Reducing Phosphorus Runoff and Improving Poultry Production with Alum[1]

P. A. MOORE, JR.,*,[2] T. C. DANIEL,† and D. R. EDWARDS‡

*USDA/ARS, Agronomy Department, Plant Sciences 115, University of Arkansas, Fayetteville, Arkansas, 72701, †Agronomy Department, University of Arkansas, Fayetteville, Arkansas 72701, and ‡Department of Agricultural Engineering, University of Kentucky, Lexington, Kentucky 40546

ABSTRACT This is a review paper on the effects of aluminum sulfate (alum) on ammonia volatilization and P runoff from poultry litter. Initially, laboratory studies were conducted that showed P solubility could be reduced in poultry litter with Al, Ca, and Fe amendments, indicating that these amendments may reduce P runoff. These results were confirmed in small plot studies in which alum applications to litter were shown to decrease P concentrations in runoff by as much as 87%, while improving tall fescue yields. Leaf tissue analyses indicated that the yield improvements were due to increased N availability, which we hypothesized was due to reduced NH_3 volatilization. This result was confirmed in laboratory studies that showed that alum was one of the most effective (and cost-effective) compounds for reducing NH_3 volatilization. Field trials conducted at commercial broiler farms in conjunction with the Environmental Protection Agency showed that alum additions to poultry litter lowered litter pH, particularly during the first 3 to 4 wk of each growout, which resulted in less NH_3 volatilization and lower atmospheric NH_3. Ammonia volatilization rates were reduced by 97% for the first 4 wk of the growout. Broilers grown on alum-treated litter were heavier than the controls (1.73 vs 1.66 kg) and had lower mortality (3.9 vs 4.2%) and better feed efficiency (1.98 vs 2.04). Electricity and propane use were lower for alum-treated houses. As a result of these economic benefits to the integrator and grower, the benefit:cost ratio of alum addition was 1.96. Phosphorus concentrations in runoff from small watersheds were 75% lower from alum-treated litter than normal litter over a 3-yr period. Long-term small plot studies on alum use have shown that alum-treated litter results in lower soil test P levels than normal litter and does not increase Al availability in soils or uptake by plants.

(*Key words*: alum, ammonia, manure, phosphorus, poultry)

1999 Poultry Science 78:692–698

INTRODUCTION

Two of the biggest problems currently facing the poultry industry with respect to waste management are nonpoint source P runoff and high levels of atmospheric NH_3 in poultry houses. Aluminum sulfate (alum) applications to poultry litter have been shown to help alleviate both of these problems. The objectives of this paper are to provide an introduction to the P and NH_3 problems and to provide an overview of the research that has been conducted on alum to combat these problems.

Phosphorus is normally the limiting element for freshwater algae and aquatic plants; hence, it is usually the limiting nutrient for the eutrophication process (Schindler, 1977). In recent years, concerns have arisen over the amount of P entering the aquatic environment, particularly on the East Coast, where *Pfisteria* outbreaks have occurred. One of the main sources of P in rivers and lakes is agricultural runoff (nonpoint source P runoff). Poultry litter applications to pastures have been shown to result in relatively high P runoff, even when litter is applied at recommended rates (Edwards and Daniel, 1992a,b, 1993). Most of the P (80 to 90%) in the runoff is in the soluble form (Edwards and Daniel, 1993), which is most available for algal uptake (Sonzogni *et al.*, 1982).

Ammonia volatilization from poultry litter can result in high levels of NH_3 gas in the atmosphere of poultry rearing facilities, which is very detrimental to the health of both the birds and farm workers. For over 30 yr, researchers have known that high levels of atmospheric NH_3 negatively affect poultry performance (Anderson *et al.*, 1964). High NH_3 levels have been shown to cause decreased weight gains, reduced feed efficiency, damage to the respiratory tract, and increased susceptibility to diseases like Newcastle, and can cause blindness (Carlile, 1984). As a result of these problems, Carlile

Received for publication August 4, 1998.
Accepted for publication November 24, 1998.

[1]Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.

[2]To whom correspondence should be addressed: philipm@comp.uark.edu

(1984) suggested that atmospheric NH_3 should not exceed 25 ppm in poultry houses.

LABORATORY AND SMALL PLOT STUDIES ON PHOSPHORUS

The goal of research on adding alum to poultry litter was initially to precipitate soluble P and thus reduce P runoff. Edwards and Daniel (1993) had shown that most of the P in runoff from pastures fertilized with poultry litter was in the soluble form. Based on this finding, we hypothesized that Al, Ca, or Fe amendments would reduce soluble P and decrease runoff. A laboratory study was conducted in which 100 different treatments (various Al, Ca, and Fe compounds at different rates) were added to poultry litter. Many of these compounds reduced soluble P levels from 2,000 to approximately 1 mg P/kg (Moore and Miller, 1994).

