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Effect of moisture content on ammonia emissions from broiler litter: A laboratory study

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Abstract A dynamic flow-through chamber system was designed to measure ammonia emissions from broiler litter and to investigate the responses of ammonia emissions to litter moisture content under laboratory-controlled conditions. It was observed that ammonia emissions from litter were very sensitive to litter moisture content. As water was added to the litter, the total ammoniac nitrogen content (TAN) in the litter increased, and can potentially increase ammonia emissions. However, measurements of ammonia concentrations in the chamber and total nitrogen losses from litter samples all suggested that water applied to the litter also had an effect of suppressing ammonia emissions for a short time. After enough time (1 to 2 weeks) was allowed, higher moisture content in litter eventually resulted in higher ammonia emissions. It was also noticed that, at very high litter moisture content, even when more time was allowed, ammonia concentrations began to decrease as moisture content further increased.

Keywords Ammonia emissions · Broiler litter

1 Implications

Intensive production of poultry and livestock in the USA has raised serious environmental concerns with the public. Specifically, ammonia is considered the most harmful gas in broiler chicken housing. This paper reports a laboratory study of ammonia emissions under different moisture content treatments, which leads to better understanding of the impact of litter moisture content on ammonia emissions. Results from this study provide useful information for developing cost-effective mitigating techniques.

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2 Introduction

Ammonia is considered the most harmful gas in broiler chicken housing (Carlile 1984). It can not only cause environment problems, but also be detrimental to the health and performance of birds (Brewer and Costello 1999). The importance of ammonia emissions from animal feeding operations (AFOs) has been well recognized (Van der Hoek 1991; Zhao and Wang 1994; Sutton et al. 1995; Aneja et al. 2000; Arogo et al. 2001; Hutchings et al. 2001; Lee and Park 2002; Battye et al. 2003; Hyde et al. 2003; Xin et al. 2003; Wheeler et al. 2003; Liang et al. 2003; Gates et al. 2004). However, the contributions of ammonia emissions from large poultry operations to the national emission inventory have not been properly documented. Numerous studies have been reported throughout the world on ammonia emissions from broiler houses, and wide variations have been found among different studies. The differences in ammonia emission fluxes from broiler houses under different conditions have been reported as high as 55 fold (Redwine et al. 2002). Variations in ammonia emissions result from the dependence of ammonia emissions on seasonal and regional conditions, house design, and management practices.

Broiler chickens are often grown in production houses at densities of 13.5–21.2 bird m^{-2} (Brewer and Costello 1999; Redwine et al. 2002; Guiziou and Beline 2005; Nicholson et al. 2004). They are normally raised on litter made up of wheat straw or wood shavings above an earthen floor. The mixture of litter and manure represents a significant source of ammonia emissions. The mechanisms related to ammonia emissions from manure involve many processes and has been summarized by Ni (1999). Theoretically, the processes involved in ammonia emissions from litter based manure include conversion of uric acid to urea, hydrolysis of urea, enzymatic and microbial generation of ammonia, diffusion of ammonia in litter, partitioning between the adsorbed and dissolved phase ammonia, the chemistry of ammonia in aqueous solution, partitioning between solid/aqueous phase and gaseous phase ammonia, and the convective mass transfer of ammonia gas from the surface into the free air stream. These processes are summarized and illustrated in Fig. 1.

