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RESEARCH ARTICLE

Effect of Poultry Litter Amendments on Ammonia Emissions and Soluble Phosphorus

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Abstract

Background and Objective: Poultry litter amendments are widely used to mitigate ammonia (NH_3) volatilization and some amendments, such as aluminum sulfate (alum), also reduce litter-soluble phosphorus (P), thereby potentially decreasing P runoff and leaching. However, the increasing cost of alum has prompted interest in alternative amendments that can simultaneously reduce NH_3 emissions and P solubility. This study evaluated the effects of several poultry litter amendments, including Alum Mud Litter Amendment (AMLA), a byproduct of alum production and TPX, a calcium silicate nanoparticle with high P adsorption capacity, on NH_3 emissions and soluble P concentrations in poultry litter.

Methodology: A pen trial was conducted to evaluate six treatments: (1) Untreated poultry litter (control), (2) Alum-treated litter, (3) Sodium bisulfate (SBS)-treated litter, (4) AMLA-treated litter, (5) Alum plus TPX and (6) SBS plus TPX. Cumulative NH_3 fluxes, litter-soluble P concentrations and other relevant litter and bird health parameters were assessed.

Results: Compared with the untreated control, cumulative NH_3 fluxes were reduced by 70, 65, 63, 63 and 56% in the alum, SBS, AMLA, SBS plus TPX and alum plus TPX treatments, respectively. At the end of the trial, alum plus TPX, alum and AMLA reduced litter-soluble P concentrations by 63, 56 and 52%, respectively, relative to the control. In contrast, SBS and SBS plus TPX increased litter-soluble P concentrations by 18% and 6%, respectively, although substantially higher concentrations were observed earlier in the grow-out period. The addition of TPX had no significant effect on cumulative NH_3 emissions or litter-soluble P concentrations. Furthermore, SBS increased litter moisture and Nitrous Oxide (N_2O) emissions and was associated with poorer footpad and hock scores.

Conclusion: AMLA performed comparably to alum in reducing both NH_3 emissions and litter-soluble P concentrations, indicating its potential as an alternative poultry litter amendment. Although SBS effectively reduced NH_3 emissions, its effects on litter-soluble P, increased litter moisture and N_2O emissions and poorer footpad and hock scores highlight potential environmental and bird welfare concerns. The addition of TPX provided no apparent additional benefit in reducing cumulative NH_3 emissions or litter soluble P under the conditions evaluated.

INTRODUCTION

The United States (US) poultry industry produced 9.4 billion broilers, 194 million turkeys and 105 billion eggs in 2025[1]. Two of the largest environmental issues associated with poultry production are ammonia (NH_3) emissions and phosphorus (P) runoff. Agricultural sources account for approximately 80% of the atmospheric NH_3 load in the US, of

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which 27% is estimated to be attributable to poultry manure[2,3]. The US produces an estimated 13 million megagrams (14 million tons) of broiler litter annually[4]. Moore *et al.*[5] determined that more than half of the nitrogen (N) excreted by broiler chickens is lost to the atmosphere as NH_3 emissions before litter cleanout and reported an emission factor of 46 g NH_3-N/bird. Based on this emission factor, annual NH_3-N emissions from 9.4 billion broilers would exceed 432 million kg, assuming that each bird emits 46 g NH_3-N. Beyond its contribution to nutrient losses, NH_3 contributes to soil acidification[6,7], eutrophication through atmospheric N deposition[8,9] and fine particulate matter formation, which is associated with respiratory health problems in humans[10,11].

Ammonia emissions can adversely affect poultry production because of elevated NH_3 concentrations in poultry rearing facilities[12,13]. These elevated concentrations can cause respiratory problems in poultry[14] and agricultural workers[15,16]. Damage to the poultry respiratory tract caused by elevated NH_3 concentrations can impair immune function, increasing susceptibility to viral diseases[17]. Kling and Quarles[18] observed an increased incidence of airsacculitis in broilers housed in facilities with high NH_3 concentrations. Elevated NH_3 concentrations can also cause ocular damage[19] and negatively affect feed conversion and weight gain[12,13].

Phosphorus (P) runoff can cause eutrophication of freshwater systems because P is generally the limiting nutrient for algal growth[20]. Soil-test P levels often become excessive in pastures fertilized with poultry litter at rates based on crop nitrogen (N) requirements because of the low N-to-P ratio in poultry litter. Furthermore, approximately 90% of the P in runoff water from pastures fertilized with poultry manure is soluble reactive P[21], the form most readily available for algal growth[22]. Because soluble P, rather than total P, drives P losses in runoff, amendments that reduce soluble P can more effectively mitigate the risk of P transport to surface waters than strategies that reduce total P alone[23-25].

Litter amendments are widely used in the poultry industry to control NH_3 concentrations in poultry houses. Alum (Al^+Clear®, Chemtrade Logistics Inc., Toronto, Ontario, Canada) and sodium bisulfate (PLT®, Jones-Hamilton Ag, Maumee, OH, USA) are two commonly used amendments. Alum and sodium Bisulfate (SBS) reduce NH_3 emissions by lowering litter pH, thereby shifting the equilibrium from volatile NH_3 toward nonvolatile ammonium (NH_4^+).

Moore[26-30] patented the use of alum to reduce NH_3 volatilization and P runoff from poultry litter, building on the work of Moore and Miller[31], who demonstrated that aluminum (Al), calcium (Ca) and iron (Fe) amendments reduced soluble P in manure. Subsequent research demonstrated that alum substantially reduced P runoff and leaching while lowering NH_3 concentrations in poultry houses, thereby improving feed conversion, weight gain and livability in broilers[32-37]. Reducing NH_3 volatilization with alum can also allow lower winter ventilation rates, resulting in reduced electricity and propane costs[33,38,39]. Eugene *et al.*[37] determined that reduced propane consumption in alum-treated poultry houses also decreased carbon dioxide (CO_2) emissions. Moore *et al.*[33] reported a benefit-to-cost ratio of 1.96 for alum treatment of poultry litter, indicating that the practice was economically beneficial under the conditions evaluated. The ability of alum to reduce NH_3 emissions and litter-soluble P, together with its associated production and environmental benefits, has led to its use in the production of approximately 40% of broilers in the US[40]. However, alum prices have nearly tripled since 1999, increasing from $220/Mg in 1999 to $605-$661/Mg. This increase has eroded much of alum's cost advantage and prompted the search for less expensive alternatives.

AMLA (alum mud litter amendment), manufactured using alum mud, bauxite and sulfuric acid[41,42], was recently developed as a poultry litter amendment. Alum mud is an acidic solid residue generated as a byproduct of alum manufacturing[43] that must currently be disposed of in landfills, resulting in substantial disposal costs[42]. Conservative estimates by Moore[42] indicate that AMLA production costs could be up to 50% lower than those of conventional alum. Moore[42] also reported that AMLA performed comparably to alum in reducing NH_3 volatilization and soluble P in treated litter, suggesting that AMLA could serve as a lower-cost alternative to alum.

