Effects of Liquid Aluminum Chloride Additions to Poultry Litter on Broiler Performance, Ammonia Emissions, Soluble Phosphorus, Total Volatile Fatty Acids, and Nitrogen Contents of Litter[1]

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ABSTRACT Recent studies have shown that the use of aluminum sulfate [alum, $Al_2(SO_4)_3 \cdot 14H_2O$] and aluminum chloride ($AlCl_3$) additions to animal manures are more effective than other chemicals in reducing ammonia (NH_3) emissions and P solubility. Although the use of $Al_2(SO_4)_3 \cdot 14H_2O$ has been intensively used in the poultry industry for many years, no research has been conducted to evaluate the effect of liquid $AlCl_3$ on these parameters. The objectives of this study were to determine the effects of applying liquid $AlCl_3$ to poultry litter on 1) broiler performance, 2) NH_3 fluxes, and 3) litter chemical characteristics, including soluble reactive P, total volatile fatty acids, and N content. Eight hundred broiler chicks were placed into 16 floor pens (50 birds/pen) in a single house for 6 wk. Liquid $AlCl_3$ treatments were sprayed on the litter surface at rates of 100, 200, and 300 g of liquid $AlCl_3$/kg of litter; untreated litter served as controls. At the 2 lower rates, liquid $AlCl_3$ treatments tended to improve weight gain and feed intake but had no effect on feed conversion or mortality, whereas the higher rate (300 g/kg of litter) had a negative effect on intake. Application of 100, 200, and 300 g of liquid $AlCl_3$ reduced NH_3 fluxes by 63, 76, and 76% during the 6-wk period, respectively, compared with the controls. Liquid $AlCl_3$ additions reduced litter soluble reactive P contents by 24, 30, and 36%, respectively, at the low, medium, and high rates. Total volatile fatty acid contents (odor precursors) in litter were reduced by 20, 50, and 51%, respectively, with 100, 200, and 300 g of liquid $AlCl_3$/kg of litter. Liquid $AlCl_3$ additions increased total N, inorganic N, and plant available N contents in litter. These results indicate that liquid $AlCl_3$ additions at the lower rates can provide significant positive environmental benefits to broiler operations.

Key words: litter, broiler performance, ammonia emission, soluble reactive phosphorus, total volatile fatty acid

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INTRODUCTION

Environmental regulations regarding the application of manure produced by the poultry industry are a challenge currently being faced by many countries. Poultry litter has a high potential for NH_3 volatilization because the N concentrations in litter are typically higher than in the manure of other animals (Kithome et al., 1999). As a result, levels of NH_3 often exceed 25 mL/m^3 (ppm) in poultry houses, which can reduce poultry performance (Reece et al., 1980; Carlile, 1984; Miles et al., 2004). Emissions from rearing facilities also affect atmospheric N loading. Battye et al. (1994) calculated that approximately 80% of NH_3 in the United States comes from agriculture sources. Other studies reported that 55% of all NH_3 emissions in the Netherlands were from livestock production (ANMF, 1995).

Nonpoint source P runoff from poultry litter can cause surface water contamination which accelerates the natural aging process (eutrophication) of lakes and rivers. According to Edwards and Daniel (1993), the majority of the P in runoff from pastures receiving poultry litter is dissolved inorganic P (80 to 90%), which is most readily available for algal uptake (Sonzogni et al., 1982). Dou et al. (2002) showed that the potential for P loss on animal farms was closely related not only to the amount of P excreted in manure and applied to fields but also to the solubility of the P in water. Sharpley and Moyer (2000) reported that P leaching losses were highly correlated with the concentration of water extractable P in the manures.

One of the greatest concerns with respect to manure management is odor. Typically odors are produced by

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anaerobic decomposition of livestock wastes (Mackie et al., 1998). However, most of the organic matter in manure is microbially transformed into nonodorous end products under aerobic conditions (Westermann and Zhang, 1997). Factors that determine odor production from livestock facilities include manure, spilled feed, bedding materials, and wash water (Jacobson et al., 2001). The most significant odorous compounds in manures are volatile fatty acids (**VFA**; C2 to C9 volatile organic acids) and aromatic compounds (Williams, 1984; Chen et al., 1994; Zahn et al., 1997). Zahn et al. (1997, 2001) found that odor was closely correlated to the concentrations of airborne VFA and volatile aromatic compounds. Kreis (1978) developed one of the earliest lists of volatile compounds associated with odors from livestock and poultry wastes and indicated that poultry, cattle and swine manure consisted of 17, 32, and 50 different compounds, respectively.

