JOURNAL OF ENVIRONMENTAL SCIENCE AND HEALTH, PART A
2018, VOL. 0, NO. 0, 1–7
https://doi.org/10.1080/10934529.2018.1428273



# A simple mathematical method to estimate ammonia emission from in-house windrowing of poultry litter

Kyoung S. Ro[a], Ariel A. Szogi[a], and Philip A. Moore, Jr.[b]

[a]US Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water & Plants Research Center, Florence, South Carolina, USA; [b]US Department of Agriculture, Agricultural Research Service, Poultry Production and Production Safety Research, Fayetteville, Arkansas, USA

**ABSTRACT**

In-house windrowing between flocks is an emerging sanitary management practice to partially disinfect the built-up litter in broiler houses. However, this practice may also increase ammonia ($NH_3$) emission from the litter due to the increase in litter temperature. The objectives of this study were to develop mathematical models to estimate $NH_3$ emission rates from broiler houses practicing in-house windrowing between flocks. Equations to estimate mass-transfer areas form different shapes windrowed litter (triangular, rectangular, and semi-cylindrical prisms) were developed. Using these equations, the heights of windrows yielding the smallest mass-transfer area were estimated. Smaller mass-transfer area is preferred as it reduces both emission rates and heat loss. The heights yielding the minimum mass-transfer area were 0.8 and 0.5 m for triangular and rectangular windrows, respectively. Only one height (0.6 m) was theoretically possible for semi-cylindrical windrows because the base and the height were not independent. Mass-transfer areas were integrated with published process-based mathematical models to estimate the total house $NH_3$ emission rates during in-house windrowing of poultry litter. The $NH_3$ emission rate change calculated from the integrated model compared well with the observed values except for the very high $NH_3$ initial emission rate from mechanically disturbing the litter to form the windrows. This approach can be used to conveniently estimate broiler house $NH_3$ emission rates during in-house windrowing between flocks by simply measuring litter temperatures.

**ARTICLE HISTORY**
Received 29 September 2017
Accepted 2 January 2018

**KEYWORDS**
Ammonia; ammonia emission; broiler production; poultry litter

## Introduction

Commercial broiler production commonly uses wood shavings or straw as bedding material. After it is used, the bedding material along with poultry manure, feathers, and spilled feed builds up into poultry litter. The same litter is reused by multiple flocks because of the high costs for complete replacement of bedding after the harvest of each flock. After using the same litter for multiple flocks, the built-up of poultry litter may increase the risk of transmitting pathogenic microorganisms such as Salmonella, *Escherichia coli*, Clostridium, Campylobacter, and others, causing an increase in bird mortality.[1] In-house windrowing is an emerging management practice used as a sanitary measure to partially disinfect the built-up litter. With this practice, growers windrow the litter in broiler houses during downtime between flocks, usually for 2 weeks. This practice results in high litter temperatures that can reduce pathogens in the litter. Simultaneously, this practice also increases ammonia ($NH_3$) emission from the litter since organic nitrogen in animal manure can be rapidly converted into $NH_3$ and released to the atmosphere under favorable environmental conditions (temperature, moisture content, and pH) of the poultry litter.[2] Although the concomitant increase in temperature and $NH_3$ is thought to provide the disinfection effect for the windrowed in-house litter,[2,3] $NH_3$ is a fugitive gas contributing to the regional acidification and eutrophication of both terrestrial and aquatic ecosystems, and a principal source of atmospheric aerosols from livestock operations.[4,5]

The extent of $NH_3$ emissions from bird housing depends on complex biochemical reactions leading to the mineralization of organic N compounds in poultry manure, and both diffusive and convective transport of $NH_3$ from the source to the ambient air.[6,7] When poultry litter is windrowed, the heat generated by microbial reactions raises the litter temperature and influences $NH_3$ emission. Comprehensive mathematical models integrating biochemical reaction kinetics, heat and mass transfer for enclosed reactor systems were successfully developed to simulate compost temperature, respiration rates, and ammonia emission rates.[8–10] These models may not be applicable for our case study of litter windrowing because they assume completely mixed compost with uniform temperature and forced aeration with well-defined air-flow rates. Although both aeration and mixing of windrowed litter are achieved by turning it, uniform temperature may not be assumed as accurate unless the windrow is turned frequently enough. In our previous experience with in-house windrowing of poultry litter, temperatures never became uniform when the windrow was turned only twice during the course of a 15-day in-house

**CONTACT** Kyoung S. Ro kyoung.ro@ars.usda.gov US Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water & Plants Research Center, Florence, South Carolina, USA.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lesa.

windrowing study.[2] Our field study measured the difference in $NH_3$ emission rates between windrowing and control broiler houses. The ratio of $NH_3$ emission rate from windrowed litter to that of control house increased to 2.98 when the litter temperature increased to 55°C. Typically, all houses are windrowed during downtime (about 2 weeks) between flocks (three to four times in a year). The farmer allowed us to use one of broiler house as a control by not windrowing it during the downtime. Thus, the results of our previous field study results were compared with the model outputs from this study.