Recent studies have reported instances in which alum treatment failed to reduce soluble P in poultry litter and, in some cases, increased its concentration[44-46]. Elevated soluble P concentrations in alum-treated litter have most often been observed when the litter was previously treated with SBS. In the US, multiple broiler flocks are typically raised on the same bedding material, which can result in the sequential application of different litter amendments over time.

Moore[44] patented the use of TPX (N-Clear Inc., Atlanta, GA, USA), a calcium-based nanoparticle, to reduce soluble P in poultry litter. TPX is currently used to reduce soluble P in poultry processing plant wastewater because of its high P adsorption capacity[47]. Moore[44,45], reported substantial reductions in soluble P in poultry litter following the application of TPX alone or in combination with alum or SBS. The addition of TPX in combination with alum or SBS was also reported to produce a synergistic effect on the reduction of litter soluble P.

The objective of this study was to evaluate the effects of several poultry litter amendments on NH_3 emissions and soluble P concentrations in poultry litter under pen trial conditions.

MATERIALS AND METHODS

Design and treatments: Pen trials were conducted at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, Arkansas. The experiment included six treatments, each with four replicates and 41 birds per experimental unit, arranged in a completely randomized block design. The six treatments were: (1) Untreated control, (2) 106 kg of alum/100 m^2, (3) 106 kg of SBS/100 m^2, (4) 106 kg of AMLA/100 m^2, (5) 106 kg of alum/100 m^2 +10.6 kg of TPX/100 m^2 and (6) 106 kg of SBS/100 m^2 +10.6 kg of TPX/100 m^2. Litter amendments were applied to 40 kg of litter from four previous flocks three days before chick placement. Forty-one 1-day-old Cobb×Cobb broiler chicks were randomly allocated to 24 pens (2.1×1.8 m), providing a stocking density of 0.09 m^2/bird. Environmental conditions were maintained using an automatically controlled system for lighting, temperature and ventilation (0.85 m^3/hrs per bird), with a single fan providing negative pressure. Each pen was equipped with an automatic bell drinker and one tube feeder. Standard corn-soybean meal diets were prepared at the University of Arkansas feed mill. Chicks received starter diets from days 1 to 14, grower diets from days 15 to 35 and finisher diets from day 36 until day 42. All broilers had free access to commercial feed and drinking water throughout the study. Because NH_3 and other gases mixed freely in the shared airspace above the pens, bird weights and feed conversion were not measured, as any observed differences in performance could not be confidently attributed to individual litter treatments.

Flux measurements: Ammonia (NH_3), nitrous oxide (N_2O) and carbon dioxide (CO_2) fluxes were measured and litter samples were collected from each pen on days 0 (the day of chick placement), 7, 14, 21, 28, 35 and 42. Gas fluxes from the litter were measured at four locations within each pen using an Innova 1512 Photo-acoustic Multi-gas Analyzer (Innova AirTech Instruments, Ballerup, Denmark) connected to a 12-L plastic flux chamber. The chamber (29 cm in diameter and 35 cm in height) was equipped with a battery-operated fan to mix the air and FEP tubing for sample collection and air return. Gas concentrations were measured immediately before chamber placement (time zero) at a point directly above the litter surface and again 1 min after the chamber was placed on the litter, as described by Choi and Moore[48]. Gas fluxes were calculated from the rate of gas accumulation in the chamber headspace between the two measurement points and normalized to the chamber's surface area and volume.

Litter samples were collected from the same four locations in each pen used for gas flux measurements. The four samples were homogenized in a clean plastic bucket and an approximately 100-g subsample was placed in a plastic bag and refrigerated at 4°C until analysis.

Litter analysis: Litter samples were analyzed for pH, electrical conductivity (EC), moisture content, soluble metals, ammonium, total nitrogen (TN), total carbon (TC) and total metals. Moisture content was determined by oven-drying a litter subsample at 60°C for seven days. Water-extractable constituents were extracted using a 1:10 litter-to-water ratio[49]. 20 g of litter and 200 mL of deionized water were added to a 250-mL centrifuge tube, shaken on a mechanical shaker for 2 h, centrifuged at 8,000 rpm for 15 min and filtered through 0.45-µm nitrocellulose filters. Litter pH and EC were measured in unfiltered aliquots of the extract. Soluble metals were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) using an Agilent 5110 ICP-OES instrument (Agilent Technologies, Santa Clara, CA, USA). Total metals were determined by nitric acid and hydrogen peroxide digestion of ground, oven-dried litter samples, followed by ICP-OES analysis.[50] Total C and N were determined by dry combustion of fresh litter using an Elementar Vario Max analyzer (Elementar Americas, Ronkonkoma, NY, USA).

Footpad dermatitis and hock burn scores: Footpad dermatitis and hock burn scores were assessed on days 21 and 42 in five birds randomly selected from each of the 24 pens at the beginning of the study. Both feet of each bird were scored for footpad dermatitis and hock burn according to the Welfare Quality[51] method. Scores ranged from 0, indicating no footpad lesions or hock burns, to 4, indicating severe footpad lesions or hock burns.

Statistical analyses: Statistical analyses were performed using the GLIMMIX procedure in SAS 9.4 to evaluate the effects of litter amendments on gas fluxes and litter characteristics. The experiment followed a completely randomized block design with four blocks. Analysis of variance (ANOVA) was conducted to evaluate the effects of litter amendment treatments, with blocks included as random effects. Treatment means were compared using Fisher's least significant difference (LSD) test at a significance level of 0.05.

RESULTS AND DISCUSSION

Litter characteristics: Litter characteristics, including pH, electrical conductivity (EC) and moisture content, play important roles in NH_3 emissions, bird health and the suitability of litter for land application. Weekly pH, EC and moisture content data are presented in Table 1. At the beginning of the flock, the pH of treated litter ranged from 5.0 to 5.9, whereas untreated control litter had a pH of 8.2. Among the treatments, AMLA resulted in the lowest initial pH (5.0), while alum+TPX had the highest pH (5.9). All amendments maintained significantly lower litter pH than the untreated control throughout the study. AMLA- and alum-treated litter had the lowest pH values on days 7, 14 and 21, indicating that these amendments maintained lower pH for a longer duration. By day 35, no significant differences in pH were observed among the amendments. The addition of TPX appeared to attenuate the pH reduction, as indicated by the higher pH of SBS + TPX-treated litter (7.3) compared with SBS-treated litter (7.1) on day 28. The NH_3-NH_4^+ equilibrium is influenced more strongly by litter pH than by amendment-specific chemistry. Therefore, amendments capable of maintaining litter pH below 7 for a longer period should provide similar benefits in reducing NH_3 volatilization[36].