In recent years, several studies to determine the relationship between NH_3 and odor have been reported. Jacobson et al. (2002) found that by covering manure storage units odors were reduced by 28 to 72%, whereas NH_3 emissions were reduced from 75 to 100%. Liu et al. (1993) reported that NH_3 emissions are not a good indicator of the odor threshold from manure.

Another important aspect of poultry manure and litter is the amount N available for crop production following land application. Although there are several methods of calculating N availability in litter, no completely satisfactory procedure for measuring the available N content of the poultry litter has been developed. Various measures of N availability include: inorganic N (Bitzer and Sims, 1988) = ammonium + nitrate; organic N (Bitzer and Sims, 1988) = TN (total N) – IN (inorganic N); available N (Knezek and Miller, 1976) = inorganic N + 0.4 × organic N; and predicted available N (Bitzer and Sims, 1988) = 0.8 × inorganic N + 0.6 × organic N.

Due to the environmental problems associated with manure cited above, it has become increasingly necessary to focus on new ways to utilize this valuable resource. One way to reduce the impact of these problems is through the use of chemical amendments to manure (Moore et al., 1995, 1996; Dao et al., 2001; Smith et al., 2001a,b). Moore and Miller (1994) first reported that chemical amendments could be added to poultry litter to reduce P solubility. Later work by Moore et al. (1995, 1996, 1999, 2000) showed the addition of alum to litter resulted in several benefits, including reduced NH_3 emissions and P in runoff, improved poultry performance, and was a cost-effective practice. Smith et al. (2001a) reported that both alum and $AlCl_3$ reduced NH_3 and soluble P levels in swine manure. However, the problem with adding alum to liquid manure, like swine manure, is that H_2S gas can form under anaerobic conditions (Smith et al., 2001a). Due to the potential production of H_2S, Smith et al. (2001a) suggested that $AlCl_3$ would be a better additive for swine manure because it does not contain sulfate. However, no studies have yet reported the effects of solid and liquid aluminum chloride additions to poultry litter on broiler performance, NH_3 volatilization, soluble reactive P, and odor. The objectives of this study were to determine the effects of spraying liquid $AlCl_3$ to poultry litter on 1) broiler performance, 2) NH_3 emissions, and 3) litter chemical characteristics, including soluble reactive P (**SRP**), total VFA, and N content.

MATERIALS AND METHODS

Birds and Management

A total of eight hundred 1-d-old broiler chicks (50/50 male/female, Cobb × Cobb) obtained from a commercial hatchery were randomly assigned to 16 pens under simulated commercial conditions at the University of Arkansas Poultry Science Farm. Chicks were vaccinated for Marek's disease, Newcastle disease, and infectious bronchitis at the hatchery. The experimental facility (single house) was solid-sided and had automatically controlled light and temperature. Ventilation (0.85 m^3/h per bird) consisted of a single fan producing negative pressure in the house. Each pen (2.1 × 1.8 m) was equipped with an automatic bell drinker and one tube feeder. Each bird had an area of approximately 0.09 m^2. Two flocks of birds were grown; the first simply developed the litter base. Approximately 8 cm of bedding (rice hulls and wood savings) was added to each pen. After the first flock, the litter was tilled and treated with liquid $AlCl_3$ treatments. Standard industry diets were utilized throughout the study, including starter (0 to 14 d), grower (14 to 28 d), and finisher diets (28 to 42 d). Water and commercial mash diets were available ad libitum throughout the experiment. Weekly feed intake, weight gain, and feed:gain were determined as described in Borges et al. (2003) below. Feed intake was calculated by the difference between supplied feed and feed left in each pen. Weight gain was determined as the difference between initial and 21 d, 21 and 42 d, and initial and 42 d of age, respectively. Feed:gain was calculated from the ratio between total feed intake and weight gain in the period for each pen. Mortalities were recorded daily, and body weights were recorded. Mortality percentages were calculated by dividing the number of birds that died in the period by the initial number of birds placed and multiplying by 100 (Borges et al., 2003). The experiment was carried out for 42 d.

Treatments

The trial design was a randomized block design with 4 treatments and 4 replication pens per treatment with 50 birds per experimental unit. Liquid $AlCl_3$ was applied by spraying onto the litter surface using a small hand pump. The rates were as follows: 1) control (normal litter), 2) T1 (100 g of liquid $AlCl_3$/kg of litter), 3) T2 (200 g of liquid $AlCl_3$/kg of litter), and 4) T3 (300 g of liquid $AlCl_3$/kg of litter).

