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Effect of a New Manure Amendment on Ammonia Emissions from Poultry Litter

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Abstract: Treating manure with aluminum sulfate (alum) is a best management practice (BMP) which reduces ammonia (NH₃) emissions and phosphorus (P) runoff from poultry litter. However, the price of alum has increased markedly in recent years, creating a need for less expensive products to control NH₃ volatilization. The objective of this study was to evaluate the effects of a new litter amendment made from alum mud, bauxite, and sulfuric acid (alum mud litter amendment or AMLA) on NH₃ emissions, litter chemistry, and poultry production in a pen trial. Three separate flocks of 1000 broilers were used for this study. The first flock of birds was used to produce the poultry litter needed for the experiment. The second and third flocks of birds were allocated to 20 pens in a randomized block design with four replicates of five treatments: (1) control, (2) 49 kg AMLA/100 m² incorporated, (3) 98 kg AMLA/100 m² incorporated, (4) 98 kg AMLA/100 m² surface applied, and (5) 98 kg alum/100 m² incorporated. Ammonia flux measurements and litter samples were collected from each pen at day 0, 7, 14, 21, 28, 35, and 42. The average litter pH for both flocks was higher in untreated litter (7.92) compared to incorporating alum (7.32) or AMLA (7.18). The two flocks' average NH₄-N concentrations at day 42 were 38% and 30% higher for the high rates of incorporated alum and AMLA compared to the untreated litter. Compared with untreated litter, AMLA reduced overall NH₃ emissions by 27% to 52% which was not significantly different from reductions in emissions by alum (35%). Alum mud litter amendment reduced cumulative NH₃ losses from litter as much as, and in some cases more than, alum applied at the same rate. These data indicate that AMLA, which can be manufactured for lower price than alum, is an effective alternative litter amendment for reducing NH₃ emissions from poultry litter.

Keywords: alum; alum mud litter amendment (AMLA); poultry; litter; ammonia emissions

1. Introduction

Ammonia (NH₃) emissions originating from poultry litter account for 27% of the total atmospheric NH₃ emissions in the United States [1]. The United States produces approximately 12.6 tons of poultry litter every year, assuming 1.4 tons of litter is produced per 1,000 birds [2,3]. Moore et al. [4] estimated the total NH₃ loss from poultry production to be 46 g NH₃ per broiler. With more than nine billion broilers produced every year in the United States [5] approximately 414 million kg of NH₃ are being lost by volatilization every year from the poultry industry. Moore et al. [4] found that half of the N excreted by broilers is lost through NH₃ emissions from the manure before the litter is cleaned from the barns. Ammonia losses from broiler production in the United States are higher than in Europe because the litter is cleaned out and replaced with each flock of birds in Europe, while in the United

States the litter is only removed once a year, with some parts of the country cleaning out once every 3 to 5 years [6,7].

Ammonia emissions from poultry litter can have a negative impact on broiler production [8–10]. High levels of NH_3 in poultry houses have been shown to cause respiratory problems in broilers, as well as in poultry workers [11,12]. When NH_3 levels were elevated in poultry houses an increase in the number of broilers with airsacculitis was observed by Kling and Quarles [13]. Anderson et al. [14] found that exposure to elevated NH_3 concentrations also affects the broilers immune system, making them more susceptible to diseases. Increased levels of NH_3 has also caused poor feed conversion and weight gains, along with blindness from ocular damage [8–10]. Several environmental issues have been linked to NH_3 emissions as well, including eutrophication resulting from N depositions into aquatic systems [15,16] and soil acidification [17,18]. The formation of fine particulate matter (ammonium nitrate or ammonium sulfate) in the atmosphere occurs when NH_3 reacts with NO_x or SO_x compounds, leading to potential respiratory health problems in humans [19,20].

Due to the production, health, and environmental concerns associated with NH_3 several methods for the control of NH_3 in poultry production have been used including ventilation, dietary manipulation, manure management, and litter amendments. Increasing ventilation rates in poultry houses leads to substantial decreases in NH_3 concentrations within the house but translates directly to higher NH_3 emissions [21]. Ammonia scrubbers (bioscrubbers, biofilters, or chemical scrubbers) on the exhaust fans of poultry building can reduce the emission of NH_3 being vented into the atmosphere, but normally does not reduce NH_3 levels inside the facility [22,23]. Dietary strategies, such as lowering the amount of crude protein in broilers diets, or reducing manure pH, have also been observed to reduce NH_3 volatilization [24,25]. Proper management of litter after poultry production is also essential in reducing NH_3 volatilization. Once the litter is removed from the house it is typically stored for some period of time before being used as a fertilizer source. During storage covers made of various materials (metal, wood, plastic, straw, peat, etc.) can be used to create a barrier that retains N reducing NH_3 emission to the atmosphere [26]. Besides being used as fertilizer, another use for poultry litter waste is as an energy source since it is rich in volatile materials [27]. Recent research investigating the combustion process of poultry litter has found that combusting biomass waste (poultry litter) with fossil fuels (coal, natural gas etc.) known as co-combustion, can reduce emissions [2,28,29].