The EC of untreated control litter ranged from 6.7 to 7.2 mS cm^{-1} throughout the study (Table 1). Over the 42-day study period, the average EC values of litter treated with AMLA, alum and alum + TPX were 11.3, 12.1 and 12.1 mS cm^{-1}, respectively, all of which exceeded the overall average for the untreated control (7.0 mS cm^{-1}). The highest numerical EC values at the final sampling were observed in SBS- and SBS +TPX-treated litter, at 16.1 and 15.7 mS cm^{-1}, respectively. Higher EC values in amended litter were expected because of the addition of aluminum and sodium bisulfate salts[48]. Unlike the reduction in pH, the elevated EC of amended litter persisted throughout the 42-day flock, reflecting the accumulation of soluble salts rather than a transient chemical reaction. The sustained increase in litter EC has implications for land application, particularly in arid environments where soil salinization is a concern.

At the beginning of the flock, litter moisture content ranged from 19-24%, with SBS-treated litter exhibiting significantly higher moisture content than all other treatments. The higher initial moisture content of SBS-treated litter may be attributable to the application of the amendments three days before chick placement (day 0). Litter moisture content increased over the course of the study in all treatments. The most pronounced differences occurred on days 14, 21 and 28, when SBS- and SBS+TPX-treated litter had significantly higher moisture content than all other treatments. On day 42, the moisture content of SBS-treated litter was 38%, compared with 30% for AMLA-treated litter, 30% for alum-treated litter and 31% for alum+TPX-treated litter. The moisture contents of AMLA-, alum- and alum +TPX-

Table 1: Litter pH, electrical conductivity and moisture content by treatment and sampling day

	Days							
Treatments	0	7	14	21	28	35	42	Average
	pH							
Control	8.2^{a}	8.0^{a}	7.8^{a}	7.9^{a}	8.2^{a}	8.3^{a}	8.1^{a}	8.1^{a}
AMLA	5.0^{c}	6.0^{bc}	6.2^{d}	6.6^{d}	7.2^{bc}	7.5^{b}	7.6^{b}	6.6^{b}
Alum	5.4^{bc}	5.9^{c}	6.1^{d}	6.7^{d}	7.2^{bc}	7.4^{b}	7.5^{b}	6.6^{b}
Alum+TPX	5.9^{b}	6.3^{bc}	6.5^{c}	6.9^{c}	7.3^{b}	7.5^{b}	7.6^{b}	6.9^{b}
SBS	5.3^{bc}	6.3^{bc}	6.4^{c}	6.9^{c}	7.1^{c}	7.5^{b}	7.6^{b}	6.7^{b}
SBS+TPX	5.5^{bc}	6.4^{b}	6.8^{b}	7.1^{b}	7.3^{b}	7.5^{b}	7.5^{b}	6.9^{b}
	Electrical conductivity mS cm^{-1}							
Control	7.1^{c}	7.2^{c}	7.0^{d}	6.7^{e}	6.8^{c}	6.9^{d}	7.2^{d}	7.0^{c}
AMLA	12.7^{b}	12.0^{b}	11.2^{c}	10.7^{d}	11.1^{b}	10.7^{c}	10.4^{c}	11.3^{b}
Alum	13.5^{b}	13.2^{b}	12.0^{bc}	11.5^{cd}	11.9^{b}	11.5^{b}	10.8^{c}	12.1^{b}
Alum+TPX	13.2^{b}	12.9^{b}	12.3^{b}	11.6^{c}	12.2^{b}	11.4^{b}	11.2^{b}	12.1^{b}
SBS	20.7^{a}	18.3^{a}	17.0^{a}	15.2^{a}	14.3^{a}	13.5^{a}	13.7^{a}	16.1^{a}
SBS+TPX	20.2^{a}	18.1^{a}	15.9^{a}	14.4^{b}	15.2^{a}	13.3^{a}	12.5^{b}	15.7^{a}
	Moisture (%)							
Control	19.0^{c}	18.0^{a}	20.0^{a}	26.0^{a}	26.0^{a}	30.0^{a}	35.0^{a}	25.0^{bc}
AMLA	19.0^{c}	17.0^{a}	20.0^{a}	23.0^{a}	23.0^{a}	27.0^{a}	30.0^{b}	23.0^{c}
Alum	20.0^{c}	18.0^{a}	20.0^{a}	26.0^{a}	23.0^{a}	28.0^{a}	30.0^{b}	24.0^{c}
Alum+TPX	21.0^{bc}	19.0^{a}	20.0^{a}	23.0^{a}	23.0^{a}	27.0^{a}	31.0^{b}	23.0^{c}
SBS	24.0^{a}	21.0^{a}	26.0^{b}	33.0^{b}	31.0^{b}	36.0^{a}	38.0^{a}	30.0^{a}
SBS+TPX	22.0^{ab}	19.0^{a}	25.0^{b}	30.0^{b}	29.0^{b}	33.0^{a}	36.0^{a}	28.0^{ab}

Values in columns followed by different letters indicate significant differences in means at an alpha level of 0.05, AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

Table 2: Litter total nitrogen (TN) and soluble reactive phosphorus (SRP) concentrations by treatment and sampling day

	Days							
Treatments	0	7	14	21	28	35	42	Average
	Total N (g kg^{-1})							
Control	27.7^{a}	28.7^{a}	27.5^{b}	25.1^{b}	24.4^{b}	23.5^{c}	22.8^{d}	25.7^{b}
AMLA	27.2^{a}	30.7^{a}	32.1^{a}	30.1^{a}	29.3^{a}	27.1^{a}	26.3^{bc}	29.0^{a}
Alum	27.7^{a}	30.4^{a}	31.3^{a}	29.0^{a}	29.6^{a}	27.5^{a}	28.2^{a}	29.1^{a}
Alum+TPX	26.0^{a}	29.4^{a}	32.5^{a}	28.6^{a}	28.6^{a}	26.6^{ab}	26.8^{ab}	28.4^{a}
SBS	25.9^{a}	29.9^{a}	27.4^{b}	25.7^{b}	26.0^{b}	25.1^{b}	25.8^{bc}	26.5^{b}
SBS+TPX	24.4^{a}	31.2^{a}	26.7^{b}	25.1^{b}	25.6^{b}	23.4^{c}	25.1^{c}	25.9^{b}
	SRP (mg kg^{-1})							
Control	1201.0^{c}	1361.0^{c}	1456.0^{c}	1188.0^{c}	967.0^{c}	838.0^{b}	967.0^{a}	1140.0^{c}
AMLA	162.0^{d}	432.0^{d}	603.0^{d}	706.0^{d}	619.0^{d}	458.0^{c}	502.0^{b}	497.0^{d}
Alum	97.0^{d}	271.0^{d}	437.0^{d}	579.0^{d}	516.0^{d}	406.0^{c}	464.0^{b}	396.0^{d}
Alum+TPX	51.0^{d}	198.0^{d}	361.0^{d}	491.0^{d}	437.0^{d}	384.0^{c}	380.0^{b}	329.0^{d}
SBS	6757.0^{a}	4817.0^{a}	4684.0^{a}	2676.0^{a}	1919.0^{a}	1217.0^{a}	1110.0^{a}	3312.0^{a}
SBS+TPX	5816.0^{b}	4067.0^{b}	2797.0^{b}	1781.0^{b}	1268.0^{b}	936.0^{b}	1008.0^{a}	2525.0^{b}

