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RESEARCH ARTICLE

Agronomic and Environmental Impacts of Treating Poultry Litter with Litter Amendments

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Abstract

Background and Objective: Treating poultry litter with aluminum sulfate (alum) has been a successful Best Management Practice (BMP) for reducing ammonia (NH_3) emissions and phosphorus (P) runoff since the 1990s. However, the rising cost of alum has created a need for alternative amendments that reduce soluble P and NH_3 losses. Therefore, the objective of this study was to determine the effects of poultry litter amendments on nutrient runoff, forage growth, and nutrient uptake by tall fescue.

Materials and Methods: The litter amendments evaluated included AMLA (alum mud litter amendment), a new product made from a byproduct of the alum industry, and TPX, a calcium silicate nanoparticle that has been shown to reduce soluble P in poultry litter. A small-plot study was conducted using seven treatments: (1) Unfertilized control, (2) Untreated poultry litter, (3) AMLA-treated litter, (4) Alum-treated litter, (5) SBS (sodium bisulfate)-treated litter, (6) Alum +TPX-treated litter and (7) SBS+TPX-treated litter.

Results: Overall, AMLA-, alum- and alum + TPX-treated litter reduced soluble P loads by 50, 60, and 38%, respectively, compared with untreated litter. Similar reductions were observed in total P loads. However, no reductions in P runoff were observed with SBS- or SBS +TPX-treated litter. Forage yield and N uptake were significantly higher in all litter-fertilized plots than in the unfertilized control. Nitrogen uptake was 32 to 38% higher in plots fertilized with alum-, alum + TPX- and SBS-treated litter than in plots receiving untreated litter or SBS +TPX-treated litter.

Conclusion: This study provides further evidence that AMLA is as effective as alum in reducing P runoff from poultry litter. The results suggest that AMLA is a promising alternative litter amendment for improving the environmental sustainability of poultry litter management while maintaining agronomic performance.

INTRODUCTION

Phosphorus (P) runoff from fields fertilized with poultry litter is one of the biggest environmental problems facing the poultry industry. Over 90% of the P in surface runoff from pastures fertilized with manure is soluble P[1]. Soluble P is of greatest concern because it is the form that contributes to eutrophication of water bodies[2,3]. Research has shown that P runoff from pastures fertilized with litter is more dependent on the soluble P content of the litter than on total P. Hence, litter with lower soluble P will result in lower P runoff[4-8]. Although, the largest losses of P in runoff from poultry litter occur during the years when litter is applied, annual poultry litter applications often create a buildup of P in the soil when P applications exceed plant P uptake, leading to greater P losses in runoff over the long term[9-11].

Poultry litter amendments, such as alum and sodium bisulfate (SBS), have been used for decades to reduce ammonia (NH_3) emissions from chicken houses, thereby improving bird health and performance. In addition to lowering NH_3, alum has been shown to reduce the soluble P content of litter, as well as P leaching and runoff[6-8,12,13]. Although, treating poultry litter with alum has been shown to have a benefit-to-cost ratio of 1.96, indicating that its use is cost-effective[13], the price of alum has more than doubled over the last decade, creating a need for alternative litter amendments[14].

An alternative to alum is AMLA (alum mud litter amendment), which is made from alum mud, bauxite and sulfuric acid[14-15]. Alum mud is a byproduct of the alum manufacturing process. Currently, alum manufacturers in the United States pay significant landfill fees to dispose of alum mud. Hence, AMLA has the potential to be produced at less than half the cost of alum[14]. Pen trials conducted by Anderson *et al.*[12] and laboratory studies conducted by Moore[14-15] showed that AMLA reduces NH_3 emissions to levels equivalent to, and in some cases greater than, those achieved with alum. Further laboratory studies by Moore[14-15] showed that mixtures containing various ratios of alum mud, bauxite, and sulfuric acid reduced soluble P in litter to the same extent as alum. However, the environmental and agronomic impacts of litter treated with AMLA have not been evaluated to date. Unlike alum and AMLA, treating poultry litter with sodium bisulfate does not reduce its soluble P content because it does not contain aluminum, calcium, or iron. In recent years, the increased use of phytase enzymes in poultry diets has reduced the amount of phytate-P in poultry litter. Since a large fraction of the P precipitated by alum has been phytate, the use of phytase has partially suppressed the mechanism through which alum reduces soluble P[16-17]. Moore[17] also demonstrated that when poultry litter is treated with sodium bisulfate, the reaction responsible for the reduction of soluble P by alum is disrupted, in some cases resulting in no reduction in soluble P when alum is added. Moore[17] hypothesized that this effect was due to the formation of sodium alunite [$NaAl(SO_4)_2(OH)_6$], which apparently does not react with either organic or inorganic forms of P.

This has created a need to combine these NH_3 control products with a product capable of binding P to reduce the amount of soluble P in runoff from poultry litter. One such product identified by Moore[17] is TPX, a calcium-based nanoparticle manufactured by N-Clear, Inc. (Atlanta, GA, USA). This product is used to remove P from wastewater in poultry processing plants. A limitation of TPX is its relatively high pH, which prevents it from reducing NH_3 volatilization on its own. Therefore, it is unlikely to provide an economic benefit when applied alone. However, Moore[17] found that treating poultry litter with alum or sodium bisulfate in combination with TPX significantly reduced soluble P compared with the application of alum or SBS alone, indicating that this treatment would likely reduce P runoff.

Research on the environmental impacts of AMLA and TPX has not yet been conducted. Therefore, the objectives of this study were to determine the effects of poultry litter amendments on nutrient runoff, as well as tall fescue growth and nutrient uptake.