In this study, prediction of litter temperature was not included in the development of the mathematical method, but litter temperature measured from full-scale in-house windrows of poultry litter was used for the simulation. Liu et al.[11] developed a simplified mathematical equation for $NH_3$ flux from an empty model bird housing assuming a negligible concentration in the air entering the bird house:

$$J = K_e C_o, \tag{1}$$

where

$J$ = $NH_3$ flux (mg m$^{-2}$ h$^{-1}$),

$K_e$ = overall emission coefficient (m h$^{-1}$),

$C_o$ = gas phase $NH_3$ concentration in equilibrium with dissolved $NH_3$ in litter (mg m$^{-3}$).

The overall emission coefficient is related to ventilation rate and the gas-phase overall mass-transfer coefficient. The gas-phase overall mass-transfer coefficient can be estimated with air velocity and temperature; while $C_o$ is related to dissolved $NH_3$ concentration in the litter and the Henry's coefficient.[11] When litter is windrowed, the increase in litter temperature will significantly increase $C_o$. For example, using an empirical equation for Henry's coefficient,[12] $C_o$ increases 2.8 times when the litter temperature increases from 25°C to 55°C having the same dissolved $NH_3$ concentration in the litter. Therefore, just considering $C_o$ alone in Eq. (1), one would expect that the $NH_3$ emission flux will increase significantly with the increase in windrowed litter temperature due to increase in $C_o$.

Surprisingly, a higher downtime $NH_3$ emission rate of 22.3 kg d$^{-1}$ house$^{-1}$ was observed from the control bird house without windrowing its litter than that from the windrowed house despite its higher windrowed litter temperature.[13] The authors explained the decrease in surface area per unit volume of the windrowed litter as the reason for the higher $NH_3$ emission rate from the control house. Since the emission rate is calculated by multiplying emission flux and the mass-transfer area (i.e., the surface area exposed to the atmosphere), the decrease in mass-transfer area due to windrowing might have more impact on the emission rate than increase in flux due to litter temperature increase. Therefore, it is necessary to further investigate Eq. (1) especially on the change in $K_e$ value due to windrowing in order to better assess the change in emission rates.

The objectives of this study were to (Eq. (1)) develop mathematical models to relate windrow size, shape, and corresponding mass-transfer area, (Eq. (2)) integrate the mass-transfer area models and currently available mass-transfer-based process models in the literature to better estimate the change in $NH_3$ emissions from the in-house litter windrowing management practice, and (Eq. (3)) verify the results of the integrated models with observed field data.

## Theoretical development

### *Change in mass-transfer area from windrowing*

Assuming the litter in the treatment house is shaped to make two identical triangular prismatic windrows (Fig. 1), the total mass-transfer area per litter volume that is exposed to air so that fugitive gas can be emitted to the air is calculated by:

$$a = \frac{A}{V} = \frac{4L\sqrt{h^2 + \left(\frac{b}{2}\right)^2}}{bhL}, \tag{2}$$

where

$a$ = volumetric mass-transfer area of litter per volume of litter (m$^2$ m$^{-3}$),

$A$ = mass-transfer area of litter (m$^2$),

$b$ = base of the prism-shaped windrow (m),

$h$ = height of the windrowed litter (m),

$L$ = length of the windrowed litter (m),

$V$ = volume of the windrowed litter (m$^3$).

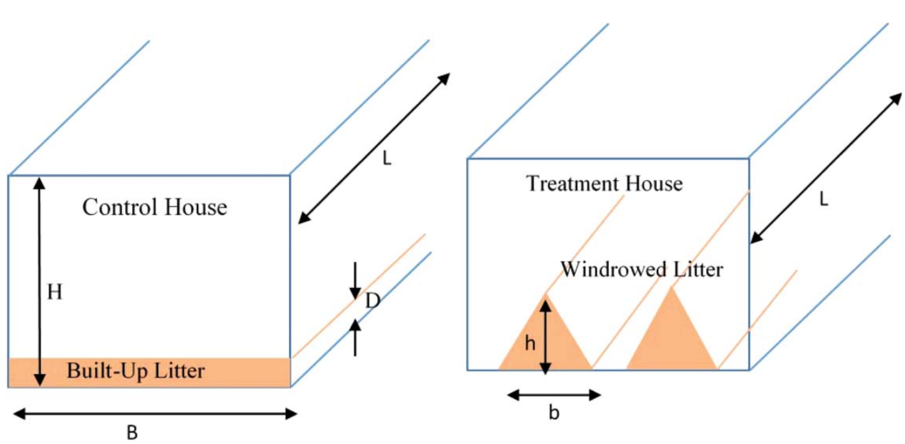


**Figure 1.** Dimensions of two identical bird houses one with and without windrowing: $B$ = width of house, $L$ = length of house, $H$ = height of house, $D$ = depth of evenly spread out litter, $b$ = base of windrowed litter, and $h$ = height of windrowed litter.

Assuming the length of the windrowed litter is the same as house dimension, the total volume of the two windrows is determined by:

$$V = bhL = DBL. \tag{3}$$

where
$B$ = width of bird house (m),
$D$ = depth of spread out litter before windrowing (m).