Values in columns followed by different letters indicate significant differences in means at an alpha level of 0.05, SRP: Soluble reactive phosphorus, AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

treated litter were also significantly lower than that of the untreated control (35%) on day 42. Applications of sodium bisulfate (PLT) have been shown to increase litter moisture content because of its hygroscopic properties[52,53]. In a study conducted in commercial broiler houses, Hunolt *et al.*[53] reported significantly higher litter moisture content in PLT-treated houses (34%) than in untreated houses (21%). Hunolt *et al.*[53] also reported reduced bird performance, as indicated by lower weight gains, in the SBS-treated house, which the farmer attributed to the higher moisture content of the treated litter. Carr *et al.*[54] found that increased litter moisture content can increase NH_3 volatilization.

Litter total nitrogen (TN) concentrations over time are presented in Table 2. At the beginning of the study, TN concentrations ranged from 24.4 to 27.7 g TN kg^{-1}, with no significant differences among treatments through day 7. On days 14, 21 and 28, AMLA-, alum- and alum + TPX-treated litter had significantly higher TN concentrations than SBS- and SBS+TPX-treated litter. Across the 42-day study, the average TN concentrations for AMLA, alum and alum + TPX were 29.0, 29.1 and 28.4 g N kg^{-1}, respectively. These values were significantly higher than those for SBS, SBS+TPX and the untreated control, which were 26.5, 25.9 and 25.7 g N kg^{-1}, respectively. On day 42, the TN concentration of alum-treated litter (28.2 g TN kg^{-1}) was 24% higher than that of the untreated control (22.8 g TN kg-^{1}) and was numerically the highest among the amendment treatments. In contrast, SBS+TPX-treated litter had the lowest TN concentration among the amended treatments (25.1 g TN kg^{-1}, Table 2). These findings suggest that aluminum-containing amendments were more effective than SBS-based amendments in conserving N in poultry litter. By retaining several additional grams of N per kilogram of litter relative to SBS-based treatments, aluminum-based amendments may reduce N losses and increase the fertilizer value of litter for subsequent land application. Sims and Luka-McCafferty[55] compared 97 alum-treated poultry houses with 97 untreated houses and reported that alum treatment increased litter TN concentrations. Anderson *et al.*[46] found that cumulative forage yields from runoff plots fertilized with litter from the current study were significantly higher for all litter treatments than for the unfertilized control. Similarly, studies using alum-treated litter reported forage yield increases of 6% and 28% relative to untreated litter, as reported by Moore and Edwards and Shreve *et al.*[32], respectively.

Litter-soluble reactive phosphorus (SRP) concentrations over time are presented in Table 2. Immediately after amendment application, AMLA, alum and alum + TPX reduced litter SRP concentrations by 86, 92 and 96%, respectively, whereas SBS and SBS+TPX increased SRP concentrations by 463% and 384%, respectively. Litter treated with aluminum-based amendments maintained lower SRP concentrations than the untreated control throughout the study. At the end of the study, alum+TPX, alum and AMLA reduced SRP concentrations by 61, 52 and 48%, respectively, relative to the control. Although alum+TPX did not differ significantly from the other aluminum-based amendments, it consistently exhibited the numerically lowest litter SRP concentrations and had an SRP concentration 18% lower than that of alum-treated litter on day 42 (Table 2). The sustained reduction in SRP throughout the 42-day flock suggests that aluminum-based amendments continued to bind P beyond the initial application, maintaining their effectiveness as litter accumulated. The SBS-based treatments had significantly higher SRP concentrations than the untreated control during

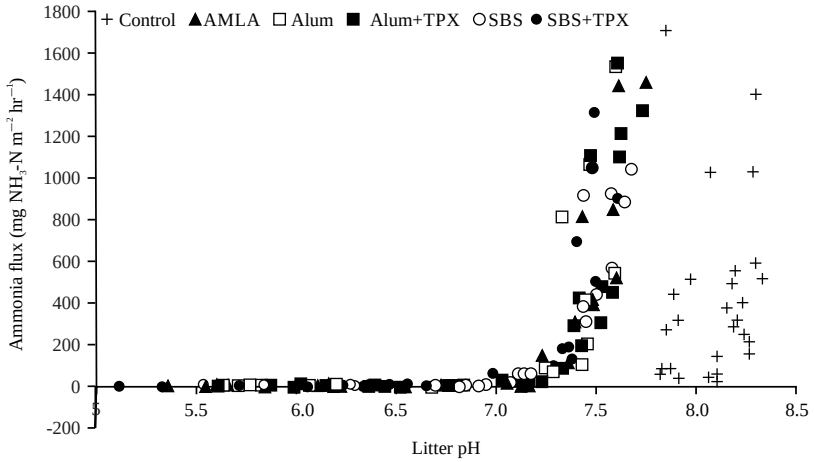


Fig. 1: Ammonia flux (NH_3-N) as a function of litter pH
AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

Table 3: Ammonia-N flux as a function of time

	Days						
Treatments	0	7	14	21	28	35	42
	Ammonia-N Flux (mg m^{-2} hr^{-1})						
Control	189.0[a]	41.0[a]	67.0[a]	383.0[a]	365[a]	510[a]	1289[a]
AMLA	-0.5[b]	0.8[b]	0.4[b]	-1.1[b]	74[b]	410[a]	1143[a]
Alum	1.8[b]	1.5[b]	0.9[b]	0.9[b]	71[b]	279[a]	1124[a]
Alum+TPX	4.7[b]	1.0[b]	1.6[b]	15.7[b]	150[b]	411[a]	1293[a]
SBS	0.8[b]	2.4[b]	2.6[b]	-1.5[b]	44[b]	420[a]	936[a]
SBS+TPX	-0.3[b]	1.9[b]	3.5[b]	29.0[b]	118[b]	360[a]	983[a]

Values in columns followed by different letters indicate significant differences in means at an alpha level of 0.05, AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

the first four weeks of the study (Table 2). The SBS+TPX treatment had significantly lower SRP concentrations than SBS alone during the first five weeks and remained numerically 9% lower at the end of the study, although this difference was not statistically significant. Moore[45] observed that alum+TPX reduced SRP concentrations by 77% relative to alum alone. In a rainfall simulation study conducted on small plots, Anderson *et al.*[46] found that litter treated with AMLA, alum and alum+TPX reduced soluble P runoff by 50, 60 and 38%, respectively.