The results obtained by Moore and Miller (1994) were promising, but did not provide direct evidence that these amendments would reduce P runoff from lands fertilized with poultry litter. Hence, a small plot experiment was conducted using rainfall simulators (Shreve *et al.*, 1995). The results from this study indicated that alum applications to poultry litter could reduce P concentrations in runoff water by 87% (Figure 1).

One possible mechanism for this reduction in soluble P is shown in Equation 1.

$$Al_2(SO_4)_3 \cdot 14H_2O + 2H_3PO_4 \rightarrow 2AlPO_4 + 6H^+ + 3SO_4^{2-} + 14H_2O \qquad [1]$$

Another possible mechanism of soluble phosphate reduction is adsorption of P to aluminum hydroxide, as follows;

$$Al(OH)_3 + H_3PO_4 \rightarrow Al(OH)_3\text{-}H_3PO_4 \qquad [2]$$

With time, this amorphous aluminum phosphate compound would probably be transformed into a crystalline mineral, such as variscite ($AlPO_4 \cdot 2H_2O$) or wavellite [$Al_3(PO_4)_2(OH)_3 \cdot 5H_2O$). Laboratory studies using pure phosphate minerals have shown that aluminum phosphate minerals, such as variscite and wavellite, are very stable under acid conditions, whereas calcium phosphate minerals, such as hydroxyapatite and fluorapatite, dissolve under acidic conditions (Moore *et al.*, 1998a). As most poultry production in the U.S. is in the Southeast, where soils are acidic, it is obvious that aluminum phosphates are preferred, because they would be expected to be stable.

Tall fescue yields were significantly higher when plots were fertilized with alum-treated litter, compared to normal litter or litter treated with ferrous sulfate. Analysis of the plant tissue indicated that the plants fertilized with alum-treated litter had higher N contents and N uptake than the other treatments, indicating that N availability to the fescue had been increased with the addition of alum (Shreve *et al.*, 1995). The most obvious mechanism of increased N availability to plants fertilized with poultry litter is a reduction in NH_3 volatilization, which would result in higher amounts of N (as NH_4^+) in the litter.

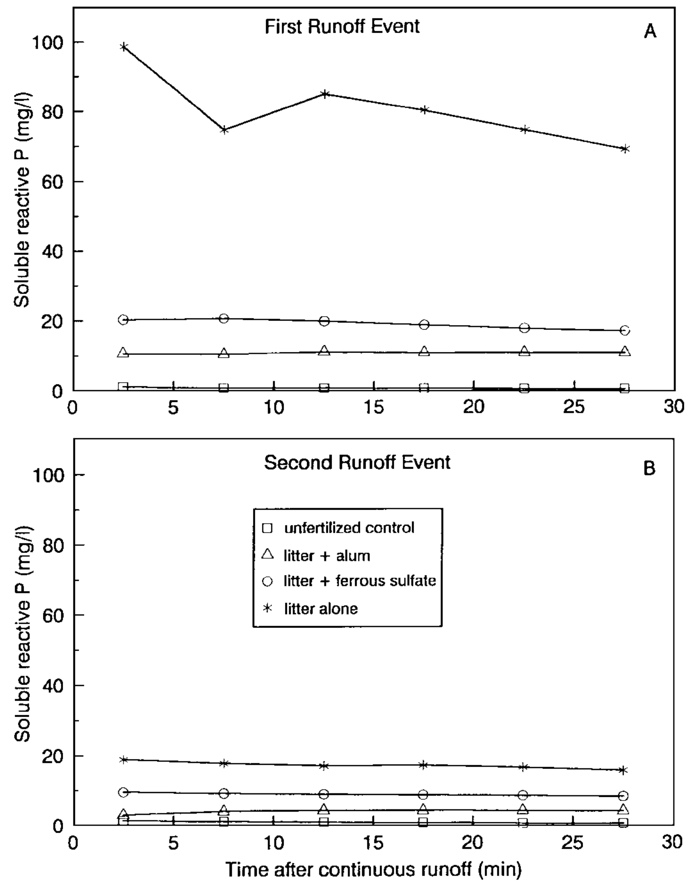

FIGURE 1. Phosphorus runoff from poultry litter with and without chemical amendments (From Shreve *et al.*, 1995).

LABORATORY STUDIES ON AMMONIA VOLATILIZATION

Ammonia volatilization experiments were conducted in the laboratory to assess the efficacy of different chemicals to reduce NH_3 emissions (Moore *et al.*, 1995, 1996). These studies showed that many of the chemicals currently used by poultry producers, such as ethylene glycol, calcium-iron silicates, sodium bisulfate, and extracts from yucca plants, had no significant effect on NH_3 volatilization from litter over a 42-d period when applied at the manufacturers' recommended rate (Moore *et al.*, 1995, 1996). Iron compounds, such as ferric chloride and ferrous sulfate, did result in a significant reduction in NH_3 loss; however, the most effective treatments were alum and phosphoric acid (Moore *et al.*, 1996). Phosphoric acid has been used for about 20 yr in the Delmarva area to reduce NH_3 volatilization from litter. Although it is efficacious and cost-effective, it results in high levels of soluble and total P in litter, which would increase P runoff (Moore *et al.*, 1996).