Combining Eqs. (2) and (3), the volumetric mass-transfer area is determined by:

$$a = \frac{4}{DB}\sqrt{h^2 + \frac{D^2B^2}{4h^2}}. \tag{4}$$

It is interesting to note that the volumetric mass-transfer area does not depend on house length. Figure 2 shows the change in the volumetric mass-transfer area of the windrowed litter with its height. The volumetric mass-transfer area reaches a minimum at certain windrow height. Since the primary objective of windrowing litter is to increase litter temperature to reduce pathogens, reduction of the litter's mass-transfer area is important to minimize heat loss to ambient air and better retain the heat generated by microbial metabolism within the litter. In addition, the decrease in mass-transfer area also decreases $NH_3$ emission rate from the windrowed litter.

The minimum litter mass-transfer area that is associated with the windrowed litter height can be determined by:

$$\frac{da}{dh} = 0. \tag{5}$$

Solving Eqs. (4) and (5), the height of windrowed litter generating the minimum mass-transfer area is calculated as a function of house width and the depth of spread-out litter.

$$h_m = \sqrt[4]{\frac{D^2B^2}{4}}, \tag{6}$$

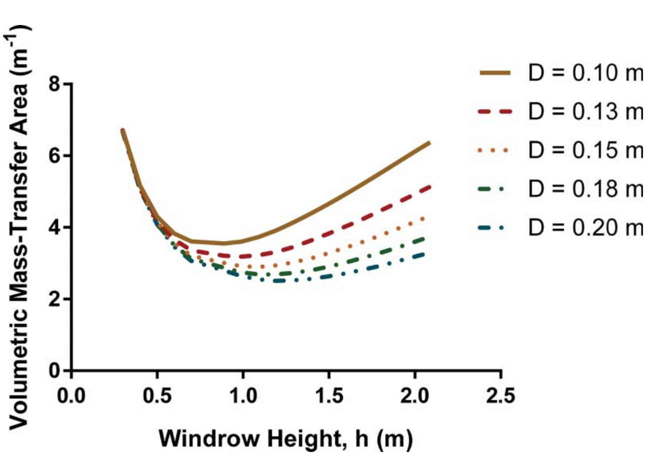


**Figure 2.** Volumetric mass-transfer area of two triangular prismatic windrows with a house width ($W$) of 12.5 m, with various litter depth ($D$).

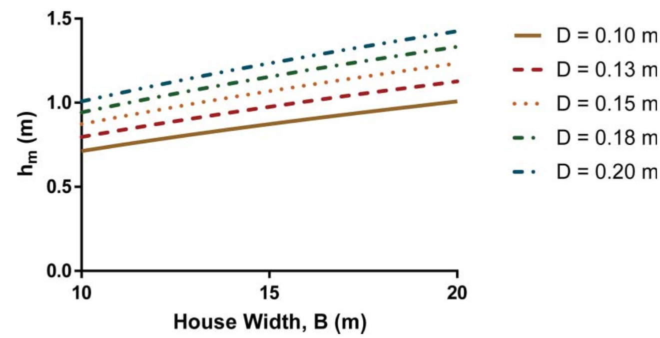


**Figure 3.** Height of triangular prismatic-shaped windrowed litter yielding the minimum mass-transfer area.

where
$h_m$ = height of windrowed litter yielding the minimum mass-transfer area (m).

The height that yields the minimum mass-transfer area of the triangular prismatic windrows is plotted against to the width of house at different spread-out litter depths (Fig. 3). As the house width or the litter depth increases, $h_m$ also increases monotonically. On the one hand, for a house with widths from 10 to 20 m, $h_m$ increases from 0.7 m for 0.1 m (4′) litter depth to 1.4 m for 0.2 m (8′) litter depth. On the other hand, the windrowed litter width also decreases with the windrow height (graph not included here).

The equations for volumetric mass-transfer area ($a$) and $h_m$ for different windrow shapes can be developed using the similar procedure. Table 1 shows the equations for triangular prismatic, rectangular prismatic, and semi-cylindrical windrows (two identical windrows per house). Notice that for the semi-cylindrical windrow, only one windrow height is possible for a given litter volume. Using dimensions of $W = 12.5$ m, $D = 0.10$ m, and $L = 145$ m for a typical broiler house, the volumetric mass-transfer areas of the two windrows with different shapes are plotted against heights (Fig. 4). The minimum mass-transfer area for the two triangular prismatic windrows is 654 m$^2$ (height = 0.8 m and base = 1.6 m); while the mass-transfer area of the evenly spread litter is 1813 m$^2$. For the rectangular prismatic windrows (windrows with the shape of a rectangular prisms with six faces that are rectangles), the minimum mass-transfer area is 658 m$^2$ (height = 0.5 m and base = 1.3 m). For the semi-cylindrical windrows, only one height is possible with the minimum mass-transfer area of 583 m$^2$ (height = 0.6 m and base = 1.3 m). Therefore, the mass-transfer area of evenly spread litter in the control house is about 2.8–3.1 times larger than that of either triangular prismatic, rectangular prismatic, or semi-cylindrical windrowed litter in the treatment house. Because the emission rate from a house is product of flux and mass-transfer area, the impact of increasing $C^{\circ}$ in Eq. (1) on the emission rate from a house due to the increase in the windrowed litter temperature (i.e., 2.8 times larger for the increase in the litter temperature from 25°C to 55°C) can be fully compensated by the decrease in mass-transfer area (2.8–3.1 times smaller) if the windrow height is at $h_m$.