Ammonia and greenhouse gas fluxes: Ammonia volatilization from litter treated with the various amendments remained near zero until the litter pH increased to approximately 7.0, at which point volatilization increased exponentially (Fig. 1). NH_3 fluxes from amended litter began to increase between days 21 and 28 and by day 35, no significant differences in fluxes were observed between amended and control litter (Table 3). Moore *et al.*[36] observed that NH_3 volatilization increases rapidly when litter pH reaches or exceeds 7. NH_3 fluxes from the control litter ranged from 189 mg NH_3-N m^{-2} h^{-1} on day 0 to 1,289 mg NH_3-N m^{-2} h^{-1} on day 42. The alum+TPX treatment generally exhibited numerically higher NH_3 fluxes than the AMLA and alum treatments. Similarly, NH_3 fluxes were numerically higher in SBS + TPX-treated litter than in litter treated with SBS alone on days 14, 21, 28 and 42 (Table 3). The effectiveness of the litter amendments in reducing NH_3 fluxes declined as litter pH increased over the course of the flock. Anderson *et al.*[57] reported similar patterns of NH_3 emission reduction in alum- and AMLA-treated litter over the course of a flock in a pen trial.

Cumulative NH_3 fluxes during the 42-day study ranged from 87 g NH_3-N m^{-2} for alum-treated litter to 292 g NH_3-N m^{-2} for the untreated control (Fig. 2a). All amendments significantly reduced cumulative NH_3 fluxes relative to the untreated control. Alum produced the greatest numerical reduction in cumulative NH_3 fluxes (70%), whereas alum + TPX produced the smallest reduction (56%); however, no significant differences were observed among the amendments. The high spatial and temporal variability

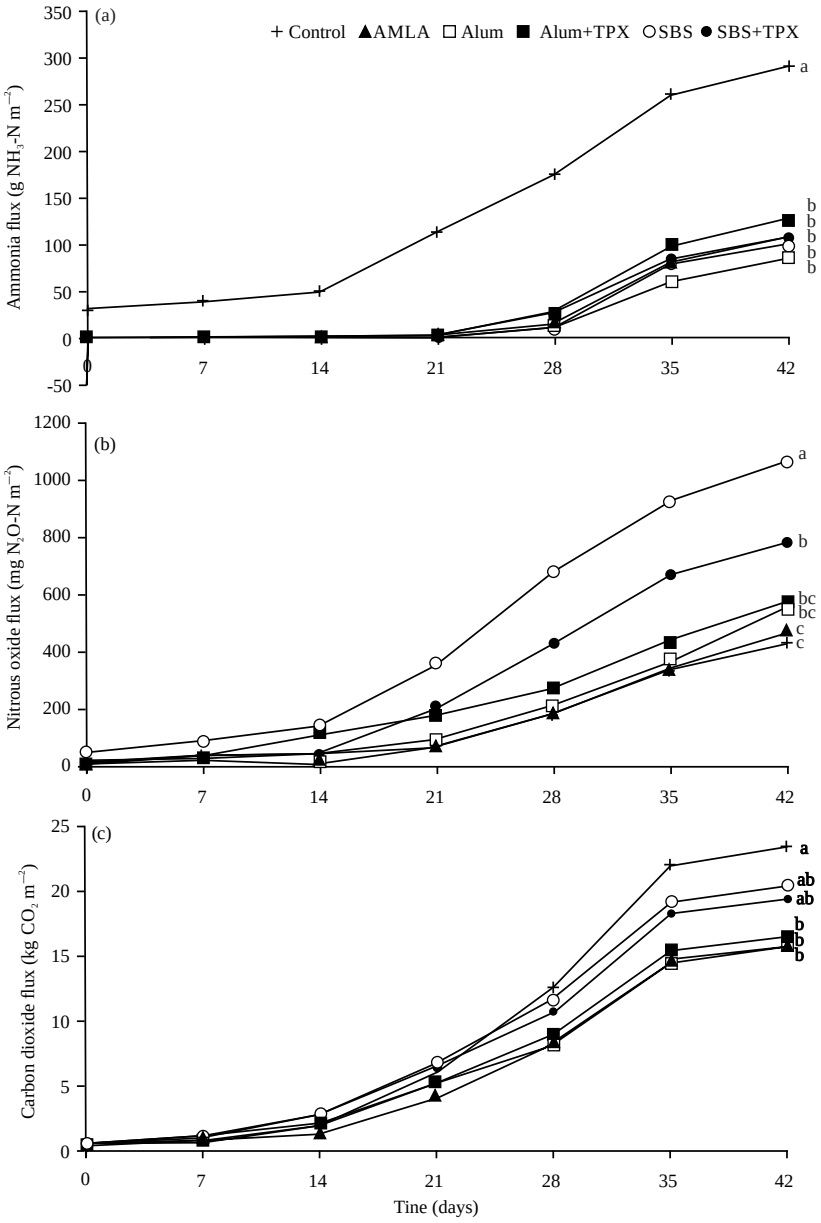


Fig. 2(a-c): Cumulative (a) NH_3-N (b) N_2O-N and (c) CO_2 emissions as a function of time
AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

inherent in chamber-based NH_3 flux measurements limited the statistical power to detect differences among amendments, despite the numerically substantial differences observed. Litter TN content may provide a complementary indicator of N conservation because of its lower variability among samples and the clear differences observed among treatments. Average TN concentrations in litter treated with aluminum-based amendments were significantly higher than those in litter treated with SBS-based amendments. In a 14-day laboratory study, Moore[42] found that alum reduced cumulative NH_3 fluxes by 86%. In the same study, reductions in cumulative NH_3 fluxes ranged from 62-73% among eight different AMLA formulations. Anderson *et al.*[57] reported reductions in NH_3 emissions of 70 and 56% for AMLA and alum, respectively. Eugene *et al.*[37] reported a 47% reduction in NH_3 emissions from poultry houses treated with alum.