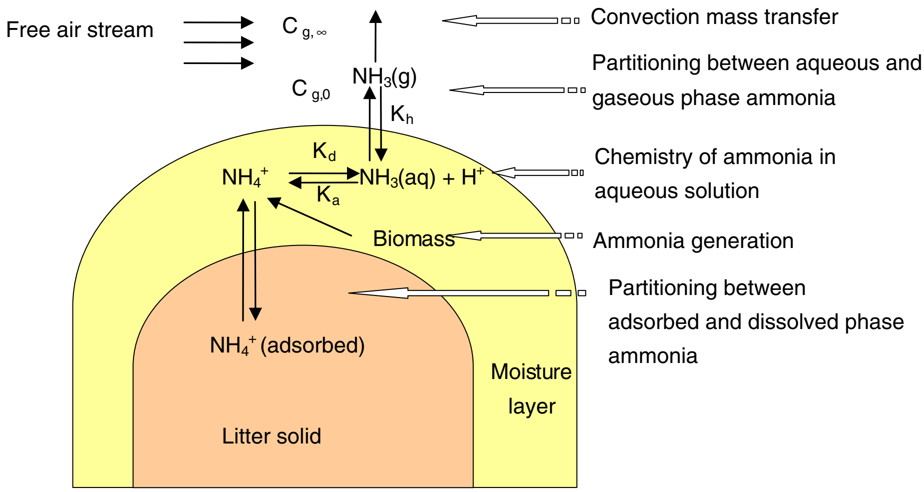


Fig. 1 Illustration of processes related to ammonia emissions from litter-based manure

2.1 Factors influencing ammonia emissions from broiler litter

In general, factors that may influence ammonia emissions from broiler litter include: air and litter temperature, air exchange rate, litter pH, litter nitrogen content, and litter moisture content.

Air and litter temperature Temperature is a very important variable during the processes of ammonia emissions from litter-based manure. Air temperature may influence the convective mass transfer coefficient. Litter temperature may influence the Henry's constant, the dissociation constant, and also the diffusion and generation of ammonia in litter. Therefore, ammonia flux can be greatly affected by temperature variation. In the broiler houses air temperature are usually managed to optimize bird health and productivity. It is often regulated with an initial temperature of 32 to 35°C which is lowered by 1°C every second day to 22±2°C after 3 weeks of age (Nicholson et al. 2004; Elwinger and Svensson 1996). The whole growth cycle of birds in broiler houses is typically about 7 weeks (Lacey et al. 2003), from 1-day-old to the time of slaughter. In warm weather, it is a common practice that the ventilation rate be increased to maintain the target air temperature. So the influences of climatic differences on ammonia fluxes from broiler litter are largely indirect. The variation of ambient temperature requires the adjustment of air exchange rate, and the variation of air exchange rate causes the variation of ammonia fluxes. For summer housed flocks, mean ammonia fluxes were almost double those from winter housed flocks because of higher ventilation rates in the warmer weather (Nicholson et al. 2004).

Air exchange rate The air exchange rate in broiler houses can vary in a large range. Air exchange rates (ventilation rates) were measured between 0.58 and 89 m^3/s in the study of Redwine et al. (2002). Air exchange rate may influence the concentration of gas phase ammonia in the free air stream and the mass transfer coefficient. It has been reported that the ammonia concentrations in boiler house are lower for higher air exchange rates (Redwine et al. 2002). However, as air exchange rates increase, although the ammonia concentration may decrease, the ammonia flux will increase (Nicholson et al. 2004).

Litter pH value The pH value of manure is one of the most important factors that determines the aqueous phase ammonia concentration, and therefore influences ammonia release. Research has demonstrated that ammonia release from litter is negligible at litter pH below 7(Reece et al. 1985). Chemical treatments have been studied in laboratory tests as a way to suppress ammonia volatilization, by chemically lowering the litter-solution pH. Witter and Kirchmann (1989) tested calcium chloride and magnesium chloride applications to liquid chicken manure and found reductions in total ammonia losses of 30 and 50%, respectively. Moore et al. (1996) tested several treatments for broiler litter and found that aluminum sulfate, phosphoric acid, and ferrous sulfate each worked well in reducing ammonia losses. However, control of litter pH over the life of the flock in practical scale has proven to be a difficult task (Lacey et al. 2004; Carr et al. 1990).