The method most commonly used in the United States to reduce NH_3 volatilization from poultry litter is addition of chemical amendments, such as alum, aluminum chloride, sodium bisulfate, and ferric sulfate or by-products containing Al, Ca, or Fe [30–36]. Treating poultry litter with alum was first done as a method to reduce soluble P in the litter and P runoff from fields fertilized with litter [37,38]. However, the greatest benefit of alum to the poultry industry is its ability to lower litter pH, converting NH_3 to the less volatile ammonium (NH_4^+) form, greatly reducing NH_3 emissions [30–32,39]. Lower NH_3 concentrations in poultry houses due to the alum applications have been shown to increase poultry performance, including higher broiler weight gains, better feed conversion, less diseases, and lower mortality rates; resulting in higher profits for poultry producers [40,41]. Another economic benefit of using alum to lower NH_3 emissions within poultry houses is the reduced amount of electricity and propane needed for ventilation in the winter months [32,39,42,43], which leads to lower carbon dioxide (CO_2) emissions. Shreve et al. [37] found that alum-treated litter increased forage yields by 28% compared to untreated litter and indicated that this increase was due to increased N availability. Laboratory studies by Moore et al. [30,31] showed that additions of alum to litter resulted in a much higher litter N content, suggesting litter treated with alum increases its value as a fertilizer source.

The production and environmental benefits of alum are the reason why over one billion broilers are being grown each year in the United States with alum additions [41]. In recent years, however, the price of alum has increased substantially. Two decades ago, Moore et al. [32] calculated the benefit/cost ratio of using alum application to be 1.96, making alum cost effect. At the time the cost of alum was around $\$220 \text{ Mg}^{-1}$. However, Moore [44] reported that the cost of alum had increased to at least

\$440 Mg⁻¹. The increased cost in alum has facilitated the need to find alternative litter amendments that are as effective in reducing NH₃ emissions as alum, but at a lower cost to farmers.

Alum mud litter amendment (AMLA) is a litter amendment made from alum mud, bauxite, and sulfuric acid [44] which was patented by Moore [45] in 2016. Alum mud is an acidic solid residue formed as a byproduct during the manufacture of alum [46]. Adak et al. [46] stated that “alum mud can be characterized as an acidic slurry of very fine particles of aluminum oxide, iron oxide, silica, titanium dioxide, etc., and/or mineralogy of different phases like biotite, mullite, quartz, hematite, and rutile”. Alum manufacturers in the United States pay around \$33 Mg⁻¹, plus transportation costs to landfill the alum mud byproduct [44]. Laboratory studies conducted by Moore [44,45], have shown that this new litter amendment was comparable to liquid or dry alum in reducing NH₃ volatilization. In these studies, Moore [44,45] found the most promising mixtures of alum mud, bauxite, and sulfuric acid reduced NH₃ losses by 62% to 73% compared to untreated litter, which was not significantly different from litter treated with alum.

The objective of this study was to evaluate the effects of AMLA on NH₃ emissions, litter chemistry, and poultry production in a poultry rearing environment. Pen trials are also needed to ascertain there are no negative effects on poultry production prior to testing in commercial broiler houses.

2. Materials and Methods

2.1. Design and Treatments

This study took place at the Poultry Farm at the University of Arkansas Agricultural Research Station in Fayetteville, Arkansas, using methods similar to those reported by Choi and Moore [47] in 2008. Three separate flocks of 500 male and 500 female Cobb × Cobb 1-d-old broiler chicks were obtained from a commercial hatchery. Each flock of chicks was randomly allocated to 20 pens (2.1 × 1.8 m, 50 birds per pen) in a single room where the atmosphere was mixed (Figure 1). The flocks were each raised for 42 d. An area of approximately 0.08 m² was allotted for each bird. Ventilation consisted of a single fan producing negative pressure in the house. Pens were equipped with one tube feeder and an automatic bell drinker. Chicks were fed starter diets from days 0 to 14, grower diets from days 14 to 35, and finisher diets from days 35 to 42. The first flock of birds was placed on 5 cm of clean wood shaving bedding (17.2 kg per pen). The purpose of the first flock of birds was to produce the poultry litter needed for the experiment. The second flock was placed one week after the removal of the first flock. Due to the longest government shutdown in U.S. history and the fear of another shutdown the third flock of birds was not placed until one year after the removal of the second flock. In between each flock the litter was tilled to break up any cake (hard layer of moist manure) that formed. Weekly feed intake, weight gains, and feed:gain were determined for each pen during the second and third flocks, as described in Borges et al. [25]. Feed intake was determined by taking the difference between feed supplied and leftover feed from each pen. Weight gain was calculated as the difference between initial weight and final weight for each pen. Both feed intake and weight gain were converted to a per bird basis by dividing the total pen value by the number of birds remaining in each pen after each week. Feed:gain was calculated as a ratio between feed intake and weight gain. Mortalities were recorded daily and were calculated by dividing the number of birds that died by the initial number of birds placed in each pen and multiplying by 100 [30]. The treatments were chosen for each of the 20 pens in a randomized block design with four replicates of five experimental treatments. The five treatments used in this study were: (1) control, (2) 49 kg AMLA/100 m² incorporated, (3) 98 kg AMLA/100 m² incorporated, (4) 98 kg AMLA/100 m² surface applied, and (5) 98 kg alum/100 m² incorporated. Litter amendments were added to the designated pens three days prior to the placing of the second and third flocks. For the surface applied treatment, amendments were evenly spread on the litter surface, whereas amendments were mixed into the top 2–3 cm of the litter for incorporated treatments.