Table 1. Effect of liquid aluminum chloride amendments on broiler performance

Treatment	Feed intake, g			Weight gain, g			Feed:gain, g:g			Mortality,[1] %		
	d 0 to 21	d 21 to 42	d 0 to 42	d 0 to 21	d 21 to 42	d 0 to 42	d 0 to 21	d 21 to 42	d 0 to 42	d 0 to 21	d 21 to 42	d 0 to 42
Control	1,105.2[ab]	2,847.7[ab]	3,952.9[a]	793.1[a]	1,524.2[ab]	2,317.3[ab]	1.39	1.87	1.71	1.51	2.02	3.53
T1[2]	1,098.6[ab]	2,840.1[ab]	3,938.7[a]	790.9[a]	1,554.5[a]	2,345.4[a]	1.39	1.83	1.68	0.50	3.02	3.52
T2[3]	1,113.3[a]	2,888.0[a]	4,001.3[a]	800.3[a]	1,571.8[a]	2,372.1[a]	1.39	1.84	1.69	2.00	2.07	4.07
T3[4]	1,070.6[b]	2,736.7[b]	3,807.3[b]	769.8[b]	1,491.6[b]	2,261.4[b]	1.39	1.83	1.68	1.00	3.04	4.04

[a,b]Means within a column with no common superscript differ significantly at $P < 0.05$ (Duncan's multiple range test).

[1]Mortality percentage was calculated by dividing the number of birds that died in the period by the initial number of birds in the room and multiplying by 100 (Borges et al., 2003).

[2]T1: 100 g of liquid $AlCl_3$/kg of litter.

[3]T2: 200 g of liquid $AlCl_3$/kg of litter.

[4]T3: 300 g of liquid $AlCl_3$/kg of litter.

Litter Sampling and Gas Measurements

A litter sample was collected weekly at 5 random locations from each pen. The random litter samples were thoroughly mixed, and 100 g was weighed into a plastic bag and refrigerated until the samples were analyzed. Ammonia fluxes from the litter were measured weekly within each pen at 4 random locations according to the method of Miles et al. (2006). Plastic flux chambers (21 L) that were equipped with a battery-operated fan to stir the air were attached to a photoacoustic multi-gas analyzer (Innova model 1412, Innova AirTech Instruments, Ballerup, Denmark). Ammonia concentrations were measured above the litter surface immediately before placing the chamber, then again inside the chamber after 60 s.

Chemical Analysis

The litter was analyzed for pH, ammonium (NH_4), SRP, and total VFA. A 20-g subsample of the litter was extracted with 200 mL of deionized water for 2 h on a mechanical shaker, then centrifuged at 3,687 × *g* for 15 min (Self-Davis and Moore, 2000; DeLaune et al., 2004). Aliquots were taken for pH, NH_4, NO_3, SRP, and total VFA. Unfiltered samples were used for pH and were analyzed immediately. Samples for ammonium and nitrate were filtered through a 0.45-µm filter and frozen (Moore et al., 1995). Ammonium was determined using salicylate-nitroprusside technique with auto-analyzer (Technicon Instrumental Systems, Tarrytown, NY) using USEPA method 351.2 (USEPA, 1979). Nitrate was analyzed using the Cd-reduction method, according to APHA method 418-F (APHA, 1992). Nitrate values were very low; hence, nitrate was not reported (Moore et al., 1995, 2000). Soluble reactive P samples were filtered through a 0.45-µm membrane filter, acidified to a pH of 2.0 with HCl, and frozen until analyzed (Moore et al., 1995). Soluble reactive P was determined using the ascorbic acid technique with an auto-analyzer (Technicon Instrumental Systems, Tarrytown, NY) according to the American Public Health Association method 424-G (APHA, 1992). Samples for total VFA were not filtered but were stored at −20°C until analyzed (Kim, 2003). Total VFA were measured using heat distillation method as described by Fenner and Elliot (1963) and Kim (2003). Following the water extraction, exchangeable NH_4 in the litter was determined by extraction with 1 *N* KCl for 2 h. After centrifuging, these samples were filtered and analyzed for NH_4 as above (Moore et al., 1995). Subsamples of litter were also analyzed for total N using an elemental analyzer (Vario Max CN, Hanau, Germany). The other N contents in litter were calculated by the following simplified equations: IN (inorganic nitrogen) = NH_4-N + NO_3-N; ON (organic nitrogen) = TN (total nitrogen) – IN (inorganic nitrogen); AN (available nitrogen) = IN (inorganic nitrogen) + 0.4 × ON (organic nitrogen); PAN (predicted available nitrogen) = 0.8 × IN (inorganic nitrogen) + 0.6 × ON (organic nitrogen).