Litter nitrogen content (diet, litter age and bird age) It would be reasonable to assume that ammonia emissions are positively related with litter nitrogen content. An increase in feed protein level may significantly increase litter nitrogen content, and therefore increase ammonia emission rate (Elwinger and Svensson 1996). Re-used litter (use of old litter as bedding for subsequent flocks) has more nitrogen content. It has been reported that ammonia flux from reused litter was six times higher than that from new bedding material at the start of a grow-out (Brewer and Costello 1999). Several researchers reported that ammonia emissions increase with age of bird (Redwine et al. 2002; Elwinger and Svensson 1996). It may also due to increase of litter nitrogen content with increase of bird age.

Litter moisture content Urea hydrolysis is a major source of ammonia as shown below:

$$CO(NH_2)_2 + H^+ + 2H_2O \rightarrow 2NH_4^+ + HCO_3^-$$

Therefore, litter moisture content may affect the conversion rate of uric acid to ammonium-N (Sims and Wolf 1994). It has been reported qualitatively that wet litter can lead to high ammonia levels in broiler houses (Elliott and Collins 1982) and may cause bird health problems such as hock burn (Tucker and Walker 1992). However, overly dry litter may result in more dust particulates, which can serve as a transport mechanism for ammonia. On the other hand, very wet conditions may slow/shut down microbial and enzymatic activities due to scarcity of oxygen.

Litter moisture content may vary in a large range. Elwinger and Svensson (1996) reported that, the dry matter content was 91.6–92.2% for fresh litter materials, and was about 64% at 35 days of age. In practice, litter moisture is also influenced by ventilation and drinking system management. The design of broiler drinking systems has been shown to influence the usage of water and broiler litter moisture content (Tucker and Walker 1992). Spillage causes excessive litter moisture.

It has been reported that higher litter dry matter content and lower ammonia emissions were measured from broilers using nipple drinkers than those using traditional bell drinkers (Nicholson et al. 2004; Elwinger and Svensson 1996). Similar results were also obtained by Da Borso and Chiumenti (1999) who found that buildings equipped to prevent water dripping onto the litter from nipple drinkers emitted less ammonia than those with standard design nipple drinkers. Carr et al. (1990) commented that it is desirable to maintain litter moisture below 30% for ammonia control. However, Carr et al. (1990) also reported a decrease in ammonia concentrations at high moisture and temperature. The decrease in ammonia concentrations at high moisture levels has also been reported by Valentine (1964) and Schefferle (1965). The comprehensive effect of litter moisture content is complex and still not well known.

2.2 Research objective

A better understanding of ammonia emission processes and influencing factors will provide a basis for developing cost-effective mitigating techniques and evaluating the impact of changes in emission characteristics on monitoring protocols and techniques. This research was to study the effect of various influencing factors on ammonia emissions from broiler litter. This paper reports results of the first step of this study, which investigated the effect of litter moisture content under laboratory-controlled conditions. Understanding of effect of litter moisture content will be helpful in improving management practices (e.g. litter management, drinker systems and ventilation systems) and may contribute to practical and cost effective strategies to mitigate ammonia emissions from broiler houses. The long term goal is to develop a multi-variable emission model that combines the effects of temperature, air exchange rate, pH, litter nitrogen content and litter moisture content.

3 Methodology

3.1 Experimental setup

In order to quantify and compare ammonia emissions from broiler litter with various moisture contents, a dynamic flow-through chamber system was designed for measurements of ammonia emissions from broiler litter under various moisture conditions. The diagram of this chamber system is shown in Fig. 2. The chamber body has a cylindrical shape with bottom diameter (inside measurements) of 40.0 cm (15.75 in.) and height of 39.4 cm (15.5 in.). Broiler litter samples were put on the bottom of the chamber and a vacuum pump was used to draw air through the chamber at a constant flow rate via flow controllers (Gilmont Shielded Industrial Flow meter, accuracy ±5%). Before entering the chamber, ambient air passed through an acid scrubber so that any background ammonia was removed. The ammonia free air passed over the litter samples to promote convective conditions similar to those in a typical broiler house. A motor-driven stainless steel impeller mixed the air inside the chamber and promoted desired convective conditions. The dynamic chamber system, with the continuous stirring provided by the impeller, meets the necessary criteria for performance as a continuously stirred tank reactor (CSTR; Aneja 1976). The entire chamber body was made of stainless steel and Teflon tubing was used to minimize the loss of ammonia. Assuming ideal mixing in the chamber, ammonia fluxes can be calculated using a mass balance approach based upon measured concentration as described in Roelle et al. (1999) and Aneja et al. (2000).