## *Change in emission coefficient ($K_e$) as a result of windrowing*

Although the impact of increase in $C_o$ due to increase in litter temperature on the house emission rate can be compensated by the decrease in mass-transfer area of the windrows, Ro et al.[2] found

**Table 1 .** Equations for volumetric mass-transfer area and the minimum-area yielding windrow height (two identical windrows per house).

| Windrow shape | Volumetric mass-transfer area, $a$ ($m^{-1}$) | Windrow height yielding the minimum mass-transfer area, $h_m$ (m) |
|---|---|---|
| Triangular prism | $a = \frac{4}{DB}\sqrt{h^2 + \frac{D^2B^2}{4h^2}}$ (4)* | $h_m = \sqrt[4]{\frac{D^2B^2}{4}}$ (6)* |
| Rectangular prism | $a = \frac{4h}{DB} + \frac{1}{h}$ (7)* | $h_m = \sqrt{\frac{DB}{4}}$ (8)* |
| Semi-cylindrical | $a = \frac{2}{h_m}$ (9)* | $h_m = \sqrt{\frac{DB}{\pi}}$ (10)* |

*Number in parenthesis is the equation number.

that the $NH_3$ emission rates from the windrowed house (26.2 and 16.6 kg $d^{-1}$ $house^{-1}$) were significantly higher than that from the control house without windrowing (14.6 and 12.8 kg $d^{-1}$ $house^{-1}$). Therefore, it is evident that $K_e$ in Eq. (1) is also impacted by the windrowing of the litter. It is necessary to further investigate the overall emission coefficient $K_e$ in Eq. (1) to explain the increase in $NH_3$ emission rates from windrowing house despite the decrease in mass-transfer area.

Liu et al.[11] defined $K_e$ as:

$$K_e = \left\{ \frac{1}{Q/A} + \frac{1}{K_G} \right\}^{-1}, \quad (11)$$

where
$Q$ = ventilation rate of the house ($m^3$ $h^{-1}$),
$A$ = mass-transfer area of litter ($m^2$),
$K_G$ = gas-phase overall mass-transfer coefficient (m $h^{-1}$).

The gas-phase overall mass-transfer coefficient can be estimated using the correlation (Eq. (12)) reported in the literature.[14] This correlation equation is an adaptation of the two-film theory for absorption of $NH_3$ from gas phase to pure water on a "wetted wall" equations.[15] By using Eq. (12), we assumed that the effect of surface roughness was negligible on $NH_3$ emissions rates.

$$K_G = 483.19\ V^{0.8} T^{-1.4}, \quad (12)$$

where
$V$ = mean air velocity (m $s^{-1}$),
$T$ = air temperature (K).

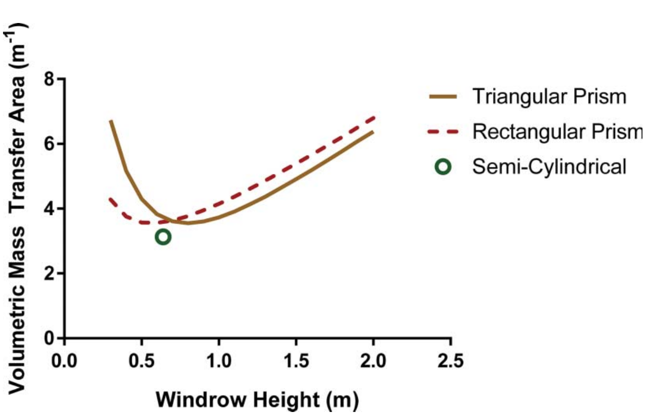


**Figure 4.** Volumetric mass-transfer areas of triangular prismatic, rectangular prismatic and semi-cylindrical windrows of different heights for a broiler house ($W$ = 12.5 m, $D$ = 0.10 m, and $L$ = 145 m).

The mean air velocity in the house can be estimated by dividing ventilation rate (volumetric flow rate) by its rectangular cross-section area excluding the top triangular ceiling section of the house with rather stagnant air. Although the $K_G$ (Eq. (12)) was adapted for use with swine manure, we assumed it was adequate for broiler litter because the pH of swine manure and broiler litter are within the range of 7.8–8.2 pH units.[16] Observations in our field study showed that N losses by $NH_3$ volatilization were so much smaller than the total N mass reserve of the litter support the assumption that slight loss of N would not significantly change the litter pH.[2] Therefore, Eqs. (11) and (12) show that $K_e$ depends on both mass-transfer area and the air temperature. The equilibrium gas-phase $NH_3$ concentration with respect to the dissolved $NH_3$ concentration in the litter in Eq. (1) can be estimated by using Henry's law.[11,12]

$$Log\ K_H = Log\left(\frac{C_w}{C_o}\right) = -1.69 + 1477.7/T_L, \quad (13)$$

where
$K_H$ = dimensionless Henry's law constant,
$C_w$ = aqueous $NH_3$ concentration in the litter (mg $m^{-3}$),
$T_L$ = temperature of litter surface (K).