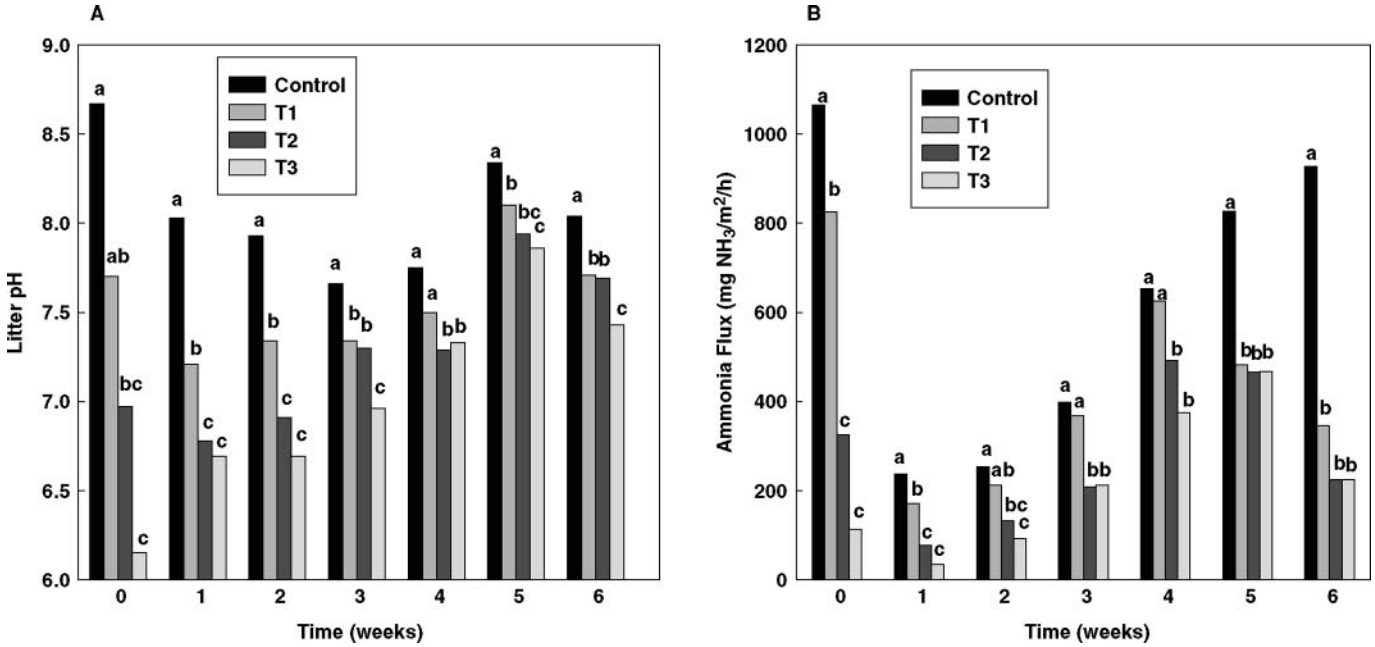

Figure 1. Effect of liquid aluminum chloride amendments to poultry litter on (A) litter pH and (B) ammonia flux. [a–c]Bars with same letters are not significantly different at $P < 0.05$. Treatment means T1 = 100 g of liquid $AlCl_3$/kg of litter; T2 = 200 g of liquid $AlCl_3$/kg of litter; T3 = 300 g of liquid $AlCl_3$/kg of litter.

Statistical Analysis

Statistical analyses of the data were performed as a randomized block design using the PROC GLM of SAS Institute (1990). Significant differences among treatment means were determined using Duncan's new multiple-range test (Duncan, 1955) at the $P < 0.05$ level.

RESULTS AND DISCUSSION

Broiler Performance

With the exception of the highest rate of liquid $AlCl_3$ (T3 = 300 g of liquid $AlCl_3$/kg of litter), there were no significant differences among control, T1 (100 g of liquid $AlCl_3$/kg of litter), and T2 (200 g of liquid $AlCl_3$/kg of litter) in feed intake and weight gain at any age (Table 1). However, feed intake and weight gain tended to be greater in the low liquid $AlCl_3$ treatments. No significant differences in feed conversion (the feed:gain ratio) and mortality were observed among all treatments in all ages.