The dynamic flow-through chamber was built to simulate the convective conditions in an actual broiler house. The ventilation rate and air velocity at the litter surface has been recognized as two important factors that affect ammonia emissions. Based on the ventilation rates reported by Lacey et al. (2004) and Guiziou and Beline (2005), the air residence time has been estimated in the range of 59 to 191 s for a tunnel-ventilated broiler house in Texas and in the range of 260 to 36,000 s for a broiler house in France. The volume of the chamber in this study was 50 l, and the air exchange rate (air flow rate through the chamber) was set at 9.8 l/min, so that the residence time was calculated as 306 s. The smaller residence times in the study of Lacey et al. (2004) are believed to be one of major reasons for their higher ammonia fluxes compared with those in the study of

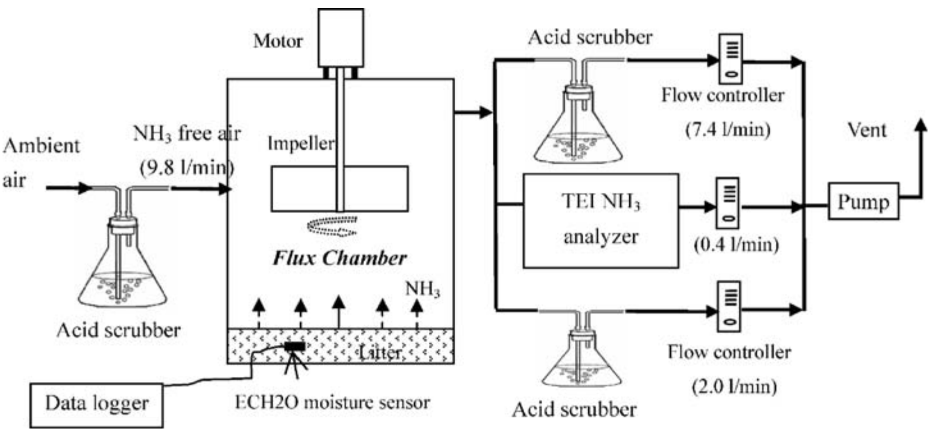


Fig. 2 The dynamic flow-through chamber system for measurement of ammonia emission from broiler litter

Guiziou and Beline (2005). The air velocity at the litter surface may influence the mass transfer coefficient, and therefore the ammonia flux. There are a very limited number of studies which have reported the air velocity at the litter surface. Brewer and Costello (1999) reported that the mean air speed at a 25 cm height is 0.24 m/s with a standard deviation of 0.14 m/s in a conventional cross-ventilated house. Although no report has been found on the litter surface air velocity in tunnel-ventilated houses, which is quite popular in USA, it is supposed that it would be higher. In this reported study, air velocity in the chamber was measured by a hotwire anemometer at 2.5 cm height above the litter surface. It was found that the air velocity at the litter surface can be controlled by adjusting RPM of the stirring impeller; and it was not obviously influenced by the chamber flow rate. The air velocity at the litter surface was 0.34±0.19 m/s at 50 RPM; and 0.68±0.34 m/s at 110 RPM. During the tests, RPM of the stirring impeller were set at 110.