MATERIALS AND METHODS

Design and treatments: This study was conducted at the University of Arkansas Agricultural Experiment Station in Fayetteville, AR, using 28 small plots (1.52×6.10 m) cropped to tall fescue (*Festuca arundinacea* Schreb.). The soil series was a Captina silt loam (fine-silty, siliceous, mesic Typic Fragiudult). Soil samples were collected prior to fertilization. A stainless-steel soil probe (2.5 cm i.d.) was used to collect five soil cores (0-5 cm) from each plot following a random sampling pattern. The sampling holes were filled with soil collected adjacent to the plots. Soil samples were extracted for Mehlich-3 extractable P (M3-P) using a 1:10 soil-to-M3 solution ratio according to Mehlich[18] and analyzed by ICP-OES as described for litter samples. Soil M3-P values were used to randomize treatments among plots so that each treatment had an average M3-P concentration of 105 mg P kg^{-1} within 1.3 mg kg^{-1}.

The plots had a 5% slope and were hydrologically isolated from the surrounding land using a 15-cm metal barrier installed on all four sides of each plot[4-5]. An aluminum trough, used to divert runoff into a collection barrel, was installed at the lower end of each plot. The treatments consisted of: (1) Unfertilized control, (2) Untreated litter, (3) AMLA-treated litter, (4) Alum-treated litter, (5) SBS-treated litter, (6) Alum+TPX-treated litter and (7) SBS+TPX-treated litter. There were four replications arranged in a randomized block design. Treatments were assigned to plots based on background Mehlich-3 P (M3-P) soil concentrations so that treatment means were within 1.3 mg P kg^{-1} of 105 mg P kg^{-1}.

The litter used in this study was obtained from a recently completed pen trial that evaluated the effects of these amendments on NH_3 and greenhouse gas emissions. The pen trial consisted of 24 pens (2.1×1.8 m), each containing 41 birds at a stocking density of 0.09 m^2 $bird^{-1}$, arranged in a randomized block design with four replicates of six treatments: (1) Control, (2) 106 kg alum 100 m^{-2}, (3) 106 kg SBS 100 m^{-2}, (4) 106 kg AMLA 100 m^{-2}, (5) 106 kg alum 100 m^{-2} +10.6 kg TPX 100 m^{-2} and (6) 106 kg SBS 100 m^{-2} +10.6 kg TPX 100 m^{-2}. Treatments were applied at the beginning of the flock to 40 kg of used litter, and birds were reared on the litter for six weeks. The litter from the pen trial was subsequently applied to the field plots at a rate equivalent to 8.96 Mg ha^{-1}. Prior to application, the litter was analyzed for moisture content, pH, Electrical Conductivity (EC), total N (TN), total C (TC), soluble ammonium (NH_4-N), exchangeable NH_4-N, nitrate (NO_3-N), total P (TP), soluble reactive P (SRP), and total metals (Table 1). Moisture content was determined by oven-drying a litter subsample at 60°C for one week. Total N and TC were determined by dry combustion of fresh litter using an Elementar Vario Max Analyzer (Elementar Americas, Ronkonkoma, NY, USA). Soluble metals, soluble NH_4-N, SRP, and NO_3-N were determined from fresh litter using a 1:10 litter-to-water extraction ratio according to Self-Davis and Moore[19]. The pH and EC were measured using a subsample of the 1:10 litter-to-water extract. Exchangeable NH_4-N was determined from fresh litter using a 1:10 litter-to-1N KCl extraction ratio according to Choi and Moore[20]. Total metals were determined by digesting oven-dried, ground litter samples with nitric acid and hydrogen peroxide according to the method of Zarcinas *et al.*[21].

Both soluble and total metals were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) using an Agilent 5110 ICP-OES (Agilent Technologies, Santa Clara, CA, USA). Soluble NH_4-N, exchangeable NH_4-N, and NO_3-N extracts were analyzed colorimetrically using a Skalar auto-analyzer (Skalar, Buford, GA, USA), following the salicylate-nitroprusside USEPA Method 351.2[22] for soluble and exchangeable NH_4-N and the Cd-reduction method according to American Public Health Association Method 418-F for NO_3-N[23].

Runoff collection and analysis: Large portable rainfall simulators were used to generate two separate runoff events, one week apart, from each plot at one and eight days after litter application using tap water. The portable simulators were equipped with eight nozzles positioned approximately 3 m above the surface of the runoff plots, producing artificial