Ammonia is produced in animal manures by the enzymatic conversion of urea and from decomposition of other N-containing compounds. Because NH_3 is uncharged, it can be released as a gas. The gaseous emission of NH_3 can be inhibited if the NH_3 is converted to NH_4^+ (ammonium); which can be accomplished by lowering litter pH. Aluminum sulfate [$Al_2(SO_4)_3 \cdot 14H_2O$], commonly referred to as alum, is an acid that produces 6 *M* of H^+ when it dissolves, in one of the following ways;

$$Al_2(SO_4)_3 \cdot 14H_2O + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ + 3SO_4^{2-} + 14H_2O \quad [3]$$

The H^+ produced by this reaction will react with NH_3 to form NH_4^+, which can react with sulfate ions if high enough concentrations are reached to form 3 moles of ammonium sulfate, as follows;

$$6NH_3 + 6H^+ \rightarrow 6NH_4^+ \quad [4]$$

$$6NH_4^+ + 3SO_4^{2-} \rightarrow 3(NH_4)_2SO_4 \quad [5]$$

Ammonium sulfate is a water-soluble fertilizer. As a result of these reactions, the amount of NH_3 emitted from litter will be reduced, which will increase the fertilizer N value of the litter.

FIELD TRIALS WITH ALUM

As a result of the above mentioned research, the U.S. Environmental Protection Agency provided support of our work to demonstrate the effectiveness of alum in reducing P runoff from agricultural fields (Moore *et al.*, 1997a). The objectives of this project were to determine the effects of alum applications to poultry litter in commercial broiler houses on 1) litter pH, 2) NH_3 volatilization and atmospheric NH_3 levels, 3) poultry performance, 4) energy use, and 5) P runoff from fields fertilized with litter.

Alum was applied and incorporated with a litter decaker between each flock of broilers at a rate of 1,816 kg per house (which is equivalent to 2 tons per house). Alum was broadcast on the litter and incorporated after each flock of birds, except after the last flock prior to litter cleanout. Alum was applied at a rate of 1,816 kg per house per flock, which corresponded to 0.091 kg per bird. Normally, five to six flocks of birds are grown per year in each house. This application rate corresponds to 10% alum by weight of the litter (20,000 broilers produce about 20 tons of moist litter per growout). This amount of alum is based on that needed to precipitate P in litter produced by 42-d-old birds. Larger birds producing more manure will require more alum.

As mentioned earlier, alum is a dry acid and reduces litter pH. Moore *et al.* (1997a) showed that alum applications lowered litter pH significantly throughout the growout, with the greatest effect during the first 3 to 4 wk of the beginning of each growout (Figure 2a). The pH of the litter increased until the birds were about 4 or 5 wk old, when the litter pH leveled off at approximately 7.5. The litter pH for the control birds remained relatively constant (around 8) throughout the study.

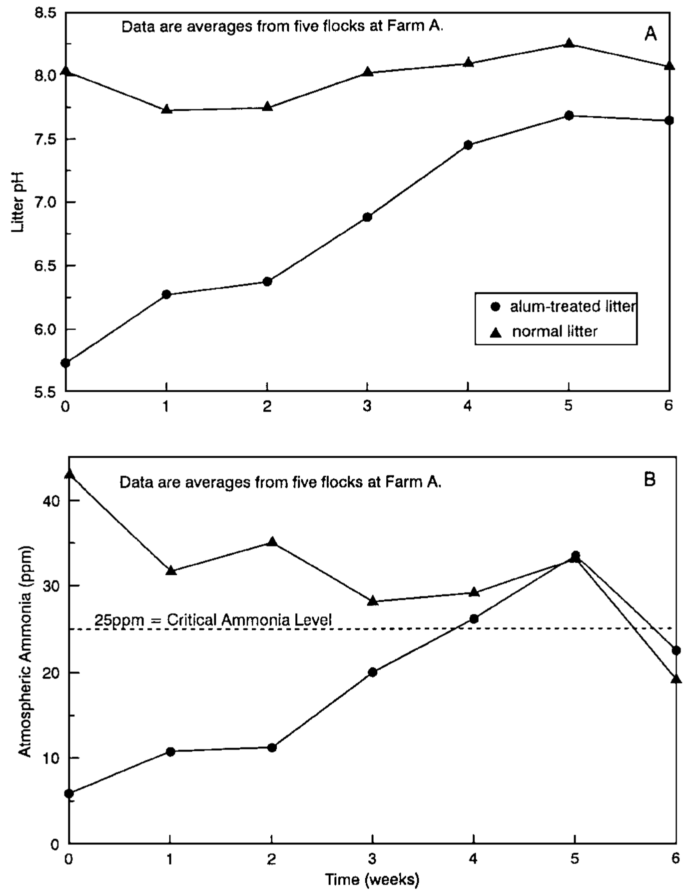

FIGURE 2. Litter pH and atmospheric NH_3 concentrations with alum-treated and normal poultry litter (From Moore *et al.*, 1997a).