Important to notice is that the air temperature of a stagnant layer (two film theory) or air pockets (penetration or surface renewal theories) within the boundary layer immediately above the litter surface is assumed to have the same temperature of the litter surface, which was used to calculate $K_H$ using Eq. (13). The litter temperature varies with the depth as observed by Ro et al.[2] The litter surface temperatures were lower than that in the middle of the windrowed litter due to evaporative and convective heat losses from the litter surface to ambient air. Assuming the same dissolved $NH_3$ concentration in the litter for the both control and windrowed litter (i.e., $C_{w,w} \approx C_{w,c}$), the change in $C_o$ due to increase in the litter temperature can be estimated by determining the change in $K_H$.

$$\frac{C_{o,c}}{C_{o,w}} \approx \frac{C_{w,w}/C_{o,w}}{C_{w,c}/C_{o,c}} = \frac{K_{H,w}}{K_{H,c}}, \quad (14)$$

where
$K_{H,w}$ or $K_{H,c}$ = $K_H$ at windrowed litter or control litter temperature,
$C_{o,w}$ or $C_{o,c}$ = $C_o$ of the windrowed or control litter.
$C_{w,w}$ or $C_{w,c}$ = $C_w$ of the windrowed or control litter.

Combining Eqs. (1) and (14), the change in $NH_3$ emission rate can be determined by:

$$\frac{ER_w}{ER_c} = \frac{J_w A_w}{J_c A_c} = \frac{K_{e,w}}{K_{e,c}} \frac{A_w}{A_c} \frac{K_{H,c}}{K_{H,w}}, \tag{15}$$

where

$ER_w$ or $ER_c$ = $NH_3$ emission rates from windrowed or control house (mg $h^{-1}$),

$J_w$ or $J_c$ = $NH_3$ fluxes from windrowed or control litter (mg $m^{-2}$ $h^{-1}$),

$A_w$ or $A_c$ = mass-transfer areas of windrowed or control litter ($m^2$),

$K_{e,w}$ or $K_{e,c}$ = overall emission coefficients of windrowed or control litter (m $h^{-1}$).

Using the same previous broiler house example (i.e., house dimensions of 12.5 width, 2.4 m height, and 145 m length) with a constant ventilation rate of 1091 $m^3$ $min^{-1}$ and 0.1 m (4′) evenly spread-out built-up litter depth before windrowing, the change in $NH_3$ emission rates from the triangular prismatic windrowed litters are calculated at different litter surface temperatures and windrow heights (Fig. 5). The free air temperatures of 24°C and 26°C are used for the control house and the treatment house, respectively. The control litter temperature of 24°C is used for the simulation. The value of $K_{e,C}$ for the control house is 0.48 m $min^{-1}$ while that for windrowed house ($K_{e,W}$) is 1.32 m $min^{-1}$, about 2.7 times higher with windrow height of 0.7 m. The increase in $K_e$ explains the increase in-house $NH_3$ emission rates from the windrowed house even though the increase in $C_o$ on house emission rate is compensated by the decrease in mass-transfer area.

When the windrowed litter surface temperature increases to 55°C, the $NH_3$ emission rate ratio ($ER_w/ER_c$) monotonically increases to 2.98 (windrow height of 1.1 m) even with the decrease in mass-transfer area. Other windrow shapes and heights yield similar values of $ER_w/ER_c$. Figure 6 compares the $NH_3$ emission rate ratios for triangular and rectangular prismatic and cylindrical windrows with the same windrow height of 0.64 m. Virtually, all three shape windrows yielded very similar emission ratios for all temperatures. The effect of windrow height and the shape (or mass-transfer area) on the change in $NH_3$ emission rate appears to be minimal. However, one must note that this analysis is based on the same litter temperature for all windrow heights and shapes. In reality, the litter height and shape impact the heat loss from the litter surface as it determines the total surface area exposed to the atmosphere. The smaller the litter surface area, the smaller the heat loss and the warmer the litter temperature will be. Therefore, in order to predict the impact of windrow height on emission rate without measuring litter surface temperature, it is necessary to develop a comprehensive predictive mathematical model integrating both mass and heat transfer phenomena as well as microbial thermogenesis processes within the windrowed litter. However, it is beyond the scope of the present study. Our model predicts the change in $NH_3$ emission rates based on measured litter surface area.

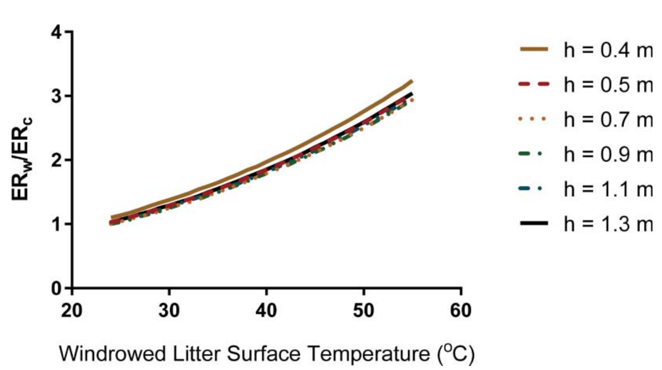


Figure 5. Change in $NH_3$ emission rate due to windowing litter with various windrow heights.