Table 1. Chemical characteristics of poultry litter used for runoff study

Parameter	Untreated litter	SBS**	SBS+TPX	Alum	Alum+TPX	AMLA
pH	8.13^{a*}	7.59^{b}	7.50^{b}	7.51b	7.61^{b}	7.60^{b}
EC, uS cm^{-1}	7.24^{d}	13.74^{a}	12.48^{ab}	10.83^{c}	11.24^{bc}	10.38^{c}
SRP, mg kg^{-1}	967.00^{a}	$1,110^{a}$	$1,008^{a}$	464.00^{b}	380.00^{b}	502.00^{b}
Total metals (g kg^{-1})						
C	271.00^{a}	234.00^{c}	244.00^{bc}	268.00^{a}	263.00^{ab}	269.00^{a}
N	22.80^{d}	25.8^{bc}	25.10^{c}	28.20^{a}	26.80^{ab}	26.30^{bc}
P	23.70^{a}	21.90^{a}	22.00^{a}	22.20^{a}	23.70^{a}	20.30^{a}
K	40.80^{a}	38.60^{a}	37.20^{a}	35.20^{a}	37.00^{a}	34.80^{a}
Ca	29.10^{a}	28.10^{a}	29.70^{a}	28.00^{a}	32.60^{a}	27.90^{a}
S	8.50^{c}	33.40^{a}	30.60^{a}	21.10^{b}	21.90^{b}	19.50^{b}
Al	0.28^{c}	0.46^{c}	0.26^{c}	6.50^{ab}	6.96^{a}	4.69^{b}
Na	7.49^{b}	25.90^{a}	25.10^{a}	6.79^{b}	7.59^{b}	6.40^{b}
Mg	5.69^{a}	5.05^{a}	5.13^{a}	5.48^{a}	5.84^{a}	5.37^{a}
Total metals (mg kg^{-1})						
Fe	252.00^{b}	245.00^{b}	235.00^{b}	414.00^{a}	431.00^{a}	307.00^{a}
Mn	558.00^{a}	505.00^{a}	502.00^{a}	540.00^{a}	557.00^{a}	515.00^{a}
Cu	554.00^{a}	514.00^{a}	497.00^{ab}	509.00^{a}	529.00^{a}	446.00^{b}
Zn	582.00^{a}	545.00^{a}	553.00^{a}	564.00^{a}	574.00^{a}	526.00^{a}
B	$70.0.0^{a}$	67.20^{a}	66.50^{a}	63.70^{a}	65.30^{a}	61.70^{a}
Ni	$13.6.0^{a}$	13.00^{a}	12.50^{a}	12.40^{a}	13.90^{a}	15.40^{a}
Ti	1.88^{b}	1.76^{b}	1.70^{b}	10.67^{a}	12.43^{a}	9.66^{a}
As	0.95^{a}	0.75^{a}	1.09^{a}	1.06^{a}	0.98^{a}	0.99^{a}
Pb	0.31^{b}	0.27^{b}	0.20^{b}	0.21^{b}	0.28^{b}	0.59^{a}
Co	0.73^{a}	0.67^{a}	0.68^{a}	0.61^{a}	0.62^{a}	0.69^{a}
Mo	3.92^{a}	3.85^{a}	3.55^{a}	4.04^{a}	4.16^{a}	3.80^{a}
Cd	0.33^{a}	0.30^{a}	0.30^{a}	0.31^{a}	0.32^{a}	0.31^{a}

*Different letters indicate a significant difference between treatments at an alpha level of 0.05, **AMLA: Alum mud litter amendment, SBS: Sodium bisulfate, TPX: A calcium silicate nanoparticle rainfall at a rate of 5 cm per hour[4,24]. The water pressure at the nozzles was maintained at 28 kPa, providing a flow rate of 126 mL sec^{-1}. This allowed water droplets to be produced with a size, velocity, and impact similar to those of natural rainfall[25]. The plots received artificial rainfall until 30 min of continuous runoff had occurred. Runoff was collected in a large barrel located at the lower end of each plot.

Total runoff volumes were calculated by measuring the depth of runoff in each collection barrel. Composite samples collected from each barrel were analyzed for pH, EC, TN, TOC, soluble NH_4-N, NO_3-N, TP, total and soluble metals, and SRP. For the analysis of soluble metals, SRP, NH_4-N, and NO_3-N, runoff samples were syringe-filtered through a 0.45-µm nitrocellulose filter and acidified to pH <2, except for NO_3-N samples, which remained unacidified. Total metals in runoff were analyzed using a nitric acid digestion procedure (Method 6010B[26]) on unfiltered samples.

Both TN and TOC were determined on unfiltered samples using a Shimadzu TOC-L Series analyzer equipped with a TN-L unit (Shimadzu Corporation, Kyoto, Japan). Total and soluble metals, as well as SRP, NH_4-N and NO_3-N, were determined by ICP-OES and colorimetric analysis using a Skalar auto-analyzer, as described for the litter samples.

Forage collection and analysis: Forage was harvested at 21, 42 and 200 days after litter application. Forage samples were collected from a 1-m^2 area (0.5 m×2 m). To avoid soil contamination, a subsample was collected manually from the center of the harvest area to a height of 10 cm using shears. A bagger mower set at a 10-cm cutting height was then used to collect the remaining forage within the 1-m^2 area. Yield, moisture content, TN, TC and total metals were measured for each sample.

Forage samples were weighed, dried at 60°C for one week, and then reweighed to determine moisture content. The dried samples were ground using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA) to pass through a 2-mm screen. The samples were analyzed for total N and total C using an Elementar Vario Max C/N Analyzer (Elementar Americas, Ronkonkoma, NY, USA). For total metal analysis, 0.5 g of dried, ground sample was digested in concentrated nitric acid and 30% hydrogen peroxide[19]. Digested samples were analyzed for total metals by inductively coupled argon plasma spectrometry using an Agilent 5110 ICP-OES (Agilent Technologies, Santa Clara, CA, USA).

Data analysis: Statistical analyses were conducted to evaluate the effects of litter amendments on runoff and forage responses using the GLIMMIX procedure in SAS 9.4[27]. A randomized block design with a one-factor treatment structure was employed. Treatments were considered fixed effects, whereas block was treated as a random effect. Fisher's least significant difference test was used to separate treatment means at the 0.05 significance level. Statistical analyses for each rainfall event and forage harvest were performed separately.