3.2 Litter samples and moisture treatments

Pine shaving litter samples from two commercial broiler farms in North Carolina were tested in this study. Five litter samples were labeled as litter A, B, C, D and E. The two farms use different units for defining the age of litter. Litter A, B, and E were from the same farm with ages of 2-year, 4-year, and 1-year, respectively. Litter C and D were from the other farm with ages of 8-flock and 12-flock respectively. Litter samples were analyzed for moisture content, total nitrogen content, total ammoniac nitrogen content (TAN), carbon content and pH. A given amount of water was applied by uniformly sprinkling and incorporated into the litter to achieve various levels of moisture content. All litter moisture contents were expressed on a wet basis by mass in this study. During the test, the moisture content of untreated litter was measured using the standard moisture content measurement method by comparing litter weight before and after oven drying. The moisture content of litter that has been treated with water was calculated from the original untreated litter moisture content and the amount of water added using the following equation.

$$MC_1 = (MC_0{}^{*}W_{Litter} + W_{H2O})/(W_{Litter} + W_{H2O})$$

In which,

MC_1 is the moisture content of the litter that has been treated with water
MC_0 is the original untreated litter moisture content that measured by standard moisture content measurement
W_{litter} is weight of litter
W_{H2O} is weight of water added

An ECH2O moisture sensor (EC5) was used in each chamber to continuously monitor litter moisture contents during the tests. The ECH2O moisture sensor was calibrated at eight moisture levels using the standard moisture content measurement method by comparing litter weight before and after oven drying. The calibration line has R-square of 0.9789. The reading of ECH2O moisture sensor showed great agreement with the calculated moisture content.

3.3 Measurement of ammonia concentrations in the chamber

Three identical chamber systems were built to ensure at least three replicates for each treatment (moisture level) with each experimental run of one hour or so. Room temperatures were kept at 22°C during the tests. Ammonia concentration in each chamber was simultaneously measured by a boric acid scrubber and a Thermo Environmental Instruments (TEI) chemiluminescence ammonia analyzer (Model 17C). The TEI ammonia analyzer provided real-time measurements of ammonia concentration inside the chamber while the acid trapping system (scrubber) provided time-weighted average ammonia concentration for each experimental run. In this paper, the data from the scrubber measurements are reported. Comparison of the measurements using these two methods is underway, and will be reported in another paper.

One hundred fifty millilitters of 2% boric acid was used in the sampling scrubber. The collection efficiency of the scrubber was determined to be as high as 99.78% when the sampling flow rate was set at 2 l/min. The acid scrubber system (Fig. 2) collected gaseous ammonia into a boric acid solution. Once samples of ammonium ions were obtained in solution, the mass of nitrogen per unit volume of solution was determined through ion chromatograph analysis in the BAE Environmental Analysis Laboratory at NC State University. Thus, the mass of nitrogen was determined for given testing time. In the meantime, the volume of air passed through the scrubber was recorded and the average ammonia mass concentration for this given period of testing time was calculated based upon the mass of nitrogen (converted to the mass of ammonia) and the volume of air passed through the scrubber during the testing period.

3.4 Measurement of nitrogen loss of litter samples

An alternative method to estimate ammonia emissions from litter is by measuring the nitrogen losses of litter samples after they are exposed to air for a certain amount of time. The total nitrogen losses from litter samples at various moisture levels were determined through analysis of litter samples, and they were compared with each other to investigate the effects of litter moisture content.

4 Results and discussions

4.1 Effect of added water in a short time

Four types of pine shaving litter samples (labeled as litter A, B, C and D) were tested in the dynamic flow-through chamber to study the relationships between ammonia concentrations and litter moisture contents. Water was gradually applied into the litter samples to achieve increasing moisture contents, and then ammonia concentrations in the chambers were measured at various moisture contents. All the ammonia measurements were taken within two days after water was applied into the litter.

As indicated in Fig. 3, ammonia concentrations for all the four litter samples decreased as litter moisture contents increased. The water applied to the litter obviously suppressed ammonia emissions in the short time range of the experiments (2 days).