The data from the low rates of liquid $AlCl_3$ for weight gain and feed conversion are somewhat consistent with those of Moore et al. (2000), which showed that alum treatment to poultry litter resulted in increased weight gains and improved feed conversion. The problem with the current study was that the atmospheres of the various pens were mixed; hence, there could be no effect of reduced atmospheric NH_3 concentrations on performance. McWard and Taylor (2000) reported that broilers grown on alum-treated litter had significantly better feed conversion, weight gain, and improved carcass quality in compared with birds raised on untreated litter. On the other hand, a study conducted by Choi (2004) reported that broiler performance of alum and $AlCl_3$-treated groups were not significantly different from control groups. Kim and Patterson (2004) found that dietary Zn supplementation (1,500 mg/kg of Zn as $ZnSO_4$) reduced body weight, feed consumption, and feed efficiency compared with the other treatments.

In contrast to our expectations, our findings from T3 were not consistent with the findings of Moore et al. (2000). Despite T3 resulting in lower feed intake and feed conversion during all periods, weight gains for broilers raised on T3 tended to be lower than that of broilers raised on control, T1, and T2. One observation made during this study was there were several birds grown on the litter treated with the high rate of liquid $AlCl_3$ (T3) that had limping problems. Liquid $AlCl_3$ is a sticky substance and appeared to have caused leg problems, at least at this high rate. The exact cause of this is unknown.

pH and Ammonia Volatilization from Poultry Litter

Litter pH and NH_3 fluxes were lowered ($P < 0.05$) in all liquid $AlCl_3$ treatments compared with the controls during 6 wk (Figure 1A and 1B). No significant differences in NH_3 fluxes existed among T1, T2, and T3 at 5 and 6 wk. As seen in Figure 1B, NH_3 fluxes for T1, T2, and T3 initially increased at 1 through 4 wk, then abruptly decreased at 5 and 6 wk. These fluxes were related to litter pH. At 6 wk, litter pH values were 8.04, 7.71, 7.69, and 7.42 for control, T1, T2, and T3, respec-

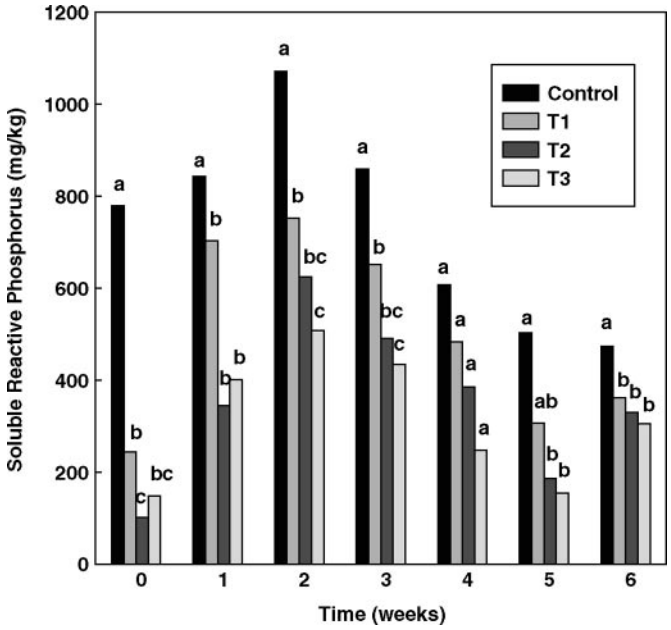

Figure 2. Effect of liquid aluminum chloride amendments to poultry litter on soluble reactive P (SRP). [a–c]Bars with same letters are not significantly different at $P < 0.05$. Treatments means T1 = 100 g of liquid $AlCl_3$/kg of litter; T2 = 200 g of liquid $AlCl_3$/kg of litter; T3 = 300 g of liquid $AlCl_3$/kg of litter.

tively. Ammonia fluxes at 6 wk had been reduced by 63, 76, and 76%, compared with the controls, for T1, T2, and T3, respectively.

These results are in agreement with those reported by Moore et al. (2000) in an on-farm comparison of alum effect. They reported that alum additions to litter significantly reduced the pH and the flux of NH_3 from the litter by 99% during the first 4 wk. Smith et al. (2004) demonstrated that $AlCl_3$ at 0.75% (vol/vol) reduced manure pH from 7.48 to 6.69 and relative NH_3 losses by 52% for a 6-wk period. Recent work by Choi (2004) showed that the $AlCl_3$ amendments (200 g/kg of rice hulls) to broiler litter reduced litter pH and atmospheric NH_3 by 97%. McWard and Taylor (2000) reported that treatments such as acidified clay, sodium bisulfate, and alum reduced NH_3 levels for up to 30 d relative to the untreated control.