RESULTS AND DISCUSSION

Runoff loads: Runoff volumes did not differ significantly among treatments (data not shown). Cumulative soluble and total P loads from the two rainfall events are presented in Fig. 1. Cumulative soluble P loads for AMLA, alum, and alum +TPX were not significantly different from one another. However, compared with untreated litter, these treatments significantly reduced soluble P loads in runoff by 50, 61 and 38%, respectively. Similarly, total P loads were significantly reduced, with AMLA, alum, and alum +TPX decreasing total P loads by 46, 61, and 36%, respectively, compared with untreated litter.

Similar reductions in P loads following alum-treated litter applications were reported by Moore *et al.*[7], who observed a 67% reduction, and by Huang *et al.*[6], who reported a 57% reduction compared with untreated litter. Moore *et al.*[27] also showed that P losses from untreated litter were 2.4 times greater than those from alum-treated litter. Furthermore, cumulative P loads from alum-treated plots were not significantly different from those of the unfertilized control, suggesting that alum has a positive environmental impact by substantially reducing P runoff.

No significant reductions in P loads were observed for SBS- or SBS +TPX-treated litter compared with untreated litter. Sodium bisulfate does not contain aluminum, calcium, or iron, which are the elements responsible for reducing P in litter. However, the addition of TPX to SBS-treated litter (SBS+TPX) was expected to reduce P because Moore[17] reported a highly significant reduction in soluble P in litter treated with SBS +TPX. However, this was not observed in the present study. Although the addition of TPX reduced the SRP content of litter compared with SBS treatment alone, SRP concentrations remained similar to those of untreated litter (Table 1). It is possible that a higher application rate of TPX was required in the pen trials. However, increasing the TPX application rate in combination with SBS or alum would likely increase litter pH, thereby reducing the effectiveness of these amendments in decreasing NH_3 volatilization from litter.

All litter treatments resulted in significantly higher cumulative inorganic N and total N loads in runoff than the unfertilized control. However, no significant differences were observed between the treated and untreated litter applications (Fig. 2).

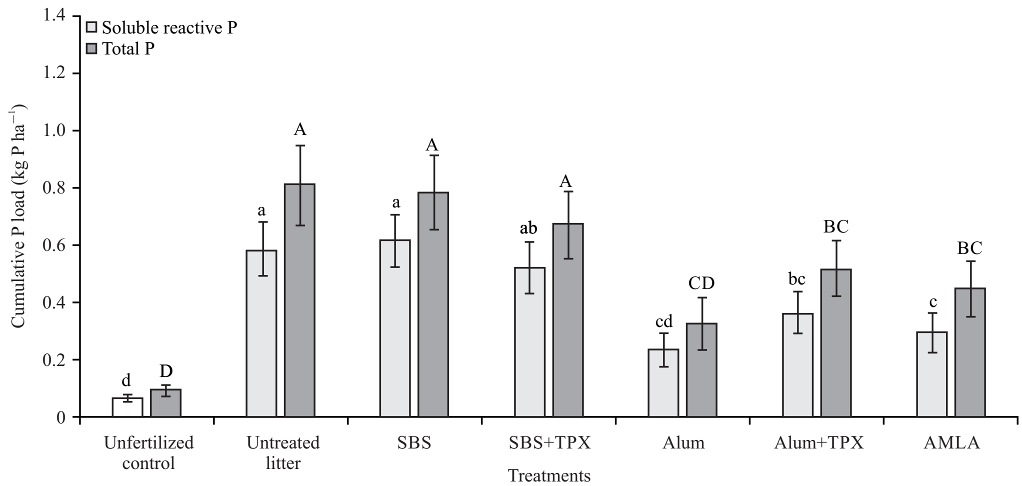

Fig. 1: Cumulative soluble reactive phosphorus (SRP) and total phosphorus (TP) loads in runoff

Different letters (lowercase for SRP; uppercase for TP) indicate significant differences between treatments at an alpha level of 0.05. Error bars represent standard error, AMLA: Alum mud litter amendment; SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

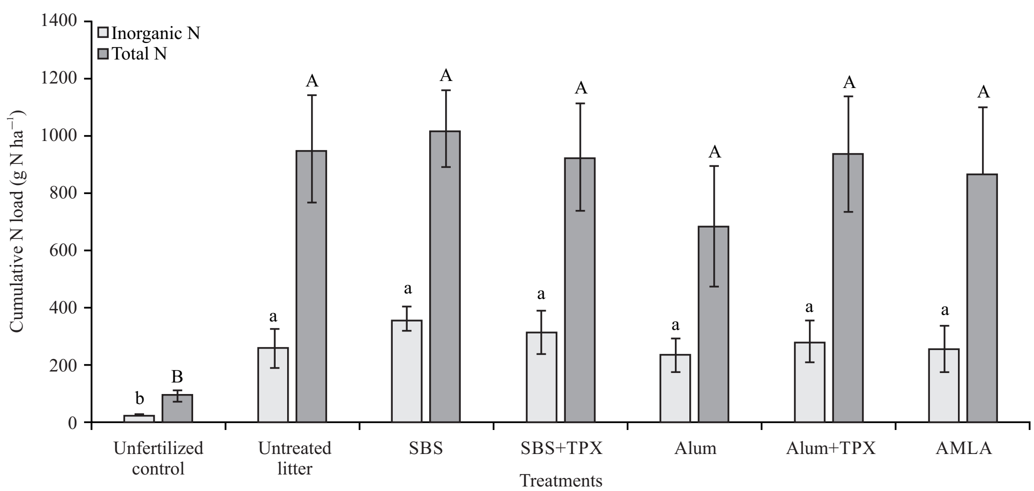

Fig. 2: Cumulative inorganic nitrogen (NH_4+NO_3) and total nitrogen (TN) loads in runoff

Different letters (lowercase for inorganic N; uppercase for TN) indicate significant differences between treatments at an alpha level of 0.05. Error bars represent standard error. AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

During the first rainfall event, runoff pH and EC were significantly higher in plots receiving litter than in the unfertilized control, with no significant differences among the litter treatments (Table 2). During the second rainfall event, runoff pH did not differ significantly among treatments. Similar to the first rainfall event, EC remained significantly higher in plots receiving litter than in the control. However, EC values for the alum- and alum +TPX-treated plots were significantly lower than those for the untreated litter treatment.