Figure 1. Photograph showing one of the pens used in the study.

2.2. Flux Measurements and Litter Collection

Ammonia flux measurements and litter samples were collected from each pen at days 0, 7, 14, 21, 28, 35, and 42. Gas emissions from the litter were measured within each pen at three random locations using a plastic flux chamber attached to an Innova 1512 Photo-acoustic Multi-gas Analyzer (Innova AirTech Instruments, Ballerup, Denmark) according to the method of Miles et al. [48] (Figure 1). The flux chamber was a cylindrical plastic container with a radius of 14.5 cm and height of 35 cm, which was equipped with a battery-operated fan to stir the air. Ammonia, CO₂, methane (CH₄), and nitrous oxide (N₂O) were measured above the litter surface before placing the chamber (time zero) and at 60, 120, and 180 s as was done by Choi and Moore [47]. The difference between the concentrations at time zero and 60 s was used in conjunction with the ideal gas law to estimate NH₃ flux from the litter. Flux measurements were converted to an aerial basis (mg NH₃-N m⁻² hr⁻¹). Moore et al. [49] found that although NH₃ fluxes (mg NH₃ m⁻² hr⁻¹) measured using a small chamber were highly correlated to measured NH₃ emissions (mg NH₃ m⁻² hr⁻¹) in a study conducted in commercial broiler houses, flux measurements tended to be somewhat higher than the actual emissions. Moore et al. [49] speculated that the higher NH₃ values observed are caused by the disturbance of the litter surface when placing the flux chamber. Atmospheric NH₃ was not measured in this study since the air from the 20 pens was mixed. Litter samples were collected from the same three locations in the pen where fluxes were measured and mixed thoroughly in a plastic bucket. A small sub-sample of this litter was placed in a plastic bag and kept refrigerated until analyzed; the excess litter was returned to the pen.

2.3. Litter Analysis

Litter samples were analyzed for moisture content, pH, electrical conductivity (EC), soluble and total metals, NH₄-N, nitrate-N (NO₃-N), and total N (TN). Ammonium-N and NO₃-N are reported on an N basis, which allows for a better comparison of the different N forms. Moisture content of litter was determined by oven drying a subsample of litter at 65 °C for 1 week. Soluble metals and NO₃-N were determined using a 1:10 (litter:water) extraction ratio according to Self-Davis and Moore [50] using fresh litter. Ammonium was determined using a 1:10 (litter: 1N KCl) extraction ratio according to Choi and Moore [51] using fresh litter. Soluble metals in the water extract were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) on an Agilent 5110 ICP-OES (Agilent Technologies, Santa Clara, CA, USA). Both NH₄-N and NO₃-N were analyzed colorimetrically on a Skalar auto-analyzer (Skalar, Breda, The Netherlands); using the salicylate-nitroprusside USEPA Method 351.2 [52] for NH₄-N and the Cd-reduction method according to American Public Health Association

Method 418-F [53] for NO₃-N. A subsample of the 1:10 (litter:water) water extraction was used to measure pH and EC. Total metals were determined by digesting oven-dried, ground litter samples with nitric acid and hydrogen peroxide according to the method by Zarcinas et al. [54] followed by ICP-OES analysis. Total N was determined by dry combustion of fresh litter using an Elementar Vario Max Analyzer (Elementar Americas, Ronkonkoma, NY, USA).

2.4. Data Analysis

Analysis of variance (ANOVA) was performed to evaluate litter amendments effect on NH₃ flux and litter characteristics using the GLIMMIX procedure in SAS 9.4 [55,56]. A randomized block design was used for the experimental design with a one-factor factorially arranged treatment design. The five different treatment levels that were evaluated included: (1) a control, (2) 49 kg AMLA/100 m² incorporated, (3) 98 kg AMLA/100 m² incorporated, (4) 98 kg AMLA/100 m² surface applied, and (5) 98 kg alum/100 m² incorporated and were considered fixed effects. Blocks and replicates within pens were considered random effects. Mean separations were performed using Fisher's LSD test at the 0.05 probability level. Statistics for each flock were done separately.