Reductions in litter pH decreased NH_3 volatilization from the litter, which resulted in significant reductions in atmospheric NH_3 in the alum-treated houses compared to controls (Figure 2b). The average NH_3 concentration in the control houses was above 25 ppm for the first 5 wk of the growout. Decreases in weight gains and poor feed conversion have been demonstrated at this level. Ammonia concentrations in the alum-treated houses were very low the first 3 to 4 wk of the study, which coincides with the stage of growth in birds when they are most sensitive to high NH_3.

Although the study by Moore *et al.* (1997a) showed reduced atmospheric NH_3 levels, the true effect of alum on NH_3 was not possible to document by measuring atmospheric NH_3, as ventilation rates were different between alum-treated and normal houses. Therefore, an NH_3 flux chamber was developed and tested by Moore *et al.* (1997b) to measure NH_3 emissions; this work showed that alum applications reduced NH_3 fluxes from litter by 97% for the first 4 wk of the growout and 75% for the full 6 wk.

These data were confirmed by Brewer (1998), who found that alum applications applied at the recommended rate resulted in a net flux of NH_3 of zero for the first 3 wk of a growout, whereas alum applied at the 0.5× rate reduced NH_3 emissions by 52% compared to controls during this time. Brewer (1998) estimated the total N release (as NH_3) from a poultry house with 20,000 broilers would be 131 kg for an alum-treated house (at the recommended rate) and 296 kg for an untreated house over a 6-wk period.

It should be noted that NH_3 emissions are also detrimental because they result in acid precipitation (van Breemen *et al.*, 1982; Ap Simon *et al.*, 1987) and atmospheric NH_3 deposition to aquatic systems (Schroder, 1985). Ap Simon *et al.* (1987) stated that atmospheric NH_3 plays an important role in acid rain production in Europe. The dominant source of NH_3 in Europe is animal manure, with long-term trends indicating a 50% increase from 1950 to 1980 (Ap Simon *et al.*, 1987). Schroder (1985) stated that N deposition from NH_3 volatilization and subsequent wet fallout was an important source of nonpoint source N loading to aquatic systems. Schroder (1985) stated that N fallout tripled from 1955 to 1980.

Another aspect of high NH_3 levels in poultry rearing facilities that is often overlooked is the effect on the grower. Poultry producers often spend up to 8 h/d in poultry houses, particularly when the birds are young. This period usually coincides with the highest NH_3 levels (occasionally in excess of 100 ppm). The limit for human exposure to NH_3 set by OSHA (Occupational Safety & Health Agency) is 25 ppm for an 8-h day and 35 ppm for a 10-min exposure. These exposure levels are often exceeded in the cooler months of the year.

Moore *et al.* (1997a) showed that broilers grown on litter treated with aluminum sulfate were significantly heavier than the controls (Figure 3). Average weights were 1.66 kg for control birds and 1.73 kg for birds grown on alum-treated litter. Moore *et al.* (1997a) hypothesized that these differences in weight gains were either due to the decrease in atmospheric NH_3 levels or due to a change in the microbiology of the litter, both of which would be related to changes in litter pH. Reece *et al.* (1981) showed that exposure of chicks to relatively low concentrations of NH_3 (25 ppm) for the first 28 d resulted in reduced body weights of 4%. The difference in average weight between control and alum-treated birds observed by Moore *et al.* (1997a) was also 4%.

Several other benefits of alum-treatment were reported by Moore *et al.* (1997a), such as improved feed conversion (1.98 vs 2.04) and lower mortality (3.9 vs 4.2%). Electricity and propane use were lower for alum-treated houses than for control houses. Higher energy use in the control houses was the result of the requirement for higher ventilation rates, particularly in the winter, needed to reduce NH_3 levels. Moore *et al.* (1997a) reported control houses used an average of 3,357 L of propane, whereas the alum-treated houses used

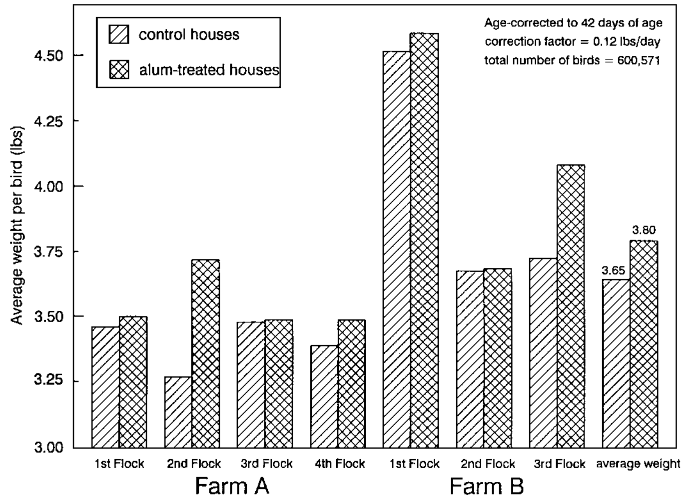

FIGURE 3. Broiler weights at 42 d of age with and without alum additions to litter (From Moore *et al.*, 1997a).