Total metal loads in runoff did not differ significantly among treatments for Al, As, Ca, Mg, or Zn during either rainfall event (Table 2). Moore *et al.*[28] and DeLaune *et al.*[29] reported that alum applications significantly reduced As and Zn loads compared with untreated litter. The metal loads reported in those studies were substantially greater than those observed in the present study, which may explain why treatment differences were detected.

Significant differences among treatments were observed for Cu, K, and Na loads. During the first rainfall event, Cu loads were significantly higher in the untreated litter, SBS, and SBS +TPX treatments than in the unfertilized control. During the second rainfall event, untreated litter, SBS, alum +TPX and AMLA produced higher Cu loads in runoff than the control. Potassium loads did not differ among the litter treatments,

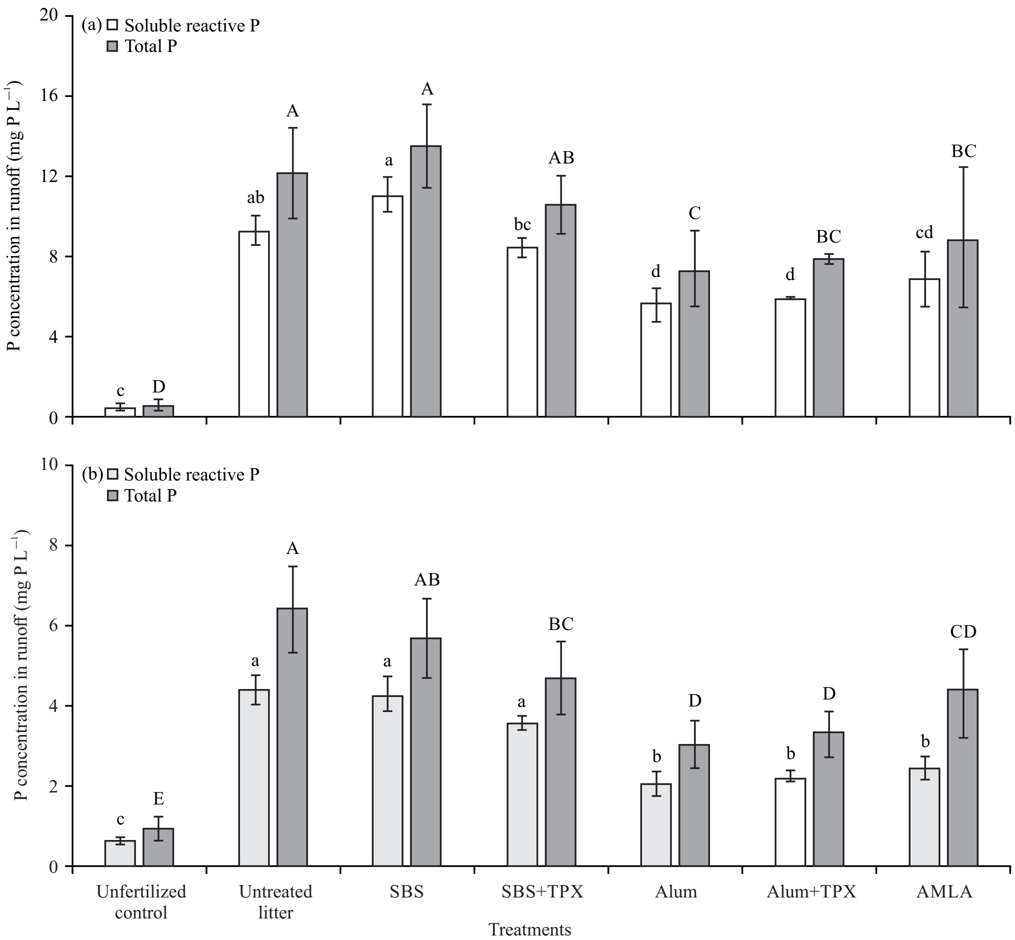

Fig. 3: Soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations in runoff from (a) First runoff event and (b) Second runoff event

Different letters (lowercase for SRP; uppercase for TP) indicate a significant difference between treatments at an alpha level of 0.05. Error bars represent standard error. AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