Cumulative nitrous oxide (N_2O) fluxes ranged from 431 mg N_2O-N m^{-2} for the untreated control to 1,064 mg N_2O-N m^{-2} for SBS-treated litter (Fig. 2b). Cumulative N_2O fluxes were higher in SBS-treated litter (1,064 mg N_2O-N m^{-2})

Table 4: Footpad and Hock Burn Scores at Day 21 and 42

	Footpad		Hock Burn	
Treatments	21	42	21	42
Control	0.35^{b}	0.43^{c}	0.00^{a}	0.85^{bc}
AMLA	0.00^{c}	0.20^{cd}	0.00^{a}	0.50^{cd}
Alum	0.00^{c}	0.25^{cd}	0.00^{a}	0.70^{bcd}
Alum+TPX	0.03^{bc}	0.00^{d}	0.00^{a}	0.33^{d}
SBS	0.88^{a}	1.35^{a}	0.00^{a}	1.43^{a}
SBS+TPX	1.03^{a}	0.90^{b}	0.00^{a}	1.10^{ab}

Values in columns followed by different letters indicate significant differences in means at an alpha level of 0.05, AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

and SBS+TPX-treated litter (780 mg N_2O-N m^{-2}) than in the control, with SBS-treated litter exhibiting higher fluxes than all other treatments. Litter moisture content was higher in the SBS treatment than in all other treatments, while SBS+TPX-treated litter had higher moisture content than litter receiving amendments without SBS (Table 1). As noted previously, the increased moisture content of SBS-treated litter was likely attributable to the hygroscopic nature of SBS. Anderson et al. reported no significant differences in N_2O fluxes among treatments in a similar pen trial involving alum- and AMLA-treated broiler litter. Cumulative N_2O fluxes reported by Anderson *et al.*[58] over a 42-day emission study were considerably higher, averaging more than 1,200 mg N_2O-N m^{-2}, compared with an average of 644 mg N_2O-N m^{-2} in the present study. Anderson *et al.*[58] reported an average litter moisture content of 35%, compared with 25% in the present study, which may partly explain the lower average N_2O emissions observed here. High manure moisture content can promote anaerobic conditions, thereby increasing denitrification within the litter [59].

Cumulative carbon dioxide (CO_2) fluxes ranged from 15.6 kg CO_2 m^{-2} for AMLA-treated litter to 23.3 kg CO_2 m^{-2} for the untreated control (Fig. 2c). Cumulative CO_2 fluxes were 15.6, 15.7 and 16.6 kg CO_2 m^{-2} for AMLA, alum and alum+TPX, respectively and all three values were significantly lower than that of the control. Cumulative CO_2 fluxes for SBS+TPX (19.5 kg CO_2 m^{-2}) and SBS (20.5 kg CO_2 m^{-2}) did not differ significantly from those of the other treatments (Fig. 2c). CO_2 fluxes increased throughout the flock as the birds grew, consistent with observations from previous studies[58,60]. Anderson *et al.*[58] reported no significant differences in cumulative CO_2 fluxes between untreated control litter and litter treated with aluminum compounds (AMLA and alum). Tasistro *et al.*[61] observed that SBS reduced CO_2 emissions during an 11-day study of broiler manure with various bedding materials. Eugene *et al.*[37] reported lower total CO_2 emissions from commercial poultry houses treated with alum than from untreated houses; however, this reduction was attributed to lower propane consumption resulting from reduced in-house NH_3 concentrations.

The lower cumulative CO_2 fluxes observed with AMLA, alum and alum+TPX, together with reduced NH_3 fluxes and, for AMLA, lower N_2O fluxes, suggest that these aluminum-based amendments may reduce emissions of multiple gases simultaneously rather than simply shifting emissions from one gaseous form to another. This potential multi-gas benefit would not be fully captured by evaluating emissions of a single gas in isolation.

Foot scores: Footpad scores for broilers raised on litter treated with SBS and SBS TPX were 0.88 and 1.03, respectively, at 3 weeks of age and were significantly higher than those of all other treatments (Table 4). The lowest footpad scores at 3 weeks were observed in birds raised on litter treated with AMLA or alum, both of which had a score of 0, compared with 0.35 for the control. Likewise, footpad scores at 6 weeks of age were highest for birds raised on SBS-treated litter (1.35) and SBS+TPX-treated litter (0.90) and numerically lowest for birds raised on alum + TPX-treated litter (0). The high footpad scores observed in broilers raised on SBS-treated litter were likely associated with the higher litter moisture content. Jong *et al.*[62] observed that increased litter moisture content caused footpad dermatitis and was associated with other welfare issues in broiler chickens.

Hock burn was not observed in birds from any treatment at 3 weeks of age (Table 4). At 6 weeks, hock burn scores were highest in birds raised on SBS-treated litter (1.43) and lowest in birds raised on alum+TPX-treated litter (0.33), which was lower than the control (0.85). Similar results were reported by Kjaer *et al.*[63], who found that the incidence of hock burn increased rapidly after 4 weeks of age in fast-growing conventional broiler hybrids, with less than 10% of birds exhibiting hock burn during the first 4 weeks. Treatments containing aluminum compounds resulted in lower footpad scores than treatments containing SBS at both 3 and 6 weeks

of age. A similar pattern was observed for hock burn scores at 6 weeks, with SBS-containing treatments exhibiting higher scores. These differences are likely related to differences in litter moisture content, as SBS-containing treatments had significantly greater average moisture contents than treatments containing aluminum compounds.

CONCLUSION

All amendments reduced cumulative NH_3 emissions and improved litter N retention relative to the untreated control, although the magnitude of these effects depended on amendment chemistry. Although, the high variability in the flux data resulted in no significant differences in cumulative NH_3 fluxes among the litter amendments, litter treated with alum, alum + TPX and AMLA had significantly greater litter TN concentrations than the untreated control and litter treated with SBS and SBS+TPX, indicating more effective N retention with the alum+TPX and AMLA treatments. Aluminum-based treatments also significantly decreased litter-soluble P compared with the control, with alum+TPX showing the greatest reduction (63%). Sodium bisulfate-based treatments increased litter-soluble P, with the greatest increase occurring at the beginning of the study, when pH values were lowest. Sodium bisulfate-based treatments also increased N_2O emissions compared with control litter. Aluminum-based treatments generally resulted in lower footpad and hock burn scores than untreated litter, whereas SBS-based treatments resulted in significantly higher footpad and hock burn scores, likely because of the increased litter moisture associated with the hygroscopic nature of SBS. When TPX was applied with SBS, litter-soluble P decreased significantly during the first five weeks of the study compared with SBS alone. However, the magnitude of this decrease was lower than previously reported and the difference was no longer significant at the end of the study. Although, the combination of TPX and alum consistently resulted in numerically lower soluble P concentrations than alum alone, the difference was not statistically significant. At some sampling times, the combination of TPX with alum or SBS resulted in significantly higher pH values than the corresponding dry acid treatment alone, which is of concern because the reduction in NH_3 volatilization depends on maintaining lower litter pH. Therefore, further research is needed to determine whether the use of TPX is cost-effective when applied in combination with dry acid amendments such as alum and SBS. AMLA had effectiveness similar to that of alum in reducing NH_3 fluxes, increasing litter N content, lowering litter soluble P and reducing contact dermatitis, as indicated by footpad and hock burn scores. Given the comparable performance of AMLA to alum and its lower production cost, AMLA may provide a viable alternative to alum for producers seeking to manage both NH_3 and P while addressing the price volatility currently affecting the alum market.