Soluble Reactive Phosphorus in Poultry Litter

Soluble reactive P concentrations in litter were reduced by all liquid $AlCl_3$ treatments compared with the control, except during wk 4 (Figure 2). Reductions of SRP concentrations for the T1, T2, and T3 treatments at 6 weeks were 24, 30, and 36%, respectively. This is also supported by Shreve et al. (1995, 1996), Moore et al. (2000), and Dao et al. (2001), who reported that Al, Ca, and Fe amendments reduced soluble P in animal manures. Shreve et al. (1995) reported that alum-treated litter lowered P concentrations in runoff by 87 and 63% compared with untreated litter for the first and second runoff events, respectively. Work done by Smith et al. (2001a) showed that alum and $AlCl_3$ treatments produced reduced SRP concentrations in runoff by as much as 84% compared with normal manure and were not statistically different from SRP concentrations in runoff from unfertilized control plots. Choi (2004) recently reported that concentrations of SRP were 83% lower for $AlCl_3$ (200 g/kg of rice hulls) treated litter. Moore et al. (1998, 1999) explained that one of the reasons alum was chosen for P control in poultry litter was because aluminum phosphates were stable over a very wide range of pH conditions.

Total VFA in Poultry Litter

In this study, total VFA concentrations were reduced by all liquid $AlCl_3$ treatments in the litter over time (Figure 3). However, there was not a significant difference among all treatments at 1 week. The range of total VFA values for control, T1, T2, and T3 treatment at 6 weeks were 10.3, 8.2, 5.1, and 5.1 m*M*/100 g of litter, respectively. When compared with the controls at 6 weeks, T1, T2, and T3 resulted in reduction in total VFA concentrations from litter by as much as 20, 50, and 51%, respectively. The mechanism of liquid $AlCl_3$ treatments with respect to reducing VFA production is uncertain. At present, we hypothesize that it was due to the pH effect of $AlCl_3$ (acid-forming compound), which would inhibit microbial growth and activity in poultry litter (Wilson, 2000; Line, 2002).

Similar findings have been observed by Varel and Miller (2004), who reported that when eugenol was added to animal manure it reduced VFA production by 70 and 50% in cattle and swine manure, respectively. They suggested that eugenol suppressed microbial activity by lowering manure pH and inhibiting the production of VFA that are considered the predominant odor compounds emitted from livestock wastes. In another study involving iron treatment to slurry, Miller and Varel (2001) reported that low manure pH inhibited the activity of the VFA-utilizing microorganisms, but enhanced odor offensiveness as a larger proportion of the VFA would be in a more volatile, nonionized state.

Estimating Available N in Poultry Litter

Total N, IN, ON, AN, and PAN contents from liquid $AlCl_3$ treated and untreated litter as a function of time are illustrated in Figure 4 (panels A through E). The TN values of treatments including control in Figure 4A were significantly different at 0, 2, and 6 wk, whereas there was no difference among all treatments at 1, 3, 4, and 5 wk. However, TN tended to increase as the rate of $AlCl_3$ increased. There were significant differences in IN among all treatments except for at 5 weeks. The highest N contents (both TN and IN) were typically observed in the T3 treatment, while the control treatment had the lowest TN and IN contents. These differences in N content are due to a reduction in NH_3

emissions with liquid $AlCl_3$. The effects of liquid $AlCl_3$ treatments on N content in this study are also consistent with those observed by Moore et al. (1995, 1999) and Shreve et al. (1995). These studies showed that the addition of alum at the higher rate resulted in a doubling of the N concentration in the litter, which would greatly increase the value of poultry litter as a fertilizer source as well as improve crop yield.

There were no significant differences in organic N among all treatments during 6 wk (Figure 4C). The data from the present study contrasts with that of Choi and Nahm (2004), who observed that addition with ferrous sulfate and alum to poultry litter resulted in higher ON compared with the controls.