3. Results and Discussion

3.1. Broiler Performance

The only significant difference observed in feed intake, weight gain, feed conversion (feed:gain), and mortality during this study was in feed intake for flock 2 (Table 1). For feed intake during flock 2, the high rate of alum and low rate of incorporated AMLA were significantly higher compared to the high rate of incorporated AMLA. The mortality tended to be greater for the alum and untreated control treatments during both flocks, however high variability between pens within the same treatments caused no significant differences to be observed.

Table 1. Effect of amendments on broiler performance during flock 2 and 3.

Treatment	Feed Intake (kg)	Weight Gain (kg)	Feed:Gain (kg:kg)	Mortality (%)
Flock 2				
Control	3.87ab [†]	2.12a	1.83a	7.00a
49 kg AMLA/100 m ² incorporated	3.98a	2.18a	1.83a	3.00a
98 kg AMLA/100 m ² incorporated	3.77b	2.08a	1.81a	5.50a
98 kg AMLA/100 m ² surface applied	3.86ab	2.15a	1.80a	4.00a
98 kg alum/100 m ² incorporated	3.95a	2.21a	1.79a	8.00a
Flock 3				
Control	4.14a	2.59a	1.62a	8.50a
49 kg AMLA/100 m ² incorporated	4.11a	2.53a	1.63a	5.50a
98 kg AMLA/100 m ² incorporated	3.97a	2.51a	1.58a	4.50a
98 kg AMLA/100 m ² surface applied	4.07a	2.53a	1.62a	5.00a
98 kg alum/100 m ² incorporated	4.00a	2.45a	1.64a	7.50a

[†] Values in columns followed by different letters indicate significant ($p < 0.05$) differences in means within each flock.

Similar to the finding in the study conducted by Choi and Moore [47] the problem with having all of the treatments in the same building is the atmospheres of the various pens were mixed; therefore, the effect of atmospheric NH_3 concentration on broiler performance was not observed. Studies by Moore et al. [44] and McWard and Taylor [40] reported that broiler performance (weight gain and feed conversion) was significantly better when grown on alum-treated litter. Although the amendments did not improve broiler performance in this study, they did not have any negative impacts either.

3.2. Litter Properties

Litter properties such as moisture and pH have been recognized as major factors affecting NH_3 volatilization from litter [57,58]. Litter moisture data for flock 2 and 3 are shown below in Figure 2a,b, respectively. There were no treatment effects on the moisture content of litter for either flock. The average litter moisture over the 42 days for both flock 2 and 3 were similar (36 and 34%, respectively). However, while the litter moisture increased by 21% during flock 2, it increased by 206% during flock 3. The moisture content at the beginning of flock 3 was very low (16%) compared to flock 2 (36%) due to increased time between the flocks, which would inhibit NH_3 volatilization. Flock 2 birds were placed one week after flock 1, while flock 3 birds were placed on 1-yr-old litter, which had dried out over time. During flock 3 the very moist conditions towards the end of the flock led to the formation of a thick layer of cake, which likely lowered NH_3 emissions, but also increased the variability in emissions.

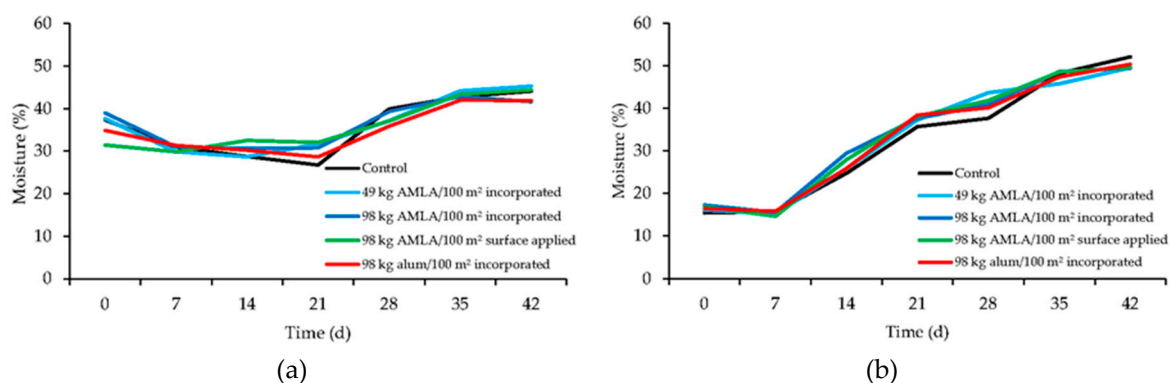


Figure 2. Litter moistures for (a) flock 2 and (b) flock 3 as a function of time.

