining the analysis to significant components resulted in linear equations to predict pH based on the number of flocks for feeder and sidewall litter pH (Table 1). However, for the waterers, only half of the house was significant ($P = 0.0105$), which indicated mean pH was 8.13 in the brood half and was significantly lower than the nonbrood half of the house (8.55). Litter NH$_4^+$ mean separation was similar to moisture content, straightforward as significantly affected by location ($P < 0.0001$). Waterer litter NH$_4^+$ was greatest followed by the feeders and sidewalls that did not appear different (Table 1).

Mean cumulative NH$_3$ released from litter at sidewalls, waterers, or feeders during mid-flock for 6 flocks on reused rice hull bedding is presented in Table 1. Two significant effects on total NH$_3$ from the litter samples included location ($P < 0.0001$) and a half house × location interaction ($P = 0.0497$). Responses were separated based on brood and nonbrood half of house. In the brood half, sidewall and feeder litter NH$_3$ appeared similar at 5.68 and 4.52 mg of N/kg of litter$^{-1}$·h$^{-1}$. At 12.3 mg of N/kg of litter$^{-1}$·h$^{-1}$, the NH$_3$ associated with the waterers in the brood half of the house was

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Sidewall</th>
<th>Waterer</th>
<th>Feeder</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative NH$_3$ [mg of N/(kg of litter·h)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brood</td>
<td>5.68$^b$</td>
<td>12.3$^a$</td>
<td>4.52$^b$</td>
<td>0.78</td>
</tr>
<tr>
<td>Nonbrood</td>
<td>7.57$^b$</td>
<td>12.2$^a$</td>
<td>2.85$^c$</td>
<td>0.65</td>
</tr>
<tr>
<td>NH$_4^+$ (mg/kg of litter)</td>
<td>2.399$^b$</td>
<td>3.119$^a$</td>
<td>2.632$^b$</td>
<td>108</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>25.8$^b$</td>
<td>45.2$^a$</td>
<td>20.0$^b$</td>
<td>1.12</td>
</tr>
<tr>
<td>Brood</td>
<td>8.13$^b$</td>
<td></td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Nonbrood</td>
<td>8.55$^a$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* a–cMeans within a parameter lacking a common letter differ significantly ($P ≤ 0.05$).
greater than the brood-sidewalls and brood-feeders, but did not appear different than the nonbrood-waterers (12.2 mg of N·kg of litter⁻¹·h⁻¹). The NH₃ volatilized from the nonbrood-sidewalls (7.57 mg of N·kg of litter⁻¹·h⁻¹) was less than the nonbrood-waterers and statistically analogous to the brood-sidewall and brood-feeder NH₃ generation. The least amount of NH₃ was generated by the nonbrood-feeder litter (2.85 mg of N·kg of litter⁻¹·h⁻¹). These results compare with rice hull litter-generated NH₃ at 14.3 mg of N·kg of litter⁻¹·h⁻¹ in a similar laboratory CAT system after 4 flocks (Moore et al., 1996).

The following discussion provides analogies between the current study results and previously reported spatial characterization of broiler litter. It should be stressed that the earlier spatial studies differed in overall objectives and in NH₃ measurement methodology. Thus, direct comparison of NH₃ emissions is not viable, but inferences based on trends are discussed.

Litter moisture content results from the present study (reused rice hulls) were comparable with litter moisture content results (after one flock on sawdust and wood shavings in a cross-flow ventilated house in Georgia) reported as feeder 17.4 ± 2% and waterer 54.6 ± 5% in the first published intensive spatial broiler litter study (Tasistro et al., 2004). They measured litter NH₃-N using an ion selective electrode in a deionized water solution, finding brood NH₃ at feeders = 540 ± 150 mg of NH₃-N/kg of dry litter and at waterers = 690 ± 340 mg of NH₃-N/kg of dry litter. The other half of the house in the Tasistro et al. (2004) study had no brooders with feeder = 440 ± 40 mg of NH₃-N/kg dry litter and waterer = 450 ± 230 mg of NH₃-N/kg of dry litter. Litter pH measurements were brood-feeder 7.86 ± 0.47 and brood-waterer 7.9 ± 0.82 with nonbrood feeder as 7.69 ± 0.29 and nonbrood-waterer 7.49 ± 0.65 (Tasistro et al., 2004). One would expect differences between the studies due to type of bedding. However, the absorbance of new wood shavings was measured at 1.88 g of H₂O/g of material vs. 1.82 g of H₂O/g material for unused rice hulls and the 2 were not statistically different for NH₃ generation in laboratory measurements on bedding/excreta mixtures (Miles et al., 2011b). Moreover, seasonal and house structure/management effects are likely the primary causes of differences between the studies. Type of waterer was not specified in the Tasistro et al. (2004) study.