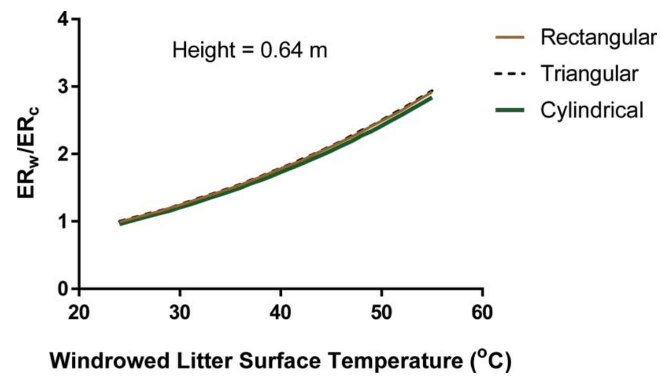


Figure 6. Change in $NH_3$ emission rates from a broiler house ($W$ = 12.5 m, $D$ = 0.10 m, and $L$ = 145 m) with different windrow shapes at the same height of 0.64 m.

## Experimental methods

In order to evaluate the accuracy of the integrated mathematical models described above, the model results were compared to that of the gas emission study conducted by US Department of Agriculture, Agricultural Research Service (USDA-ARS) in two tunnel-ventilated broiler houses on a commercial broiler farm in Arkansas during October 18–24, 2012.[2] Typical flock sizes for these houses were between 25,000 and 30,700 birds. One of the two houses (houses #2) was used as a control (without windrowing litter) and the other house with windrowed litter was the treatment house (house #3). Two days after harvest, the litter in the treatment house was windrowed. The dimensions of the houses were approximately 145 m × 12.5 m. Each broiler house was continuously ventilated with only two of the ten 122-cm-tunnel ventilation fans during the study period. The remaining eight tunnel fans in each house were not operated. The ventilation rates of the control and treatment houses were 960 ± 22.8 and 1091 ± 12.6 $m^3$ $min^{-1}$, respectively. The air flow rates of the exhaust fans were evaluated with the Fan Assessment Numeration System (FANS).[17] Because these fans were operated continuously at constant ventilation rates, the average air flow rates of each fan were used to calculate emission rate during that period. Gas concentrations were measured at two tunnel fans in each house which were operating continuously during the study period. A photoacoustic gas analyzer (PGA) (Innova model 1412; California Analytical Instruments) and multi-sampler (CBISS; California Analytical) were used to sequentially measure $NH_3$ concentration at each fan. Teflon tubing (6.35 mm, o.d.) with a small particulate filter was installed inside each fan housing and connected to the PGA centrally located between the two houses. Average ambient gas concentrations outside the houses for the duration of the study were used as influent gas concentrations.

More detailed description of this study sites and instrumentations can be found elsewhere.[2]

The $NH_3$ emission rate was calculated by multiplying $NH_3$ concentration and the ventilation rate. The $NH_3$ concentrations as converted to mass concentration using the ideal gas law.

$$ER = Q(C_f - C_o)P\ MW/(1000\ RT), \qquad (16)$$

where

$ER$ = emission rate (g min$^{-1}$),
$Q$ = ventilation rate (m$^3$ min$^{-1}$),
$C_f$ = $NH_3$ concentration in the fan housing ($\mu$L L$^{-1}$),
$C_o$ = influent $NH_3$ concentration ($\mu$L L$^{-1}$),
$MW$ = molecular weight of $NH_3$ (17 g mol$^{-1}$),
$P$ = barometric pressure at the study site (atm),
$R$ = universal gas law constant (0.08206 L atm mol$^{-1}$ K$^{-1}$),
$T$ = air temperature (K).

The depth of litter before windrowing in both houses was about 0.1 m (4′). Two days after harvest (10/19/2012), windrowing started in the treatment house. The litter in the treatment house was windrowed to make two approximately rectangular prismatic windrows. The average base length of the windrows was about 2.82 ± 0.22 m. The average windrow height (0.23 m) was then estimated using the average windrow base length and the total volume of litter in the house. Litter temperature at mid-depth was measured in the control and the treatment houses before windrowing. After windrowing, the windrowed litter temperatures were measured at three depths, 7.6 cm below the surface, at the middle, and the bottom (1–2 cm above ground) of the litter. Litter temperatures in both houses prior to windrowing were monitored at 10 points during certain time periods of each day as representative of the entire house litter.

## Results and discussion

### Litter temperature

Litter temperature in the control house (24.0 ± 2.5°C) did not change much during the study periods as shown in Figure 7. The mid-depth windrowed litter temperature reached 53.2°C on day 2 after windrowing and decreased slightly to 47.2°C on day 5. The average mid-depth temperature of the windrowed litter in the treatment house was 43.4 ± 13.3°C. Within the windrowed litter, there was a vertical temperature gradient as shown in Figure 6. The highest temperature achieved at the mid-depth. The near-surface (7.6 cm below surface) increased to 44.9 ± 3.0°C on day 3 and decreased to 33.7 ± 5.0°C on day 5. This decrease in the surface windrowed litter temperature was resulted from the convective heat loss to the ambient air.[18,19] The bottom temperatures of the windrowed litter were similar to the surface litter resulting from the conductive heat loss to the floor. The near-surface temperature (7.6 cm below the surface) was used for subsequent $NH_3$ emission calculations.