3,020 L; a reduction of 11%. Similarly, the electricity used for control houses was 13% higher than alum-treated houses (8,330 vs 7,320 kWh).

ECONOMICS OF ALUM USE

The price of aluminum sulfate will vary, but it usually can be purchased for $200 to $225/ton in most of the U.S. The charge for alum application and incorporation into the litter will also vary, but should be less than $100 per house depending on labor cost and the size of the house (Moore *et al.*, 1997a). Economic returns from alum applications will be realized by both the integrators and growers (Moore *et al.*, 1997a). As mentioned earlier, these benefits include 1) heavier birds, 2) improved feed conversion, 3) lower mortality, 4) lower propane and electricity costs, and 5) improved fertilizer value of litter. Moore *et al.* (1997a) provided a summary of the economic benefits of using alum in poultry houses (Tables 1 and 2). These data indicate that the total benefit from alum is approximately $940.34 per growout, when the benefits to the grower and integrator are summed. Assuming the cost of the alum, including application and incorporation, is approximately $480.00

TABLE 1. Summary of production parameters in alum-treated and control houses (adapted from Moore *et al.*, 1997a)

Parameter	Alum-treated houses	Control houses
Propane use, L/growout	3,020	3,357
Electricity use, kW/growout	7,320	8,330
Weight gains, kg/bird	1.73	1.66
Feed conversion, kg feed:kg bird	1.98	2.04
Mortality, %	3.90	4.20
Percentage of total weight rejected, %	1.50	2.00
Litter N content, %	3.85	3.45

TABLE 2. Savings associated with alum to the integrator and grower per growout (adapted from Moore *et al.*, 1997a)

Parameter	Integrator	Grower
Lower propane use	0	106.80
Lower electricity use	0	6.06
Heavier birds	???	150.00
Improved feed conversion	480.00	???[1]
Lower mortality	24.48	21.00
Higher % total weight accepted	128.00	0
Higher litter N content, %	0	24.00
Total savings	632.48	307.86

[1]Note: Improved feed conversion will increase the amount per pound the grower will receive for his/her birds. However, the formula used to determine this varies greatly from company to company.

per growout, the benefit:cost ratio of this practice is 1.96 (Moore *et al.*, 1997a).

WATERSHED STUDIES

The poultry litter produced from the alum field trials was used by Moore *et al.* (1997a) to evaluate P runoff from small watersheds. Moore *et al.* (1997a) reported that alum-treated litter was similar to normal litter, except for total Al and total S, which were both higher in the alum-treated litter (Table 3). The higher Al content in the alum-treated litter resulted in an Al:P ratio of near 1.

Both soluble and total P in runoff water were monitored from paired 1-acre watersheds for 3 yr. Litter application rates were 2.5, 4.0, and 4.0 tons/acre (5.6, 9.0, and 9.0 Mg/ha) for Years 1, 2, and 3, respectively. Results from this study are shown in Figure 4. Alum applications reduced soluble P concentrations in runoff water by 75% over the 3-yr period. The average soluble P in runoff from normal litter was 6.29 mg P/L over the 3 yr, whereas it was 1.60 mg P/L for alum-treated litter (75% reduction). Total P in runoff followed the same trends (6.77 mg P/L vs 1.90 mg P/L).

Aluminum concentrations in runoff were not significantly different between alum-treated and normal litter (Moore *et al.*, 1997a). These results were supported by small plot studies conducted by Moore *et al.* (1998b), who showed that Al runoff from tall fescue plots fertilized with alum-treated litter was not significantly different from runoff from normal litter.