Alum mud litter amendment and alum additions reduced the pH of the litter as expected (Table 2). During flock 2 the average pH was lower when incorporating the high rate of alum (7.58) and AMLA (7.45) compared to the untreated litter (7.99). Likewise, during flock 3, the average pH for the high rate of incorporated alum (7.06) and AMLA (6.91) was also lower than untreated litter (7.85). In fact, the pH of the treated litter was lower compared to the untreated litter for 5 of the 7 weeks during flock 2 and for all 7 weeks during flock 3. In general, the treatments lowered the pH of flock 3 more than flock 2 (Table 2). Choi and Moore [47] found that dry alum reduced the pH of litter by 0.86 units compared to the untreated litter, which is slightly lower than the change observed for day 0 to day 42 during flock 3 of this study (0.96 units), but higher than the average change between the 2 flocks (0.53 units). The lower pH in the treated litter shifts the NH_3/NH_4 equilibrium towards the less volatile NH_4 -N form. However, with time, as the birds produced more manure, the pH of the treated litter increased. The average pH for the two flocks increased from day 0 to day 42 by 1.07 and 1.02 units for both incorporated and surface applied AMLA, respectively, and by 0.53 units for incorporated alum. Moore et al. [33] found that when litter pH exceeds 7, the NH_3 volatilization rate increases rapidly. This study showed similar results, with NH_3 -N flux ($\text{mg NH}_3\text{-N m}^{-2} \text{hr}^{-1}$) rapidly increasing once litter pH increased above 7 (Figure 3). The volatilization of NH_3 has been shown to be very dependent on litter pH, with NH_3 volatilization increasing as pH increases [57].

Table 2. Litter pH for flock 2 and 3 by treatment by day.

Treatment	Day							Avg.
	0	7	14	21	28	35	42	
Flock 2								
Control	8.30a †	8.21a	7.72a	7.99a	7.76a	7.92a	8.06a	7.99a
49 kg AMLA/100 m ² incorporated	7.76ab	7.92ab	7.46a	7.57b	7.62b	7.81ab	7.91a	7.72b
98 kg AMLA/100 m ² incorporated	6.83c	7.52c	7.53a	7.38b	7.42c	7.68b	7.80a	7.45c
98 kg AMLA/100 m ² surface applied	7.41bc	7.72bc	7.52a	7.45b	7.48c	7.75b	7.77a	7.58bc
98 kg alum/100 m ² incorporated	7.76ab	7.66bc	7.22a	7.50b	7.45c	7.66b	7.83a	7.58bc
Flock 3								
Control	8.19a	8.08a	7.78a	7.83a	7.67a	7.77a	7.62a	7.85a
49 kg AMLA/100 m ² incorporated	6.87b	6.93b	7.11b	7.34b	7.45b	7.62ab	7.45ab	7.25b
98 kg AMLA/100 m ² incorporated	6.09cd	6.54b	6.73cd	7.07c	7.34bc	7.36c	7.26b	6.91cd
98 kg AMLA/100 m ² surface applied	5.63d	6.49b	6.53d	7.03c	7.17d	7.33c	7.31b	6.78d
98 kg alum/100 m ² incorporated	6.41bc	6.98b	6.81c	7.14c	7.22cd	7.51bc	7.37b	7.06bc

† Values in columns followed by different letters indicate significant ($p < 0.05$) differences in means within each flock.

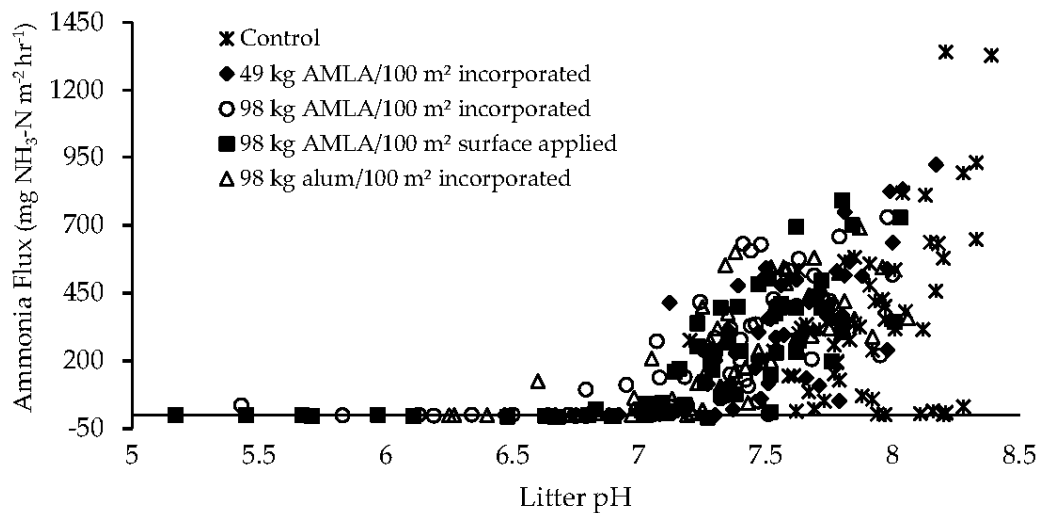


Figure 3. Ammonia flux ($\text{mg NH}_3\text{-N m}^{-2} \text{hr}^{-1}$) as a function of litter pH.