Table 2: pH, EC and total metal loads in runoff

Treatment	pH	EC (µs cm^{-1})	Al	As	Ca	Cu	Fe	K	Mg	Na	Zn
			g ha^{-1}								
Rainfall 1											
Unfertilized Control	6.70^{b*}	195^{c}	17.1^{a}	0.20^{a}	824^{a}	1.12b	10.94^{a}	154c	173^{a}	313^{c}	1.90^{a}
Untreated Litter	7.26^{a}	360^{ab}	15.5^{a}	0.12^{a}	591^{a}	4.69^{a}	9.15^{a}	1245^{ab}	216^{a}	440^{bc}	2.63^{a}
SBS**	7.33^{a}	416^{a}	16.8^{a}	0.23^{a}	682^{a}	4.55^{a}	8.66^{a}	842^{ab}	249^{a}	708^{ab}	5.16^{a}
SBS+TPX	7.23^{a}	384^{ab}	11.7^{a}	0.26^{a}	896^{a}	4.94^{a}	9.95^{a}	1097^{ab}	290^{a}	907^{a}	4.60^{a}
Alum	7.33^{a}	352^{ab}	13.5^{a}	0.11^{a}	496^{a}	2.78^{ab}	7.06^{a}	598^{bc}	159^{a}	278c	2.70^{a}
Alum+TPX	7.15^{a}	348^{b}	15.3^{a}	0.13^{a}	600^{a}	3.16^{ab}	5.85^{a}	757^{ab}	190^{a}	325c	1.81^{a}
AMLA	7.14^{a}	367^{ab}	17.4^{a}	0.08^{a}	495^{a}	2.91^{ab}	8.04^{a}	669^{abc}	163^{a}	293c	1.82^{a}
Rainfall 2											
Unfertilized Control	7.03^{a}	197^{c}	24.5^{a}	0.22^{a}	1542^{a}	1.62c	14.90^{a}	250c	306^{a}	569^{a}	1.78^{a}
Untreated Litter	7.20^{a}	263^{a}	34.8^{a}	0.50^{a}	1465^{a}	6.12^{a}	16.63^{a}	1405^{a}	554^{a}	775^{a}	2.93^{a}
SBS	7.09^{a}	263^{a}	20.7^{a}	0.40^{a}	1489^{a}	4.74^{ab}	13.38^{a}	749^{bc}	497^{a}	881^{a}	2.60^{a}
SBS+TPX	7.09^{a}	259^{ab}	23.4^{a}	0.18^{a}	1068^{a}	3.42^{bc}	14.04^{a}	550^{bc}	308^{a}	649^{a}	2.22^{a}
Alum	7.21^{a}	243^{b}	14.8^{a}	0.39^{a}	1232^{a}	3.37^{bc}	7.60^{a}	597^{bc}	315^{a}	495^{a}	1.81^{a}
Alum+TPX	7.01^{a}	242^{b}	50.5^{a}	0.25^{a}	2083^{a}	6.67^{a}	41.37^{a}	1036^{ab}	560^{a}	860^{a}	4.28^{a}
AMLA	7.10^{a}	250^{ab}	31.5^{a}	0.21^{a}	1503^{a}	5.03^{ab}	19.92^{a}	843^{b}	469^{a}	649^{a}	2.53^{a}

*Different letters indicate a significant difference between treatments at an alpha level of 0.05, **AMLA: Alum mud litter amendment; SBS: Sodium bisulfate; TPX: A calcium silicate nanoparticle whereas alum- and AMLA-treated plots were not significantly different from the unfertilized control during the first rainfall event.

During the first rainfall event, Na loads in runoff were significantly higher for the SBS and SBS + TPX treatments than for all other treatments. This can be explained by the fact that SBS is sodium bisulfate. Litter treated with SBS or SBS +TPX increased Na concentrations by approximately 257% compared with the other litter treatments (Table 1). No significant differences in Na loads among treatments were observed during the second rainfall event.

Runoff concentrations: Soluble and total P concentrations were significantly higher in plots fertilized with litter than in the unfertilized control plots during both rainfall events (Fig. 3a and b). During both the first and second rainfall events, litter treated with AMLA, alum and alum +TPX resulted in significantly lower soluble P concentrations in runoff than untreated litter. During the first rainfall event, soluble P concentrations were reduced by 26, 39 and 36% for AMLA, alum, and alum + TPX, respectively, compared with untreated litter. Greater reductions in soluble P concentrations were observed during the second rainfall event, with reductions of 44, 53, and 49% for AMLA, alum, and alum +TPX, respectively, compared with plots fertilized with untreated litter. Similar reductions in soluble P concentrations in runoff from alum-treated litter have been reported previously[5-8,13].

During the first rainfall event, SBS +TPX reduced soluble P concentrations by 10% compared with untreated litter and by 24% compared with SBS-treated litter. Similar reductions were observed in total P concentrations in runoff, with AMLA-, alum- and alum +TPX-treated litter producing significantly lower concentrations than untreated litter. During the second rainfall event, total P concentrations in runoff from SBS +TPX-treated litter were 27% lower than those from SBS-treated litter. No significant differences in soluble or total P concentrations in runoff were observed among AMLA, alum, and alum + TPX during either rainfall event. Concentrations of