TABLE 3. Chemical characteristics of alum-treated and normal poultry litter after five growouts (adapted from Moore *et al.*, 1997a)

	Alum-treated litter		Normal litter	
Parameter	x̄	SD	x̄	SD
pH	7.59	0.77	8.04	0.18
EC	10,833	471	6,611	311
	(g/kg)			
N	38.5	1.1	34.5	2.7
S	33.9	9.8	6.8	0.4
Ca	29.4	3.6	34.1	4.2
K	27.4	2.7	26.4	1.6
P	18.9	1.8	22.4	1.7
Al	18.7	6.0	1.18	0.2
Na	7.54	0.6	7.85	0.6
Mg	5.79	0.7	6.57	0.4
	(mg/kg)			
Fe	1,717	312	1,095	155
Mn	893	216	956	134
Cu	679	93	748	102
Zn	598	51	718	69
B	46	4	51	4
Ti	31	11	44	19
As	20	8	43	4
Ni	21	5	15	2
Pb	8	2	11	2
Co	6	2	6	1
Mo	5	0.5	6	0.5
Cd	3	0.4	3	0.2

LONG-TERM STUDIES ON ALUM

One obvious gap in research is on the effects of long-term applications of poultry litter to land. Therefore, we initiated long-term studies on 52 tall fescue plots in 1995. There are a total of 13 treatments in this study; an unfertilized control, four rates of normal poultry litter, four rates of alum-treated litter, and four rates of ammonium nitrate. The four rates of litter application are 1, 2, 3, and 4 tons/acre (2.24, 4.49, 6.73, 8.98 mg/ha). Ammonium nitrate is being applied at rates roughly equivalent to the amount of N supplied by alum-treated litter (65, 130, 195, and 265 kg N/ha). The fertilizers will be applied once each year (in the spring) for 20 yr. The objectives are to determine the effects of normal litter, alum-treated litter, and ammonium nitrate on soil chemical characteristics, yields, and nutrient uptake by tall fescue, and runoff water quality.

Large differences in soil test P have been observed after only 3 yr of annual applications (Figure 5). Water-soluble P levels have increased dramatically in the plots

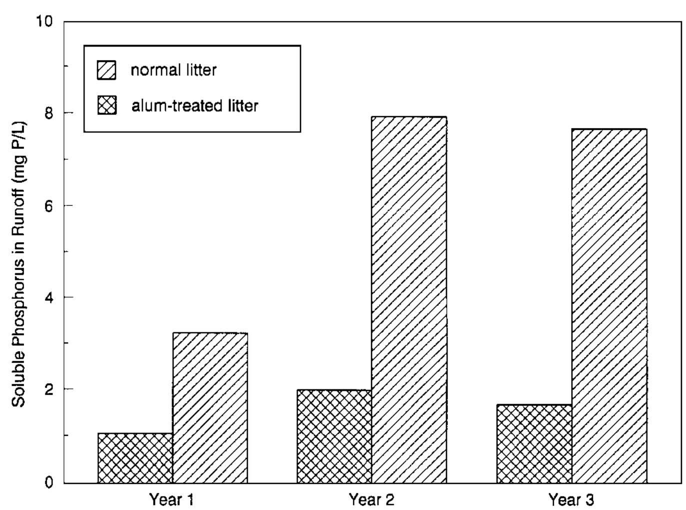

FIGURE 4. Soluble reactive P in runoff water from land fertilized with alum-treated and normal litter.

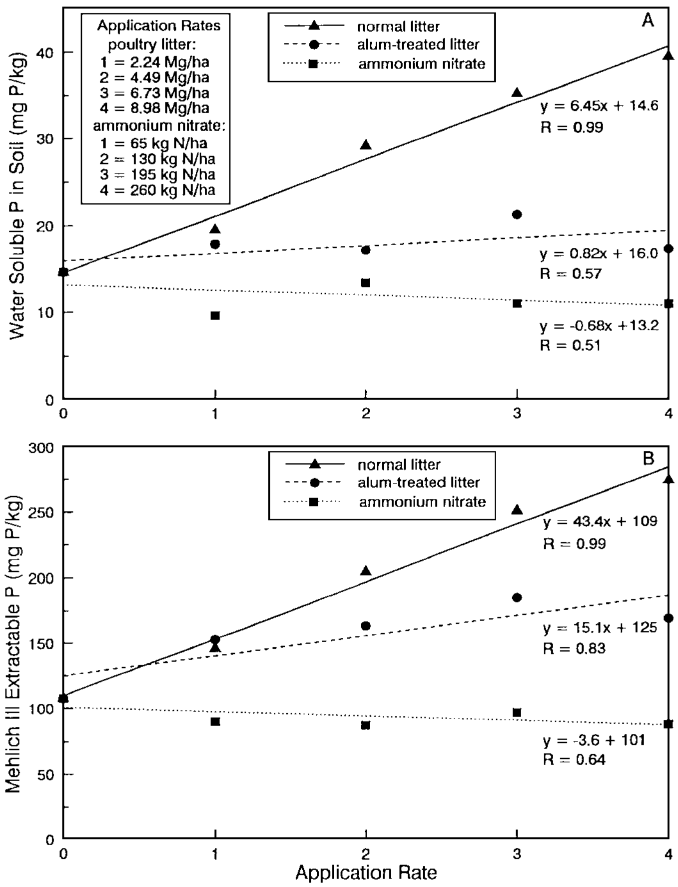

FIGURE 5. Effect of fertilizer type on soil test P (From Self-Davis *et al.*, 1998).

fertilized with normal litter, particularly at the higher rates, whereas soluble P in plots fertilized with alum-treated litter is not different from that in the unfertilized control plots (Self-Davis *et al.*, 1998). Studies have shown that water-soluble P in soils is a very good predictor of P concentrations in runoff water (Pote *et al.*, 1996).