Electrical conductivity ranged from 5.46 to 8.97 mS cm^{-1} during flock 2 and from 6.84 to 11.63 mS cm^{-1} during flock 3 (data not shown). Average EC in litter for both flock 2 and flock 3 was greater when incorporating high rates of alum and AMLA as well as when surface applying AMLA compared to untreated litter. The higher EC in the treated litter is associated with sulfate salts such as, ammonium sulfate, calcium sulfate, and potassium sulfate which are added from alum and AMLA [33,51].

Litter $\text{NH}_4\text{-N}$ concentrations as a function of time are shown in Table 3 for flocks 2 and 3. As expected a buildup of $\text{NH}_4\text{-N}$ in litter occurred over time with all treatments for both flocks, as the amount of manure produced by the birds increased. During both flocks the untreated litter had lower $\text{NH}_4\text{-N}$ concentrations for all 7 weeks compared to litter with high rates of alum and AMLA additions. The highest $\text{NH}_4\text{-N}$ concentrations were typically observed in the high rates of incorporated alum and AMLA for both flocks. At day 42, the $\text{NH}_4\text{-N}$ concentrations for flock 2 were 37.5% and 25.2% higher for litter incorporated with high rates of alum and AMLA, respectively, compared to untreated litter. During flock 3 the $\text{NH}_4\text{-N}$ concentrations found with high rates of incorporated alum and AMLA

were significantly higher (38.4% and 33.9%, respectively) at day 42 compared to untreated litter. The differences observed in $\text{NH}_4\text{-N}$ concentrations between the alum and AMLA treated litter and the untreated litter are due to a reduction in NH_3 emissions from the alum and AMLA (see ammonia flux). The effects of alum treatments on $\text{NH}_4\text{-N}$ are consistent with those observed by Choi and Moore [47] and Moore et al. [30,32]. These studies showed that the higher rates of alum resulted in a significant increase in $\text{NH}_4\text{-N}$ concentrations within the litter. In a laboratory study conducted by Moore [44], litter amended with mixtures of alum mud, bauxite, and sulfuric acid resulted in approximately 45% increase in $\text{NH}_4\text{-N}$ concentrations of the litter compared to the untreated control. These results are higher than the change in $\text{NH}_4\text{-N}$ for AMLA treatments observed in this study, however, the study by Moore [44] was done in a controlled laboratory.

Table 3. Litter ammonium ($\text{g NH}_4\text{-N kg}^{-1}$) for flock 2 and 3 by treatment by day.

Treatment	Day							Avg.
	0	7	14	21	28	35	42	
Flock 2								
Control	2.79b [†]	2.29c	2.14d	2.17c	2.24c	3.73d	4.64b	2.86c
49 kg AMLA/100 m ² incorporated	4.51a	3.87b	3.78c	3.42b	3.47b	4.76c	5.93a	4.25b
98 kg AMLA/100 m ² incorporated	5.45a	6.72a	6.27a	5.11a	4.38a	5.18bc	5.81a	5.56a
98 kg AMLA/100 m ² surface applied	5.21a	5.79a	4.73b	4.70a	4.15a	5.34ab	6.46a	5.20a
98 kg alum/100 m ² incorporated	4.99a	5.73a	5.46ab	4.94a	4.37a	5.64a	6.38a	5.36a
Flock 3								
Control	1.30c	1.14d	1.55c	2.52c	3.27c	4.52b	6.67b	2.99b
49 kg AMLA/100 m ² incorporated	2.76b	2.86c	2.83b	3.66b	4.42b	5.10b	8.44a	4.29a
98 kg AMLA/100 m ² incorporated	3.90a	3.90a	3.60a	4.44a	5.42a	6.91a	8.93a	5.30a
98 kg AMLA/100 m ² surface applied	3.80a	3.68ab	3.42a	4.04ab	5.07a	6.49a	8.93a	5.06a
98 kg alum/100 m ² incorporated	3.83a	3.50b	3.34a	3.93ab	5.12a	6.66a	9.23a	5.09a

[†] Values in columns followed by different letters indicate significant ($p < 0.05$) differences in means within each flock.

Alum mud litter amendment and alum additions to the litter also resulted in higher TN litter concentrations for both flocks (Table 4). The TN concentrations were significantly different at days 0, 7, and 14 during flock 2 and days 14, 21, 28, and 35 during flock 3. Total N in litter tended to increase over time for both flocks and was on average higher for litter incorporated with alum (23.0 g kg^{-1}) and AMLA (21.8 g kg^{-1}) compared to untreated litter (19.9 g kg^{-1}). As N is typically the limiting nutrient for most crops the higher concentrations of $\text{NH}_4\text{-N}$ and TN observed in the alum and AMLA treated litter would be expected to increase yields [33]. A long-term alum study conducted by Moore and Edwards [59] reported a 6% increase in tall fescue yields when alum-treated litter was applied to plots compared to plots with applications of untreated litter, suggesting greater N availability in litter treated with alum.