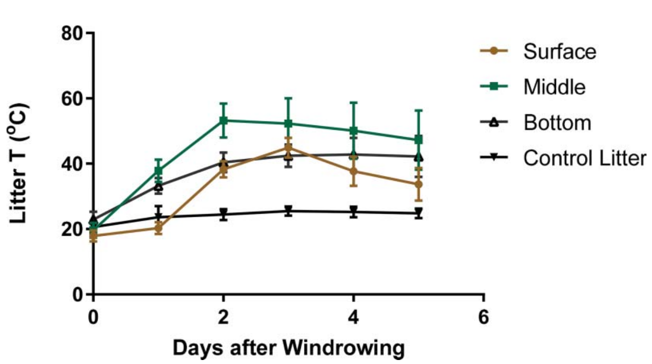


**Figure 7.** Control and windrowed litter temperatures after windrowing.

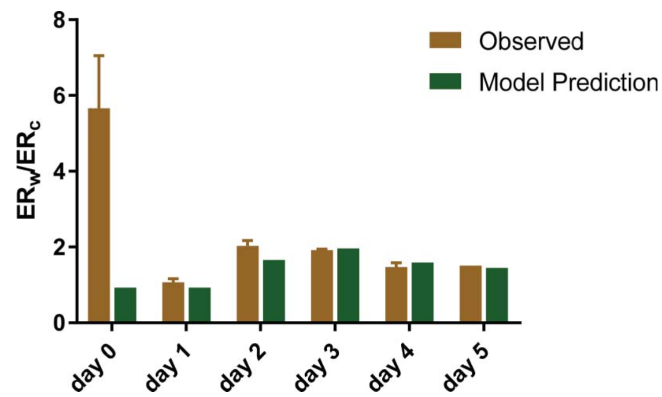


**Figure 8.** Comparison between observed $NH_3$ emission ratio versus model prediction.

### Comparison of theoretical and observed emission ratios

Using the same procedure as discussed previously, the ratios of $NH_3$ emission rates of the windrow treatment house to that of control house for the study period were predicted (Fig. 8). The observed average hourly $NH_3$ emission rates of each house for the duration of litter temperature measuring period were compared to the predicted values. There was a huge discrepancy of the predicted to the observed $NH_3$ emission ratio on day 0 because the emission rate was measured immediately after windrowing started. Mechanically disturbing litter to form windrows resulted in very high $NH_3$ emission rate, which was not accounted in the model development. On day 5, only one observed hourly emission rate taken at 07:00–08:00 AM was used because $NH_3$ concentration monitoring stopped at 8:00 AM. Litter temperature measured between 9:09 AM and 12:29 PM on day 5 was used for model calculation. Other than day 0, the ratios of the observed $ER_w/ER_C$ to model $ER_w/ER_C$ ranged from 0.92 to 1.22 with an average of 1.06 ± 0.12. These results demonstrated the applicability of the integrated $NH_3$ emission model to predict the change in emission rate resulting from in-house windrowing treatment.

## Conclusions

Several complex mathematical models with uncertain accuracies are found in the literature for predicting windrowed litter temperature during composting. Litter temperature significantly influences ammonia emission from the windrowed litter. However, temperature measurements in a windrowed litter are simple and inexpensive to obtain. Therefore, our modelling approach uses the actual litter temperature and mathematical equations to determine the height of windrow yielding the minimum mass-transfer area to estimate the change in $NH_3$ emission rate from a broiler house practicing windrow litter treatment in between flocks. The accuracy of predicted $NH_3$ emission rates was evaluated with field test results.

1. The volumetric mass-transfer area changes with the height of windrow. The heights yielding the minimum mass-transfer area are 0.8 and 0.5 m for triangular and rectangular prismatic windrows, respectively. Only one height (0.6 m) is possible for semi-cylindrical windrows.
2. The minimum mass-transfer areas of these windrows in the treatment house are 2.8–3.1 times smaller than evenly spread out litter in the control house. This decrease in mass-transfer area compensates the impact of increase in $C_o$ (the gas-phase $NH_3$ concentration in equilibrium with dissolved $NH_3$ in litter) due to increase in litter temperature on house emission rates. However, the increase in $K_e$—overall emission coefficient of windrowed litter—explains the increase in $NH_3$ emission rates from the windrowed house.
3. The $NH_3$ emission rate change calculated from the developed method compared well with the observed values except for the very high $NH_3$ emission rate from mechanically disturbing the litter to form windrows on day 0.
4. Since measuring actual emission requires extensive instrumental and human resources, simple litter temperature measurements can be used to estimate the change in ammonia emission rates using the model developed in this study.