Interpreting the Tasistro et al. (2004) results relative to the current study, we found a higher pH in the reused rice hulls vs. one growout on wood shavings, an expected result because litter pH tends to increase over time (Nahm, 2003). Tasistro et al. (2004) did not consistently show greater litter NH₃ at waterers at the end of the flock, whereas the current study shows significantly higher NH₃ at waterers during the mid-growout measurements. In addition, the cross-flow house had comparable feeder and higher waterer litter moisture contents with the current study. At the 45% litter moisture contents in the current study, the increase in NH₃ at waterers is expected. Recent work reported maximum litter NH₃ volatilization between 42 and 46% litter moisture content for reused wood shavings litter (Miles et al., 2011c). Tasistro et al. (2004) stated that the litter moisture near waterers in that study (approximately 55%) was at the threshold of becoming anaerobic, which would cause NH₃ evolution to decrease.

More recent spatial studies provide mid-growout NH₃ flux with litter moisture content and pH throughout tunnel-ventilated broiler houses for wood shavings litter and from these respective flocks: 29 (summer), 13 (winter), 15 (winter), and 17 (summer) in commercial broiler houses in Mississippi (Miles et al., 2006b, 2008b, 2011a). In the first study (Miles et al., 2006b), brood vs. nonbrood half NH₃ flux indicated lower brood NH₃ flux (136 vs. 310 mg·m⁻²·h⁻¹) with somewhat lower pH (7.6 vs. 7.9) and litter moisture content (23.4 vs. 25.5%) during the 29th flock on reused litter. The second study, Miles et al. (2008b), which compared 2 commercial houses, reported litter moisture contents at 27 and 27.6%, pH at 8.24 and 8.51, and NH₃ flux at 412 and 294 mg·m⁻²·h⁻¹, respectively, during the 13th flock on reused litter. The most recent study (Miles et al., 2011a) reported similar values for whole-house litter pH, moisture content, and NH₃ flux as the 2 aforementioned studies. Although the data were presented as pooled for the entirety of the houses, color varigrams indicated an effect of half-of-house management for some parameters (e.g., brood half litter temperature at the beginning of the flocks), but the effect was limited to NH₃ flux at the mid-growout. Miles et al. (2011a) measured a greater summer flux (522 vs. 278 mg·m⁻²·h⁻¹ in winter) and an increased nonbrood flux (482 vs. 316 mg·m⁻²·h⁻¹). The latter study sampled litter and NH₃ flux at an equidistance between the feeders and waterers to capture gross trends in this area due to traffic and cake formation. At the mid-growout, the combined feeder/waterer samples were inconsistent with respect to high or low moisture content and did not appear different than surrounding samples for NH₃ flux. Like Tasistro et al. (2004) at the end of the growouts, the combined feeder/waterer samples exhibited lower NH₃ flux than surrounding samples, likely due to heavy cake forming a seal over the litter in those areas (Miles et al., 2011a).

The complexity and impact of cake formation has scarcely been discussed in the literature relative to gaseous emissions. Sistani et al. (2003) characterized the rate of cake production during 1 yr on 3 commercial farms and reported 57% of litter remained in the house after decaking between flocks. In pen trials, Coufal et al. (2006a) found that top dressing litter reduced cake production, but did not affect total litter production. With qualitative notes of litter condition at grid sampling sites, Miles et al. (2008b, 2011a) noted low NH₃ flux in caked areas near fans and feeder/waterer lines. In the current research, there was some cake formation; however, choosing the mid-flock measurement preclud-
ed the sealing effect that was noted in earlier spatial flux measurements. Significant variability was found when comparing results of the present study with earlier reports of litter NH$_3$, moisture content, and pH. This is not surprising when considering the dynamic confluence of factors affecting these parameters. Still, it is logical to make inferences based on housing characteristics and management practices. The present study is the first of its kind to specifically assess NH$_3$ generation at sidewalls, feeders, and waterers in modern commercial broiler houses during 6 flocks on reused litter. By sampling at mid-flock, intermittently during 2 yr (6 flocks total), the present study consistently demonstrated the effect of litter location at sidewalls, feeders, and waterers relative to potential for NH$_3$ generation and differences in moisture content, pH, and litter NH$_4^+$. The effect of half of house was less pronounced, indicating lower NH$_3$ at feeders in the nonbrood area and higher pH of half of house was less pronounced, indicating lower

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