One of the reasons alum was chosen for P control was because aluminum phosphates are stable under a wide range of soil physical and chemical conditions. Iron phosphate minerals are affected by redox reactions and can be reduced under wet conditions, releasing soluble P. Likewise, calcium phosphate minerals are not stable under acid conditions, as stated earlier (Lindsay, 1979; Moore *et al.*, 1998c). Aluminum phosphates are not affected by redox reactions and are stable over a very wide range of pH conditions (Lindsay, 1979; Moore *et al.*, 1998c). Hence, the aluminum phosphate mineral that forms when alum is added to poultry litter should be stable for geological time periods.

Another important parameter that has been affected is soil pH. Acidity produced via nitrification of NH_4 from ammonium nitrate fertilizer has resulted in lower soil pHs on plots fertilized with ammonium nitrate, particularly at the higher rates (Moore *et al.*, 1998b). On the contrary, soil pH has increased with both normal litter and alum-treated litter. This increase is due to the fact that poultry litter (even alum-treated litter) contains more lime (calcium carbonate) than potential acidity from nitrification (Moore *et al.*, 1998b). Soil pH is considered to be one of the most important parameters affecting soil chemistry. One effect of lower pH noted in plots fertilized with ammonium nitrate was an increase in exchangeable Al, with the high rate of ammonium nitrate causing exchangeable Al concentrations to be five times higher than that observed with both normal and alum-treated litter (Moore *et al.*, 1998b). This increase in exchangeable Al is expected to continue with time, as the pH of the soils fertilized with ammonium nitrate decreases. Eventually, we expect that the fescue yields and Al concentrations will be negatively impacted by this acidity formed when ammonium nitrate fertilizer is used, although this has not been documented to date. Studies conducted on these plots have shown that alum-treated litter does not increase Al runoff (Moore *et al.*, 1998a) or Al uptake by plants (Moore *et al.*, 1997c).

Research has also shown that alum applications to poultry litter reduce estrogen and heavy metal concentrations in runoff water. Nichols *et al.* (1997) found β17-estradiol concentrations in runoff water were significantly lower from alum-treated litter than from normal litter. It should be pointed out that these estrogens are naturally occurring and not augmented by additions of man-made estrogens to feed. It should also be noted that the environmental impacts of estrogen runoff (at these concentrations) are unknown.

Moore *et al.* (1998a) also found that heavy metal (As, Cu, Fe, and Zn) concentrations in runoff were significantly reduced by alum. Copper concentrations in runoff from normal litter were as high as 1 mg Cu/L (Moore *et al.*, 1998a). Reductions in heavy metal runoff with alum were believed to be due to reductions in soluble organic C runoff, as organics like humic and fulvic acids have a high affinity for metals. As with estrogen, the environmental impacts of trace metals are unknown. However, reductions in trace metal runoff (particularly Cu), would definitely be beneficial.

CONCLUSIONS

The results of these studies indicate that alum additions to poultry litter reduce litter pH, which reduces NH_3 volatilization. Reductions in NH_3 emissions from the litter results in a lower atmospheric NH_3 level in the poultry house, which leads to improved broiler production. Bird performance parameters, such as weight gain and feed conversion, were positively affected by alum addition. Alum applications also lowered energy use. These benefits results in economic returns to both integrators and growers.

Alum additions to litter also reduce the solubility of P in litter, resulting in reductions in P runoff. Phosphorus concentrations in runoff water were, on average, 75% lower from pastures fertilized with alum-treated litter than from those fertilized with normal litter. Long-term studies show that whereas normal litter results in a buildup in soil test P levels (water-soluble P in soils), particularly at high litter rates, this does not occur with alum-treated litter. Results from these studies have also shown that alum use does not increase Al availability in soils, Al runoff, or Al uptake by plants. In conclusion, treating poultry litter with alum is a cost-effective management practice that significantly reduces nonpoint source P runoff.

REFERENCES

Anderson, D. P., C. W. Beard, and R. P. Hanson, 1964. The adverse effects of ammonia on chickens including resistance to infection with Newcastle Disease virus. Avian Dis. 8:369–379.

Ap Simon, H. M., M. Kruse, and J.N.B. Bell, 1987. Ammonia emissions and their role in acid deposition. Atmospheric Environ. 21:1939–1946.

Brewer, S. K., 1998. Ammonia flux from fresh, re-used, and alum-treated broiler litter. M.S. thesis, University of Arkansas, Fayetteville, AR.

Carlile, F. S., 1984. Ammonia in poultry houses: A literature review. World's Poult. Sci. J. 40:99–113.