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REFERENCES

1. United States Department of Agriculture, National Agricultural Statistics Service (USDA, NASS), 2026. Poultry-Production and Value 2025 Summary. Pages: 14. https://esmis.nal.usda.gov/sites/default/release-files/795885/plva0426.pdf
2. Battye, R., W. Battye, C. Overcash and S. Fudge, 1994. Development and selection of ammonia emission factors. EC/R Incorporated, Durham, North Carolina, USA. U.S. Environmental Protection Agency, Office of Research and Development. Washington, DC, USA. Report No.: EPA/600/R-94/190. EPA contract No.: 68-D3-0034. https://tinyurl.com/2rfj48k3
3. USEPA, 2005. National emission inventory: Ammonia emissions from animal agricultural operations. U.S. Environmental Protection Agency. Washington, DC, USA. https://downloads.regulations.gov/EPA-HQ-SFUND-2007-0469-0531/attachment_14.pdf
4. Ashworth, A.J., J.P. Chastain and P.A. Moore, 2020. Nutrient characteristics of poultry manure and litter. In: Animal manure: Production, characteristics, environmental concerns and management, Waldrip, H.M., P.H. Pagliari and Z. He, (Eds.). Wiley, Madison, Wisconsin, USA, pp: 63-87.
5. Moore, P.A., D. Miles, R. Burns, D. Pote, K. Berg and I.H. Choi, 2011. Ammonia emission factors from broiler litter in barns, in storage and after land application. J. Environ. Qual., 40: 1395-1404.
6. ApSimon, H.M., M. Kruse and J.N.B. Bell, 1987. Ammonia emissions and their role in acid deposition. Atmos. Environ. (1967), 21: 1939-1946.
7. Breemen, N.V., P.A. Burrough, E.J. Velthorst, H.F.V. Dobben, T.D. Wit, *et al.*, 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. Nature, 299: 548-550.
8. Hutchinson, G.L. and F.G. Viets, 1969. Nitrogen enrichment of surface water by absorption of ammonia volatilized from cattle feedlots. Sci., 166: 514-515.

9. Schrøder, H., 1985. Nitrogen losses from Danish agriculture - trends and consequences. Agric., Ecosyst. Environ., 14: 279-289.
10. Barthelmie, R.J. and S.C. Pryor, 1998. Implications of ammonia emissions for fine aerosol formation and visibility impairment: A case study from the lower fraser valley, British Columbia. Atmos. Environ., 32: 345-352.
11. McCubbin, D.R., B.J. Apelberg, S. Roe and F. Divita, 2002. Livestock ammonia management and particulate-related health benefits. Environ. Sci. Technol., 36: 1141-1146.
12. Carlile, F.S., 1984. Ammonia in poultry houses: A literature review. World's Poult. Sci. J., 40: 99-113.
13. Miles, D.M., S.L. Branton and B.D. Lott, 2004. Atmospheric ammonia is detrimental to the performance of modern commercial broilers. Poult. Sci., 83: 1650-1654.
14. Beker, A., S.L. Vanhooser, J.H. Swartzlander and R.G. Teeter, 2004. Atmospheric ammonia concentration effects on broiler growth and performance. J. Appl. Poult. Res., 13: 5-9.
15. Patterson, P.H. and J.P. Blake, 1996. Proceedings of the 1996 National Poultry Waste Management Symposium. National Poultry Waste Management Symposium, Oct 21-23, 1996. National Poultry Waste Management Symposium Committee, Harrisburg, Pennsylvania, USA, Pages: 354.
16. Blake, J.P. and P.H. Patterson, 2000. Proceedings, 2000 National Poultry Waste Management Symposium. National Poultry Waste Management Symposium, Oct 16-18, 2000. National Poultry Waste Management Symposium Committee, Ocean City, Maryland, USA, Pages: 390.
17. 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.
18. Kling, H.F. and C.L. Quarles, 1974. Effect of atmospheric ammonia and the stress of Infect bronchitis vaccination on leghorn males. Poult. Sci., 53: 1161-1167.
19. Miles, D.M., W.W. Miller, S.L. Branton, W.R. Maslin and B.D. Lott, 2006. Ocular responses to ammonia in broiler chickens. Avian Dis., 50: 45-49.
20. Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes. Science, 195: 260-262.
21. Edwards, D.R. and T.C. Daniel, 1993. Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescuegrass plots. J. Environ. Qual., 22: 361-365.
22. 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.
23. DeLaune, P.B., P.A. Moore, D.K. Carman, A.N. Sharpley, B.E. Haggard and T.C. Daniel, 2004. Development of a phosphorus index for pastures fertilized with poultry litter–Factors affecting phosphorus runoff. J. Environ. Qual., 33: 2183-2191.
24. DeLaune, P.B., P.A. Moore, D.K. Carman, A.N. Sharpley, B.E. Haggard and T.C. Daniel, 2004. Evaluation of the phosphorus source component in the phosphorus index for pastures. J. Environ. Qual., 33: 2192-2200.
25. Kleinman, P.J.A., A.N. Sharpley, B.G. Moyer and G.F. Elwinger, 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual., 31: 2026-2033.
26. Moore, P.A. Jr., 1997. Use of alum to inhibit ammonia volatilization and to decrease phosphorus solubility in poultry litter. Patent Number: US 5,622,697. Patent Office: United States Patent and Trademark Office (USPTO). United States of America. https://patents.google.com/patent/US5622697A/en
27. Moore, P.A. Jr., 1999. Use of alum to inhibit ammonia volatilization and to decrease phosphorus solubility in poultry litter. Patent Number: US 5,914,104. United States Patent and Trademark Office (USPTO). United States. https://patents.google.com/patent/US5914104A/en
28. Moore, P.A. Jr., 1999. Methods for decreasing non-point source pollution from poultry manure. Patent Number: US5928403. https://scholarworks.uark.edu/pat/188/
29. Moore, P.A. Jr., 1999. Use of alum to inhibit ammonia volatilization and to decrease phosphorous solubility in poultry litter. Patent No. 5,961,968. United States Patent and Trademark Office, USA. https://patents.google.com/patent/US5961968A/en
30. Moore, P.A. Jr., 1999. High-rise laying hen rearing facility and method. United States Patent and Trademark Office (USPTO). Patent Number: US 5,865,143. https://patents.google.com/patent/US5865143A/en
31. Moore, P.A. and D.M. Miller, 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium and iron amendments. J. Environ. Qual., 23: 325-330.
32. Shreve, B.R., P.A. Moore, T.C. Daniel, D.R. Edwards and D.M. Miller, 1995. Reduction of phosphorus in runoff from field applied poultry litter using chemical amendments. J. Environ. Qual., 24: 106-111.
33. Moore, P.A., T.C. Daniel and D.R. Edwards, 1999. Reducing phosphorus runoff and improving poultry production with alum. Poult. Sci., 78: 692-698.
34. Anderson, K.R., P.A. Moore, D.M. Miller, P.B. DeLaune, D.R. Edwards, *et al*., 2018. Phosphorus leaching from soil cores from a twenty year study evaluating alum treatment of poultry litter. J. Environ. Qual., 47: 530-537.
35. Huang, L., P.A. Moore, P.J.A. Kleinman, K.R. Elkin, M.C. Savin, *et al*., 2016. Reducing phosphorus runoff and leaching from poultry litter with alum: Twenty year small plot and paired watershed studies. J. Environ. Qual., 45: 1413-1420.
36. Moore, P.A., T.C. Daniel and D.R. Edwards, 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. J. Environ. Qual., 29: 37-49.