Inorganic N represented 11 to 66% of the TN contents from control and all liquid $AlCl_3$ treatments (Figure 4A and 4B), whereas the percentage ON of TN contents from control and all liquid $AlCl_3$ treatments ranged from 33 to 90% (Figure 4A and 4C). These data are very similar to those reported by Sims (1986, 1987) and Chadwick et al. (2000). Several workers have reported that the largest fraction of N in poultry manure is usually in the organic fraction, whereas about 20 to 40% of the total N in poultry manure is in the inorganic form (Sims, 1986, 1987; Westermann et al., 1987). The content of NH_4 and mineralizable organic N fraction (plant-available N) in manure, and litter plays an important role in determining the value of animal wastes as N fertilizer.

Predicted available N contents followed similar trends to AN, with the liquid $AlCl_3$ treated litter having the highest PAN (Figure 4D and 4E). Significant differences were observed ($P < 0.05$) among all treatments in AN and PAN contents except at 4 wk for AN. There were no significant differences among T1, T2, and T3 in both AN and PAN at 4 and 5 wk. The lowest AN and PAN contents among all treatments were control treatments that ranged from 8.9 g/kg at 0 wk to 12.7 g/kg at 6 wk for AN and from 11.1 g/kg at 0 wk to 13.3 g/kg at 6 wk for PAN. The T3 treatment had the highest AN and PAN contents. One of the important facts from this data are that the AN and PAN contents may be elevated when TN and IN contents are higher due to liquid $AlCl_3$ treatments (Figure 4A, B, D, and E). These results were somewhat consistent with other research using these equations for estimating N content of poultry litter, AN and PAN contents from ferrous sulfate and alum-treated litter increased (Choi and Nahm, 2004). The N availability indices, such as AN and PAN, indicate that crop yields should be higher with litter treated with $AlCl_3$, as has been found for alum-treated litter (Shreve et al., 1995; Moore and Edwards, 2005).

Conclusions

In conclusion, additions of liquid $AlCl_3$ to broiler litter resulted in lower litter pH, which reduced NH_3 emissions. Lower N losses resulted in higher contents in litter, including total and inorganic N, along with higher amounts of available N. This additional N should make litter treated with liquid $AlCl_3$ a better fertilizer. Soluble P levels were also lower in litter receiving liquid $AlCl_3$, indicating P runoff problems should be reduced with this treatment. Likewise, total VFA contents were significantly reduced with liquid $AlCl_3$ (up to 50%), which suggests that odor problems may be less with this treatment.

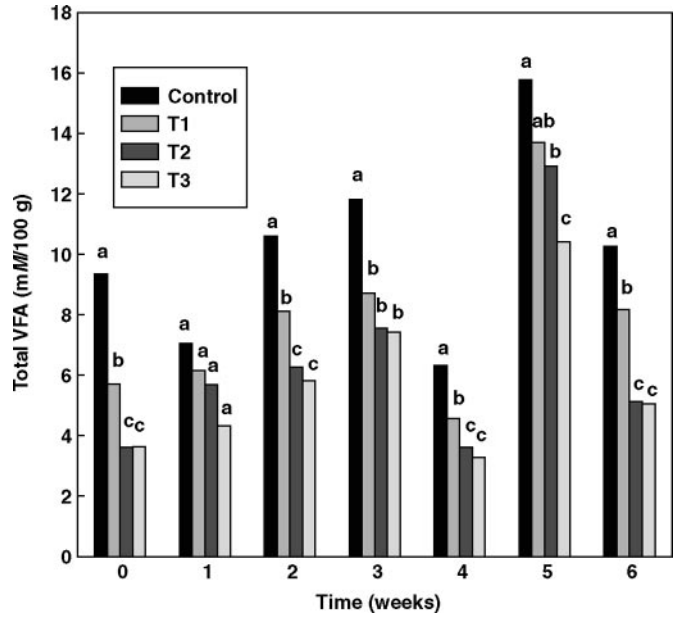

Figure 3. Effect of liquid aluminum chloride amendments to poultry litter on total VFA. [a–c]Bars with same letters are not significantly different at $P < 0.05$. Treatment means T1 = 100 g of liquid $AlCl_3$/kg of litter; T2 = 200 g of liquid $AlCl_3$/kg of litter; T3 = 300 g of liquid $AlCl_3$/kg of litter.

Unlike prior work involving litter amendments such as alum, there were no benefits in poultry production noted in this study. This may be due to the fact that the atmosphere of all the pens was mixed; hence, reductions in NH_3 emissions from one pen would not necessarily translate into improved air quality for those birds. In addition, at the highest rate of liquid $AlCl_3$ there were some obvious limping problems with birds that were probably associated with this treatment. The exact cause of this problem is unknown. Hence, if this treatment is utilized in poultry houses, rates of 200 g/kg of litter or below are recommended.