Edwards, D. R., and T. C. Daniel, 1992a. Potential runoff quality effects of poultry manure slurry applied to fescue plots. Am. Soc. Agric. Eng. 35:1827–1832.

Edwards, D. R., and T. C. Daniel, 1992b. Environmental impacts of on-farm poultry waste disposal—A review. Bioresource Technol. 41:9–33.

Edwards, D. R., and T. C. Daniel, 1993. Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescue plots. J. Environ. Qual. 22:361–365.

Lindsay, W. L., 1979. Chemical Equilibria in Soils. John Wiley and Sons. New York, NY.

Moore, P. A., Jr. and D. M. Miller, 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium and iron amendments. J. Environ. Qual. 23: 325–330.

Moore, P. A., Jr., T. C. Daniel, D. R. Edwards, and D. M. Miller, 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. J. Environ. Qual. 24: 293–300.

Moore, P. A., Jr., T. C. Daniel, D. R. Edwards, and D. M. Miller, 1996. Evaluation of chemical amendments to reduce ammonia volatilization from poultry litter. Poultry Science 75:315–320.

Moore, P. A., Jr., B. E. Haggard, T. C. Daniel, D. R. Edwards, B. R. Shreve, and T. J. Sauer, 1997a. Demonstration of Nutrient Management for Poultry Litter using Alum Precipitation of Soluble Phosphorus. Final Report to U.S. EPA for Federal Assistance Project No. 9006749920.

Moore, P. A., Jr., W. E. Huff, T. C. Daniel, D. R. Edwards, and T. C. Sauer, 1997b. Effect of aluminum sulfate on ammonia fluxes from poultry litter in commercial houses. Pages 883–891 *in*: Proceedings of the Fifth International Symposium on Livestock Environment. Vol. II. American Society of Agricultural Engineering, St. Joseph, MI.

Moore, P. A., Jr., G. E. Aiken, T. C. Daniel, D. R. Edwards, J. T. Gilmour, D. W. Kennedy, and T. J. Sauer, 1997c. Agricultural and environmental effects of treating poultry litter with aluminum sulfate. Final Report to U.S. Poultry & Egg Association.

Moore, P. A., Jr., W. F. Jaynes, and D. M. Miller, 1998a. Effect of pH on the solubility of phosphate minerals. Pages 328–333 *in*: Proceedings 1998 Poultry Waste Management Symposium. J. P. Blake and P. H. Patterson, ed. Auburn University Printing Service, Auburn, AL.

Moore, P. A., Jr., T. C. Daniel, J. T. Gilmour, B. R. Shreve, D. R. Edwards, and B. H. Wood, 1998b. Decreasing metal runoff from poultry litter with aluminum sulfate. J. Environ. Qual. 27:92–99.

Moore, P. A., Jr., T. C. Daniel, D. R. Edwards, and J. T. Gilmour, 1998c. Effect of alum-treated poultry litter, normal litter, and ammonium nitrate on aluminum availability and uptake by plants. Pages 320–327 *in*: Proceedings 1998 Poultry Waste Management Symposium. J. P. Blake and P. H. Patterson, ed. Auburn University Printing Service, Auburn, AL.

Nichols, D. J., T. C. Daniel, P. A. Moore, Jr., D. R. Edwards, and D. H. Pote, 1997. Runoff of estrogen hormone 17β-estradiol from poultry litter applied to pasture. J. Environ. Qual. 26:1002–1006.

Pote, D. H., T. C. Daniel, A. N. Sharpley, P. A. Moore, Jr., D. R. Edwards, and D. J. Nichols, 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

Reece, F. N., B. D. Lott, and J. W. Deaton, 1981. Low concentrations of ammonia during brooding decrease broiler weight. Poultry Sci. 60:937–940.

Schindler, D. W., 1977. The evolution of phosphorus limitation in lakes. Science 195:260–262.

Schroder, H., 1985. Nitrogen losses from Danish agriculture—Trends and consequences. Agric. Ecosystems Environ. 14: 279–289.

Self-Davis, M. L., P. A. Moore, Jr., T. C. Daniel, and D. R. Edwards, 1998. Effect of alum-treated and untreated poultry litter on soil test phosphorus. *In*: Proceedings of Arkansas Water Research Conference. University of Arkansas, Fayetteville, AR. (in press).

Shreve, B. R., P. A. Moore, Jr., T. C. Daniel, and D. R. Edwards, 1995. Reduction of phosphorus in runoff from field-applied poultry litter using chemical amendments. J. Environ. Qual. 24:106–111.

Sonzogni, W. C., S. C. Chapra, D. E. Armstrong, and T. J. Logan, 1982. Bioavailability of phosphorus inputs to lakes. J. Environ. Qual. 11:555–563.

van Breemen, N., P. A. Burrough, E. J. Velthorst, H. F. van Dobben, T. de Wit, T. B. Ridder, and H.F.R. Reijinders, 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. Nature 299:548–550.