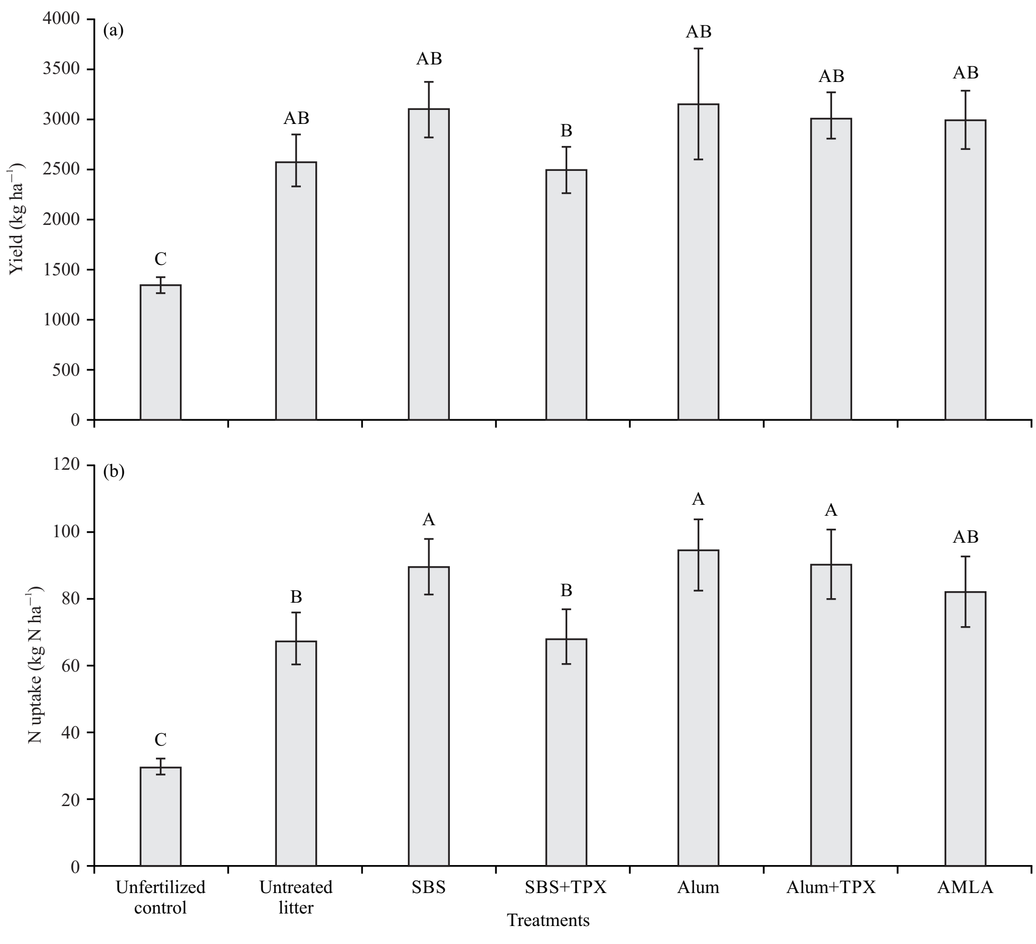

Fig. 4: Continue

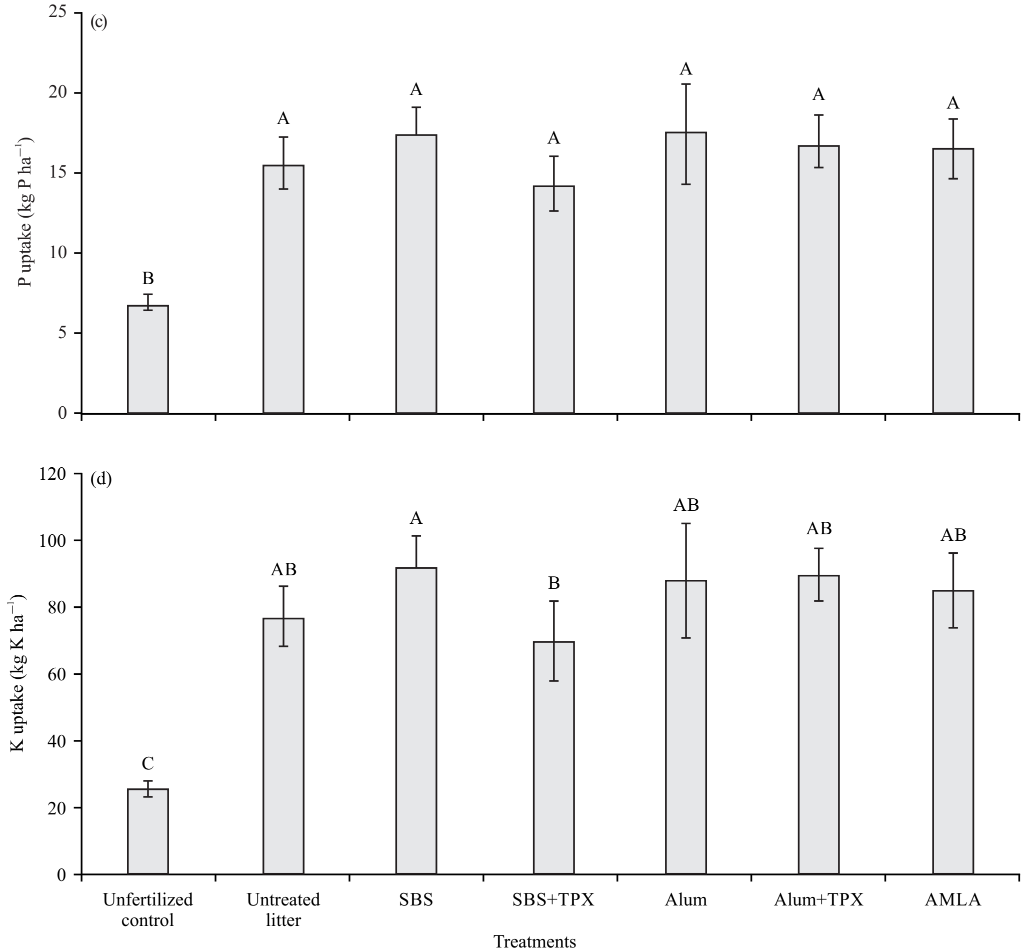

Fig. 4(a-d): Effect of fertilizer treatments on (a) Forage yield, (b) N uptake, (c) P uptake and (d) K uptake

Different letters indicate a significant difference between treatments at an alpha level of 0.05. Error bars represent standard error. AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

total cadmium, chromium, and lead in runoff from all treatments were below 0.01 mg L^{-1} (data not shown). Concentrations of the other heavy metals ranged from 0.02 to 0.18 mg L^{-1} for total Cu and from 0.02 to 0.37 mg L^{-1} for total Zn (data not shown).