## Acknowledgments

The authors would like to acknowledge the technical support provided by Mr. Melvin Johnson, Mr. Jerry H. Martin of the USDA-ARS Coastal Plains Soil, Water & Plant Research Center, Florence, SC, and Mr. Jerry Martin of the USDA-ARS Poultry Production and Products Safety Research, Fayetteville, AR. This research is part of the USDA-ARS National Programs 212 and 214. Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

## References

[1] Lavergne, T. K.; Stephens, M. F.; Schellinger, D.; Carney, W. A. In *House Pasteurization of Broiler Litter*. LSU AgCenter Publication: Baton Rouge, LA, **2006**; 2955.

[2] Ro, K. S.; Moore, Jr., P. A.; Szogi, A. A.; Millner, P. D. Ammonia and nitrous oxide emissions from broiler houses with downtime windrowed litter. J. Environ. Qual. **2017**, *46*, 498–504. doi:10.2134/jeq2016.09.0368.

[3] USDA-APHIS, Mortality composting protocol for Avian Influenza infected flocks. Febrary 5. (https://www.aphis.usda.gov/animal_health/emergency_management/downloads/hpai/mortalitycompostingprotocol.pdf; accessed 9-18-**16**). **2016**.

[4] Doorn, M.R.J.; Natschke, D. F.; Thornloes, S. A.; Southerland, J. Development of an emission factor for ammonia emissions from US swine farms based on field tests and application of a mass balance method. Atmos. Environ. **2002**, *36*, 5619–5625. doi:10.1016/S1352-2310(02)00689-1.

[5] Phillips, J. *Control and Pollution Prevention Options for Ammonia Emissions*; US Environmental Protection Agency, Office of Air Quality Planning and Standards: Springfield, VA, **1995**.

[6] Bolan, N. S.; Szogi, A. A.; Chuasavathi, T.; Seshardri, B.; Rothrock, Jr., M. J.; Paneerselvam, P. Uses and management of poultry litter. World Poutry Sci. J. **2010**, *66*, 673–698. doi:10.1017/S0043933910000656.

[7] Ro, K. S.; Szogi, A. A.; Vanotti, M. B.; Stone, K. C. Process model for ammonia volatilization from anaerobic swine lagoons incorporating varying wind speeds and gas bubbling. Trans. ASABE. **2008**, *51*, 259–270. doi:10.13031/2013.24219.

[8] Ahn, H. K.; Richard, T. L.; Choi, H. L. Mass and thermal balance during composting of a poultry manure—Wood shavings mixture at different aeration rates. Process Biochem. **2007**, *42*, 215–223. doi:10.1016/j.procbio.2006.08.005.

[9] Liang, Y.; Leonard, J. J.; Feddes, J. J.; McGill, W. B. A simulation model of ammonia volatilization in composting. Trans. ASABE. **2004**, *47*, 1667–1680. doi:10.13031/2013.17609.

[10] Petric, I.; Selimbasic, V. Development and validation of mathematical model for aerobic composting process. Chem. Eng. J. **2008**, *139*, 304–317. doi:10.1016/j.cej.2007.08.017.

[11] Liu, Z.; Wang, L.; Beasley, D. B.; Shah, S. B. Modeling ammonia emissions from broiler litter at laboratory scale. Trans. ASABE. **2009**, *52*, 1683–1694. doi:10.13031/2013.29131.

[12] Hales, J. M.; Drewes, D. R. Solubility of ammonia at low concentrations. Atmos. Environ. **1979**, *13*, 1133–1147. doi:10.1016/0004-6981(79)90037-4.

[13] Liang, Y.; Tabler, G. T.; VanDevender, K. W. Ammonia emissions from downtime litter management in broilder housing. In *International Symposium on Air Quality and Manure Management for Agriculture*; ASABE: Dallas, TX, **2010**.

[14] Ni, J. Mechanistic models of ammonia release from liquid manure: A review. J. Agric. Eng. Res. **1999**, *72*, 1–17. doi:10.1006/jaer.1998.0342.

[15] Haslam, T. T.; Hershey, R. L.; Kenn, R. H. Effect of velocity and gas temperature onrate of absorption. Ind. Eng. Chem. **1924**, 16,1224–1230. doi:10.1021/ie50180a004.

[16] Cantrell, K. B.; Hunt, P. G.; Uchimiya, M.; Novak, J. M.; Ro, K. S. Impact of pyrolisis temperature and manurte source on physicochemical characteristics of biochar. Bioreour. Technol. **2012**, *107*, 419–428. doi:10.1016/j.biortech.2011.11.084.

[17] Gates, R. S.; Casey, K. D.; Xin, H.; Wheeler, E. F.; Simmons, J. D. Fan assessment numeration systems (FANS) design and calibration specifications. Trans. ASABE. **2004**, *47*, 1709–1715. doi:10.13031/2013.17613.

[18] Ro, K. S.; Preston, K. T.; Seiden, S.; Bergs, M. Remediation composting process principles-focus on soils contaminated with explosive compounds. Crit. Rev. Environ. Sci. Technol. **1998**, *28*, 253–282. doi:10.1080/10643389891254223.

[19] Kaiser, J. Modelling composting as a microbial ecosystem: A simulation approach. Ecol. Model. **1996**, *91*, 25–37. doi:10.1016/0304-3800(95)00157-3.