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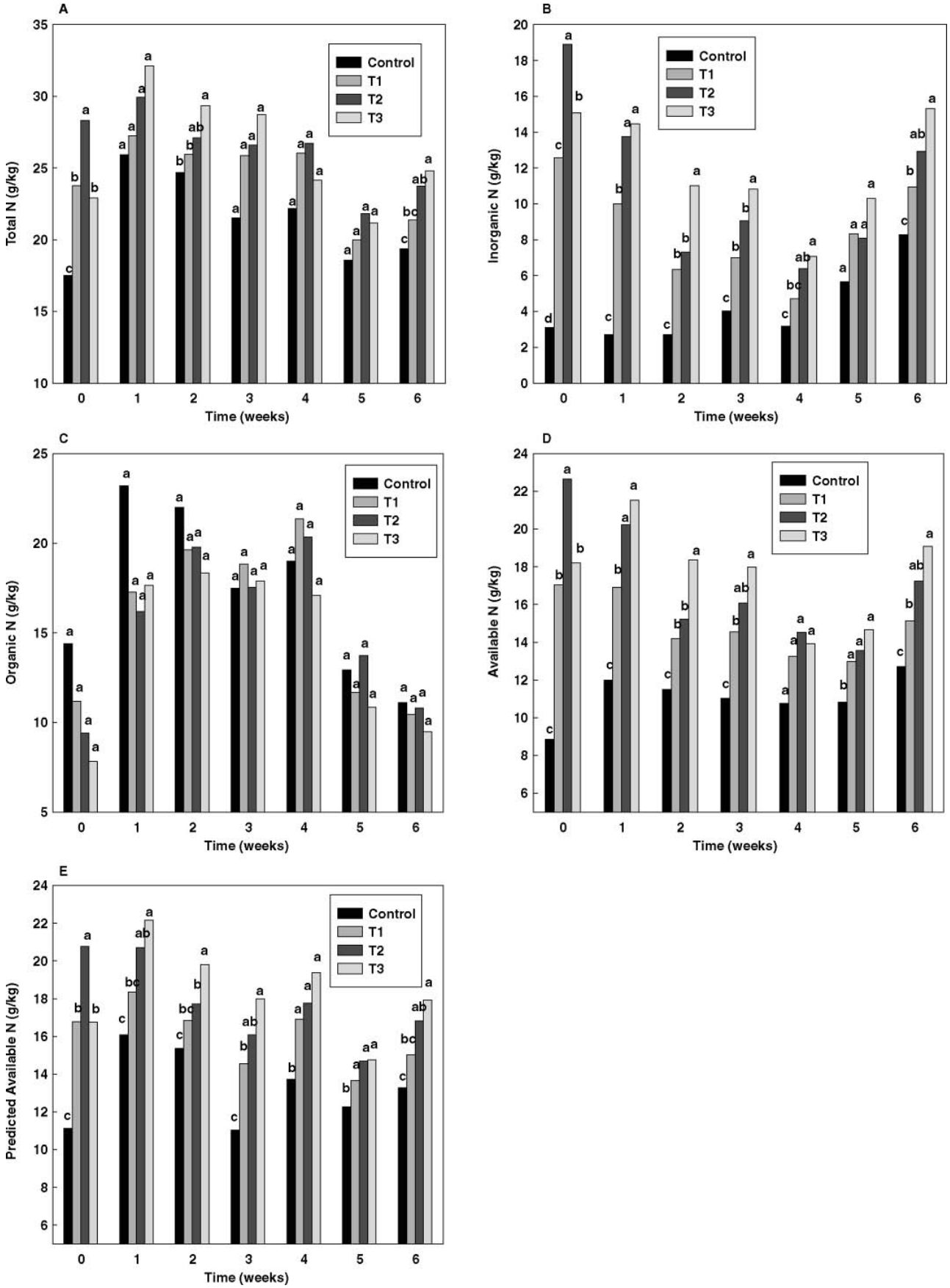

Figure 4. Effect of liquid aluminum chloride amendments to poultry litter on (A) total N (TN), (B) inorganic N (IN), (C) organic N (ON), (D) available N (AN), and (E) predicted available N (PAN). [a–c]Bars with same letters are not significantly different at $P < 0.05$. Treatment means T1 = 100 g of liquid $AlCl_3$/kg of litter; T2 = 200 g of liquid $AlCl_3$/kg of litter; T3 = 300 g of liquid $AlCl_3$/kg of litter.

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