3.3. Ammonia Flux

The highest NH_3 flux measured in this study (1052 $\text{mg NH}_3\text{-N m}^{-2} \text{ hr}^{-1}$) was measured in the control treatment at day 0 of flock 2 (Table 5), which was likely due to the buildup of $\text{NH}_4\text{-N}$ from flock 1. One of the most important times to have low NH_3 concentrations in poultry rearing facilities is at the beginning of a flock, since 1-d-old chicks, which are very susceptible to high NH_3 levels are placed in the chicken houses [30]. Alum mud litter amendments and alum during day 0 reduced NH_3 emissions by 51–82% for flock 2, with the high rate alum by 71% and AMLA by 82%. At day 7, the high rate of incorporated AMLA (370 $\text{mg NH}_3\text{-N m}^{-2} \text{ hr}^{-1}$) was statistically lower than the untreated

litter (694 mg NH₃-N m⁻² hr⁻¹), whereas alum was not. There were no statistical differences between treatments observed in NH₃ emission for the remaining five weeks (days 14 to 42) in flock 2. The overall cumulative emissions (Figure 4a) were significantly lower compared to untreated litter (574 g NH₃-N m⁻²) for the high rate of incorporated and surface applied AMLA (370 and 380 g NH₃-N m⁻², respectively). These were not significantly different from incorporated alum (403 g NH₃-N m⁻²). This represents a 36%, 34%, and 30% reduction in NH₃ volatilization for high rates of incorporated AMLA, surface applied AMLA, and incorporated alum, respectively, during flock 2. The higher litter moisture at the start of this flock may potentially have caused rapid dissolution of alum and AMLA. This could cause the acidity from the amendments to be neutralized relatively early on in the flock.

Table 4. Litter total N (g TN kg⁻¹) for flock 2 and 3 by treatment by day.

Treatment	Day							Avg.
	0	7	14	21	28	35	42	
Flock 2								
Control	13.3c †	15.4b	18.4c	18.2a	19.6a	19.2a	21.3a	17.9b
49 kg AMLA/100 m ² incorporated	17.7ab	19.4a	21.3ab	21.0a	20.5a	20.5a	22.1a	20.3a
98 kg AMLA/100 m ² incorporated	16.4b	19.4a	22.2a	21.3a	20.7a	20.9a	22.5a	20.5a
98 kg AMLA/100 m ² surface applied	18.8a	19.8a	19.4bc	20.0a	21.9a	21.0a	22.5a	20.5a
98 kg alum/100 m ² incorporated	17.2ab	21.1a	21.9a	22.2a	22.6a	22.3a	23.2a	21.5a
Flock 3								
Control	22.1a	22.3a	22.3b	19.7b	20.7d	20.3b	24.8a	21.8c
49 kg AMLA/100 m ² incorporated	22.7a	22.1a	24.0b	21.2ab	21.9bc	22.4ab	25.6a	22.9b
98 kg AMLA/100 m ² incorporated	22.8a	21.7a	22.7ab	23.0a	23.0b	22.9a	25.4a	23.1b
98 kg AMLA/100 m ² surface applied	20.8a	23.4a	23.7ab	23.2a	23.2c	23.7a	25.1a	23.3b
98 kg alum/100 m ² incorporated	21.8a	25.1a	25.0a	23.7a	24.5a	24.2a	26.3a	24.4a

† Values in columns followed by different letters indicate significant ($p < 0.05$) differences in means within each flock.

Table 5. Average ammonia flux (mg NH₃-N m⁻² hr⁻¹) for flock 2 and 3 by treatment by day.

Treatment	Day							Avg.
	0	7	14	21	28	35	42	
Flock 2								
Control	1052a †	694a	277a	363a	435a	502a	668a	570a
49 kg AMLA/100 m ² incorporated	513b	623a	354a	299a	464a	484a	573a	473b
98 kg AMLA/100 m ² incorporated	189c	370b	321a	328a	521a	394a	559a	383c
98 kg AMLA/100 m ² surface applied	220c	578ab	218a	282a	446a	452a	469a	381c
98 kg alum/100 m ² incorporated	310bc	472ab	246a	324a	521a	450a	516a	406bc
Flock 3								
Control	15.7a	3.68a	41.9a	202a	286a	187a	200a	134a
49 kg AMLA/100 m ² incorporated	0.13b	1.27b	7.60b	107b	258a	84.7a	225a	97.9ab
98 kg AMLA/100 m ² incorporated	-0.64b	1.71b	-2.35b	23.0c	208a	76.1a	205a	73.2b
98 kg AMLA/100 m ² surface applied	-1.09b	-0.23b	-2.84b	27.2c	136a	43.0a	183a	55.2b
98 kg alum/100 m ² incorporated	0.22b	1.30b	2.67b	37.5c	213a	164 a	236a	93.8ab

† Values in columns followed by different letters indicate significant ($p < 0.05$) differences in means within each flock.