4.2 Effect of litter moisture contents vs time

Water applied to the litter may affect ammonia emissions through various processes in the litter, such as generation of ammonia in the litter as well as mass transfer of ammonia in the litter and from litter to air. It was found that time played an important role for the comprehensive effect of the added water. It may take some time for all the effects to be

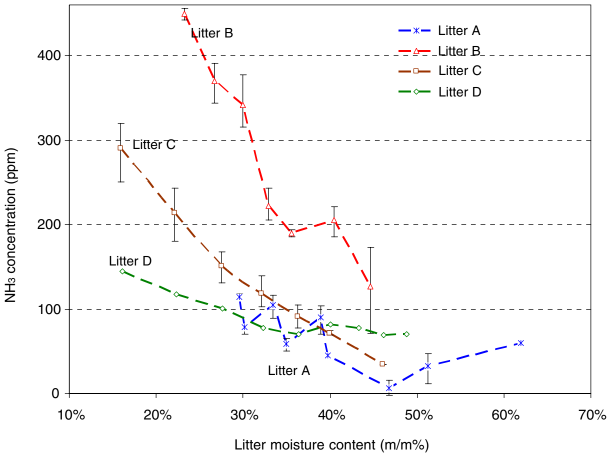


Fig. 3 Average ammonia concentrations vs litter moisture contents

observed. Litter A had moisture content of 22.8% when no water was applied, and the corresponding ammonia concentration in the chamber was 102 ppm. Right after water was applied and the moisture content of litter A was increased to 46.8%, the corresponding ammonia concentration in the chamber was reduced to 6 ppm. However, when the ammonia concentration was measured one week after water was applied, the corresponding ammonia concentration in the chamber for litter A with the same moisture content (46.8%) was found to increase to 91 ppm. Litter E was tested in the dynamic flow-through chamber for a time range of 25 days. As days went by, water was gradually added into the litter to achieve increasing moisture content. The resulting moisture contents and the corresponding average ammonia concentrations at each day are plotted in Fig. 4. It was found that when the