Forage yield and nutrient uptake: Cumulative forage yields were significantly higher for all litter-fertilized treatments than for the unfertilized control (Fig. 4a). However, no significant differences in cumulative forage yield were observed among the litter treatments. Ashworth *et al.*[30] also reported that poultry litter amended with alum did not affect forage yield compared with untreated litter. In contrast, Shreve *et al.*[8] reported that forage yields were 28% higher with alum-treated litter than with untreated litter. Similarly, Moore and Edwards[31] reported a 6% increase in forage yield from alum-treated litter compared with untreated litter.

Nutrient uptake in plots fertilized with litter was significantly higher for cumulative N (Fig. 4b), P (Fig. 4c) and K (Fig. 4d) than in unfertilized plots. Alum, SBS, and alum +TPX increased cumulative N uptake by 38, 32 and 33%, respectively, compared with untreated litter. In addition, during the second harvest, both forage yield and N uptake were significantly higher in plots fertilized with AMLA- and SBS-treated litter than in plots fertilized with untreated litter.

Table 3 presents the average nutrient and metal concentrations in forage across the three harvests. Nitrogen and K were the only nutrients with significantly lower concentrations in the unfertilized control than in the litter-fertilized treatments. Nickel, Mn, and Mo concentrations were significantly higher in forage fertilized with untreated litter than in forage from all other treatments.

Table 3: Forage nutrient and total metal characteristics

Parameters	Unfertilized control	Untreated litter	SBS	SBS+TPX	Alum	Alum+TPX	AMLA
	g ha^{-1}						
N	22.10^b	27.70^a	30.80^a	28.70^a	31.40^a	31.30^a	29.0^a
C	448.00^a	445.00^a	446.00^a	447.00^a	445.00^a	440.00^a	444^a
P	5.22^a	6.45^a	5.99^a	6.08^a	5.92^a	6.11^a	5.88^a
K	19.1^b	31.30^a	31.50^a	28.90^a	29.60^a	31.50^a	29.6^a
Ca	7.37^a	5.82^a	6.30^a	6.37^a	6.74^a	6.41^a	6.25^a
S	3.10^a	3.52^a	3.73^a	3.68^a	3.80^a	3.64^a	6.50^a
Na	0.64^c	0.63^c	0.89^a	0.84^{ab}	0.64^c	0.61^c	0.67^{bc}
Mg	2.19^a	2.24^a	2.36^a	2.12^a	2.33^a	2.44^a	2.37^a
	mg kg^{-1}						
Al	54.7^a	50.70^a	40.90^a	38.50^a	57.60^a	63.80^a	63.5^a
Fe	71.4^a	76.70^a	74.40^a	64.60^a	75.00^a	63.40^a	63.6^a
Mn	97.8^b	126.00^a	109.00^b	106.00^b	94.50^b	96.80^b	104b
Cu	8.3^a	11.60^a	10.90^a	13.10^a	11.70^a	12.40^a	11.9^a
Zn	36.5^a	40.40^a	40.00^a	44.30^a	43.80^a	42.70^a	40.1^a
B	18.40^a	17.10^a	18.90^a	17.70^a	19.20^a	19.30^a	17.3^a
Ni	1.15^a	2.10^b	1.10^a	1.03^a	1.01^a	1.07^a	1.18^a
Ti	0.11^a	0.10^a	0.09^a	0.15^a	0.11^a	0.08^a	0.12^a
As	0.48^a	0.52^a	0.53^a	0.57^a	0.49^a	0.52^a	0.54^a
Pb	0.15^a	0.18^a	0.17^a	0.15^a	0.16^a	0.13^a	0.15^a
Co	0.10^a	0.09^a	0.09^a	0.08^a	0.11^a	0.06^a	0.08^a
Mo	2.66^b	3.54^a	2.68^b	2.75^b	2.41^a	2.84^b	2.72
Cd	0.09^a	0.12^a	0.10^a	0.08^a	0.09^a	0.09^a	0.09^a

Different letters indicate a significant difference between treatments at an alpha level of 0.05, AMLA: Alum mud litter amendment, SBS: Sodium bisulfate and TPX: A calcium silicate nanoparticle

CONCLUSION

Phosphorus runoff from pastures fertilized with poultry litter has been shown to be highly correlated with the soluble P content of the litter. Therefore, reducing soluble P in litter can have a positive environmental impact by decreasing P loads in surface runoff. Litter amendments such as alum have been shown to reduce soluble P in litter. However, rising costs have created a need for alternative amendments, such as AMLA and TPX. The environmental impacts of land application of litter treated with these alternative amendments had not previously been investigated. A significant reduction in cumulative soluble P loads was observed with AMLA, alum, and alum + TPX, which reduced soluble P loads by 50, 60, and 38%, respectively. Soluble P runoff from AMLA-treated litter was not significantly different from that of alum-treated litter. Similar reductions were also observed in cumulative total P loads. All litter treatments resulted in significantly higher forage yields and N uptake than the unfertilized control. No negative effects were observed following the land application of litter treated with the alternative amendments. The results of this study provide strong evidence that treating poultry litter with AMLA is a sustainable best management practice for reducing P runoff and is as effective as alum.

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