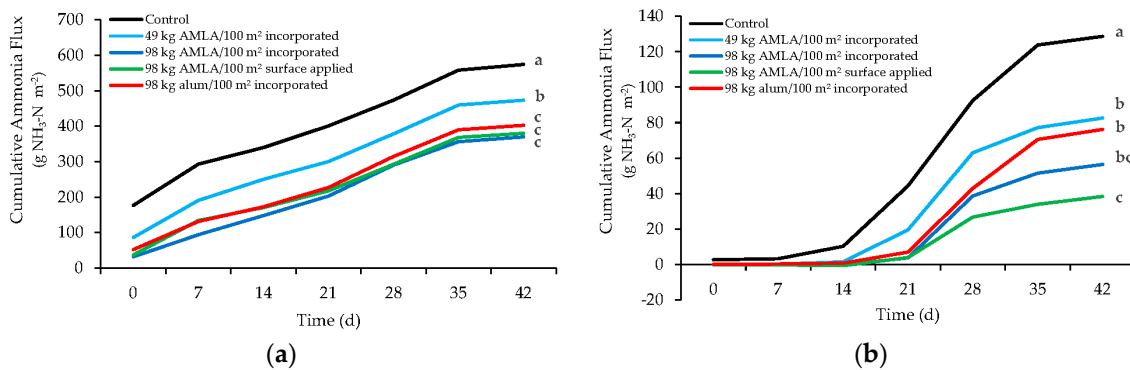


Figure 4. Cumulative ammonia flux ($\text{mg NH}_3\text{-N m}^{-2}$) for (a) flock 2 and (b) flock 3 as a function of time. Treatments on day 42 not sharing a common letter are significantly different ($p < 0.05$).

At the start of flock 3 the majority of the $\text{NH}_3\text{-N}$ present at the end of flock 2 had volatilized from the litter, which was not surprising, since almost one year elapsed between these flocks (Table 5). Additions of alum and AMLA amendments significantly reduced NH_3 fluxes from the litter for the first three weeks (days 0 to 21) of flock 3, which was probably due to lower litter pH and drier litter. In fact, negative NH_3 fluxes were observed for the alum and AMLA treated litter during the first three weeks. On day zero the high rate of incorporated AMLA and alum reduced NH_3 emissions by 99 and 104%, respectively, compared to untreated litter. By day 21 the high rate of incorporated alum and AMLA reduced NH_3 emissions by 81% and 89%, respectively. On days 28 and 35 the NH_3 emissions from alum and AMLA were not significantly lower than the controls. This may have been due to the tremendous variability within the pens, which was caused by thick cake formed under the moist litter conditions. Cumulative NH_3 emissions from the high rates of incorporated alum ($76 \text{ g NH}_3\text{-N m}^{-2}$) and AMLA ($57 \text{ g NH}_3\text{-N m}^{-2}$) were reduced by 41% and 56%, respectively, compared to untreated litter ($129 \text{ g NH}_3\text{-N m}^{-2}$) (Figure 4b). During this flock (flock 3) the high rate of surface applied AMLA, had the greatest effect on NH_3 emissions, significantly reducing them by 70%.

The overall NH_3 reduction from the additions of alum from both flock 2 (30%) and flock 3 (41%) of this study was less than that found in laboratory studies conducted by Choi and Moore [51] and Moore [31]. In those studies, the additions of dry alum reduced NH_3 losses by 77% [51] and 86% [44]. It is important to note that the presence of broiler chickens, which are continually adding water and manure, does not occur with laboratory studies. In an on-farm comparison of alum, Moore et al. [33] reported additions of alum to litter significantly reduced the flux of NH_3 from litter by 99% during the first four weeks. Those results were similar to the results observed during flock 2 of this study where alum-treated litter reduced NH_3 emissions by 81% in the first three weeks.

This was the first pen trial evaluating the effects of AMLA on NH_3 emissions. In the laboratory study Moore [44] found mixtures of alum mud, bauxite, and sulfuric acid dramatically decreased NH_3 volatilization from litter. These results were not significantly different from litter treated with alum. The results from this pen trial also showed no significant difference between AMLA and alum. The data from this study indicates that AMLA, which can be manufactured for a much lower price than alum, is an effective litter amendment for reducing NH_3 emissions from poultry litter.

4. Conclusions

Litter characteristics (pH, EC, $\text{NH}_4\text{-N}$, and TN) for both the high rates of incorporated alum and AMLA were very similar in this study. The average litter pH for both flocks was higher in untreated (control) litter (7.92) compared to incorporating alum (7.32) and AMLA (7.18). The two flocks' average $\text{NH}_4\text{-N}$ concentrations at day 42 were 38% and 30% higher for high rates of incorporated alum and AMLA, respectively, compared to untreated litter. The higher N content of treated litter observed in this study suggests that poultry litter treated with alum and AMLA may have higher value as a fertilizer source.

Alum mud litter amendment reduced NH₃ emissions equivalent to, and in some cases greater than, alum. Average NH₃ emissions over two flocks were reduced 35% when incorporating alum and 46% when incorporating AMLA. Hence, alum mud litter amendment can be considered a cheaper and effective alternative for alum for reducing NH₃ emissions in a poultry rearing environment. Future research evaluating the effects of this new litter amendment on broiler production and NH₃ emissions in commercial houses is planned.

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