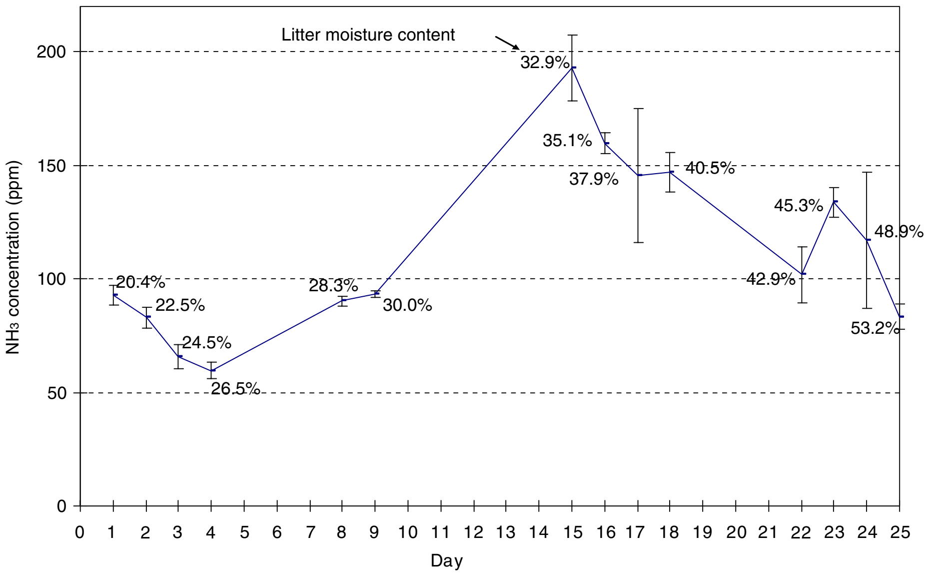


Fig. 4 Average ammonia concentrations from litter E (1-year) as a time series

ammonia measurements were taken within five days after water was applied into the litter, ammonia concentrations decreased as litter moisture contents increased, which was consistent with what has been reported in previous section of this paper. However, after 5 days, ammonia concentrations began to increase as moisture contents increased. At day 1, the average ammonia concentration was only 92.9 ppm with litter moisture content of 20.4%. At day 15, the average ammonia concentration reached the highest value, 192.8 ppm, with a litter moisture content of 32.9%. It suggested that water applied to litter had an effect of suppressing ammonia emissions in the short term; however, after a longer time, higher moisture contents in litter eventually resulted in higher ammonia emissions. It was also noticed that when litter moisture contents were 35.1% or higher, even after a long time, ammonia concentrations began to decrease as moisture contents further increased. Elliot and Collins (1982) and Carr et al. (1990) have reported that wet litter can lead to high ammonia levels in broiler houses. And the decrease in ammonia concentrations at high moisture levels has also been reported by Carr et al. (1990), Valentine (1964) and Schefferle (1965).

4.3 TAN contents in litter vs ammonia emissions

Before water was applied to the litter samples, the total nitrogen contents, TAN contents, moisture contents, and pH values of the five litter samples were analyzed as listed in Table 1, together with the average ammonia concentration measurements in the chambers for each litter samples. The ratios of TAN contents to total nitrogen content were in the range of 5.4% to 14.54% in the five litter samples. It was obvious that the measured ammonia concentrations were positively related with the TAN contents in litter. As shown in Fig. 5, higher TAN contents in litter tend to have higher ammonia concentrations.

4.4 Effect of litter moisture contents on TAN contents

Eight sub-samples of litter A were treated with water to achieve eight various moisture levels from 22.6 to 48.9%. Each of these sub-samples was analyzed for TN, TAN, etc.. The ratios of TAN contents to total nitrogen contents at the eight moisture levels for litter A were plotted in Fig. 6. It was indicated that, the TAN contents in litter were obviously influenced by the litter moisture contents. As more water was added to the litter samples, the TAN contents in litter increased. Therefore, water applied to litter can potentially increase ammonia emissions.

Table 1 Litter properties and ammonia emissions

Litter	Farm	Total nitrogen content in litter (μg/g)	NH_3–N content in litter (μg/g)	Litter moisture content (%)	pH	Average NH_3 concentration in chamber (ppm)
E (1-year)	1	25,020	1,980	19.8	8.48	95.8
A (2-year)	1	30,200	1,630	22.8	8.43	102.0
B (4-year)	1	42,000	6,108	23.2	8.00	449.9
C (8-flock)	2	43,000	4,070	15.9	7.73	290.6
D (12-flock)	2	46,100	4,280	16.1	7.34	144.5