37. Eugene, B., P.A. Moore, H. Li, D. Miles, S. Trabue, *et al.*, 2015. Effect of alum additions to poultry litter on in-house ammonia and greenhouse gas concentrations and emissions. J. Environ. Qual., 44: 1530-1540.
38. Worley, J.W., L.M. Risse, M.L. Cabrera and M.P. Nolan Jr., 1999. Bedding for broiler chickens: Two alternative systems. Appl. Eng. Agric., 15: 687-693.
39. Worley, J.W., M.L. Cabrera and L.M. Risse, 2000. Reduced levels of alum to amend broiler litter. Appl. Eng. Agric., 16: 441-444.
40. Moore, P.A., A.N. Hotz, K.R. Anderson and J.W. Martin, 2025. Thirty year paired watershed study shows treating poultry litter with alum reduces the legacy effect on phosphorus runoff. J. Environ. Qual., 54: 1619-1630.
41. Moore, P.A. Jr., 2016. Compositions and methods of treating animal manure. U.S. Patent No. 9,301,440. United States Patent and Trademark Office, USA. https://patents.google.com/patent/US9301440B2/en
42. Moore, P.A, 2016. Development of a new manure amendment for reducing ammonia volatilization and phosphorus runoff from poultry litter. J. Environ. Qual., 45: 1421-1429.
43. Adak, A., D. Mallik, S. Khanra and S.K. Chaudhuri, 1999. Alum mud: Phase identification and catalytic potential for aqueous-phase decomposition of hydrogen peroxide. Clays Clay Miner., 47: 234-238.
44. Moore, P.A. Jr., 2024. Composition and method for reducing ammonia and soluble phosphorus in runoff and leaching from animal manure. U.S. Patent No. 11,944,951. United States Patent and Trademark Office, USA. https://patents.google.com/patent/US11944951B2/en
45. Moore, P.A, 2026. Using calcium silicate nanoparticles to reduce phosphorus solubility in poultry litter treated with alum or sodium bisulfate. J. Environ. Qual., Vol. 55. 10.1002/jeq2.70231
46. Anderson, K.R., P. Moore, A.N. Hotz, J.W. Martin, P.R. Owens, *et al.*, 2026. Agronomic and environmental impacts of treating poultry litter with litter amendments. Int. J. Poult. Sci., 25: 123-132.
47. Odom, S.A. and D.J. Ivey, 2019. Compositions and methods for the removal of phosphates and other contaminants from aqueous solutions. U.S. Patent No. 10,246,346. United States Patent and Trademark Office, USA. https://patents.google.com/patent/US10246346B2/en
48. Choi, I.H. and P.A. Moore, 2008. 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. Poult. Sci., 87: 1955-1963.
49. Pierzynski, G.M, 2000. Methods of Phosphorus Analysis for Soils, Sediments, Residuals and Waters. North Carolina State University, Raleigh, North Carolina, USA, ISBN: 1-58161-396-2. Pages: 396.
50. Zarcinas, B.A., B. Cartwright and L.R. Spouncer, 1987. Nitric acid digestion and multi element analysis of plant material by inductively coupled plasma spectrometry. Commun. Soil Sci. Plant Anal., 18: 131-146.
51. Welfare Quality®, 2009. Welfare Quality® Assessment Protocol for Poultry (Broilers, Laying Hens). 1st ed., ASG Veehouderij BV, Lelystad, The Netherlands, ISBN: 978-90-78240-06-8, 90-78240-06-2. Pages: 111.
52. Sun, H., Y. Pan, Y. Zhao, W.A. Jackson, L.M. Nuckles, *et al.*, 2008. Effects of sodium bisulfate on alcohol, amine and ammonia emissions from dairy slurry. J. Environ. Qual., 37: 608-614.
53. Hunolt, A.E., R.O. Maguire, J.A. Ogejo, B.D. Badgley, W.H. Frame and M.S. Reiter, 2015. Multiple applications of sodium bisulfate to broiler litter affect ammonia release and litter properties. J. Environ. Qual., 44: 1903-1910.
54. Carr, L.E., F.W. Wheaton and L.W. Douglass, 1990. Empirical models to determine ammonia concentrations from broiler chicken litter. Trans. Asae, 33: 1337-1342.
55. Sims, J.T. and N.J. Luka McCafferty, 2002. On farm evaluation of aluminum sulfate (alum) as a poultry litter amendment. J. Environ. Qual., 31: 2066-2073.
56. Moore, P.A. and D.R. Edwards, 2005. Long term effects of poultry litter, alum treated litter and ammonium nitrate on aluminum availability in soils. J. Environ. Qual., 34: 2104-2111.
57. Anderson, K., P.A. Moore, J. Martin and A.J. Ashworth, 2020. Effect of a new manure amendment on ammonia emissions from poultry litter. Atmosphere, Vol. 11. 10.3390/atmos11030257
58. Anderson, K., P.A. Moore, J. Martin and A.J. Ashworth, 2021. Evaluation of a novel poultry litter amendment on greenhouse gas emissions. Atmosphere, Vol. 12. 10.3390/atmos12050563
59. Meda, B., M. Hassouna, C. Aubert, P. Robin and J.Y. Dourmad, 2011. Influence of rearing conditions and manure management practices on ammonia and greenhouse gas emissions from poultry houses. World's Poult. Sci. J., 67: 441-456.
60. Miles, D.M., P.R. Owens and D.E. Rowe, 2006. Spatial variability of litter gaseous flux within a commercial broiler house: Ammonia, nitrous oxide, carbon dioxide and methane. Poult. Sci., 85: 167-172.
61. Tasistro, A.S., M.L. Cabrera, C.W. Ritz and D.E. Kissel, 2008. Manipulating bedding materials and PLT™ to reduce NH_3 emissions from broiler manure. Bioresour. Technol., 99: 1952-1960.
62. Jong, I.C.D., H. Gunnink and J.V. Harn, 2014. Wet litter not only induces footpad dermatitis but also reduces overall welfare, technical performance and carcass yield in broiler chickens. J. Appl. Poult. Res., 23: 51-58.
63. Kjaer, J.B., G. Su, B.L. Nielsen and P. Sørensen, 2006. Foot pad dermatitis and hock burn in broiler chickens and degree of inheritance. Poult. Sci., 85: 1342-1348.

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