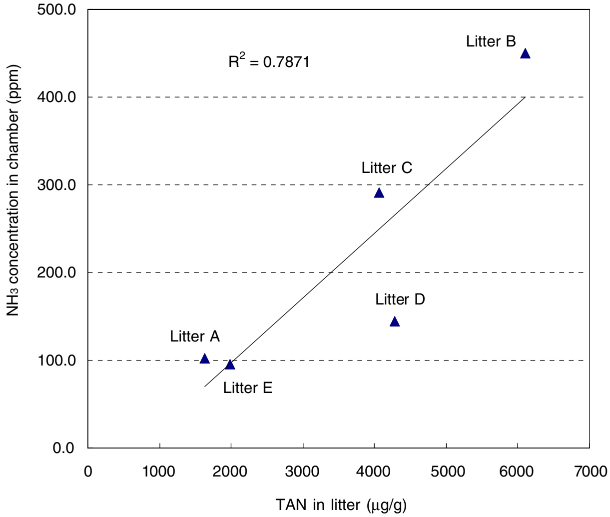


Fig. 5 Ammonia concentrations vs TAN contents in the litter samples

4.5 Nitrogen losses of litter samples

An alternative method to estimate ammonia emissions from litter is by measuring the nitrogen losses of litter samples. The eight sub-samples of litter A with various moisture levels from 22.6 to 48.9% were put into eight identical uncovered Petri dishes and were allowed to release ammonia for two weeks. After two weeks of ammonia volatilization, each of these sub-samples was analyzed for nitrogen content again. By comparing the litter nitrogen content before and after ammonia volatilization, the nitrogen losses of litter samples at eight moisture levels in these two weeks were obtained. The results are shown in Fig. 7. It was found that the litter sub-sample that was not treated with water (moisture content was 22.6%) had the highest nitrogen loss. And the litter sub-samples that were

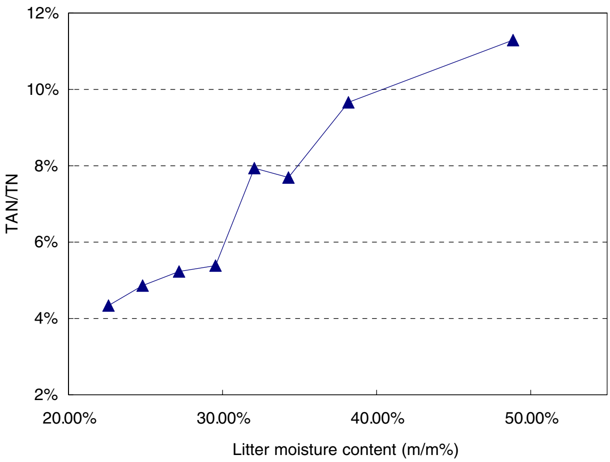
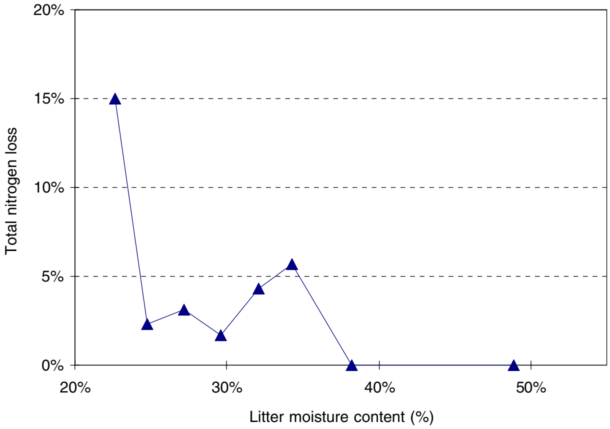


Fig. 6 TAN contents in litter vs litter moisture contents (litter A)

Fig. 7 Nitrogen losses of litter samples vs litter moisture contents (litter A)



treated with most amount of water (moisture content were 38.2 and 48.9%) had the least nitrogen losses. These results are consistent with what has been reported in previous sections, which indicated that water applied to the litter had an effect of suppressing ammonia emissions in a short time range. Although increased litter moisture contents resulted increased TAN contents in litter as was discussed in the previous section, it did not necessarily result in increased ammonia emissions in the time range of the experiments (within 2 weeks).

5 Conclusions

Ammonia emissions from broiler litter samples were tested at various litter moisture contents under laboratory-controlled conditions. It was observed that ammonia emissions were very sensitive to litter moisture content. Water applied to the litter may affect ammonia emissions through various processes in the litter, such as generation of ammonia in the litter as well as mass transfer of ammonia in the litter and from litter to air. It was found that time played an important role for the comprehensive effect of the added water. As water was added to the litter, the TAN contents in litter increased, and can potentially increase ammonia emissions. However, measurements of ammonia concentrations in the chamber and nitrogen loss of litter all suggested that water applied to the litter also had an effect of suppressing ammonia emissions in a short time range. After enough time (1 to 2 weeks) was allowed, higher moisture contents in litter eventually resulted in higher ammonia emissions. It was also noticed that at very high litter moisture contents, even when more time was allowed, ammonia concentrations began to decrease as moisture contents further increased.

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