5-1-2008

Effect of poultry litter amended with aluminum sulfate on plant growth and soil properties

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EFFECT OF POULTRY LITTER AMENDED WITH ALUMINUM SULFATE ON PLANT GROWTH AND SOIL PROPERTIES

By

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A Dissertation Submitted to the Faculty of Mississippi State University in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Agronomy in the Department of Plant and Soil Sciences

Mississippi State, Mississippi

August 2008

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TITLE: EFFECT OF POULTRY LITTER AMENDED WITH ALUMINUM SULFATE ON PLANT GROWTH AND SOIL PROPERTIES

Pages in Study: 95

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Amending litter with aluminum sulfate (Al-S) has proven to be effective in reducing water-soluble P but there are concerns that it could result in soil pH reduction and increase levels of extractable soil Al if applied to acidic soils. A glasshouse study with soybean (*Glycine max*, L Merr) and cotton (*Gossypium hirsutum* L) as test crops was conducted to determine the impact of applying litter amended with Al-S at 0, 10 and 20% to an acidic sandy loam soil. These treatments were applied to meet N needs of a crop grown in soil with pH levels of 4.5, 5.0, 5.5 and 6.5. The experimental design was a randomized complete block.

Application of BL + 20% Al-S to soil with initial pH of 4.5 or 5.0 significantly decreased the pH compared to BL. The decrease in soil pH with application of BL + 20% Al-S was attributed to high concentrations of geochemically labile Al which released hydrogen ions upon hydrolysis. Both BL and BL + 10% Al-S increased the initial soil pH and decreased extractable soil Al. Application of BL + 20% Al-S resulted in significant higher levels of extractable soil Al than BL and the differences were greater in the lower pH soils. Mehlich-3 extractable soil P, K, Mg, Ca, and Cu decreased with BL + 10 or 20% Al-S relative to BL. Soybean or cotton biomass from BL + 20% Al-S fertilization was significantly decreased relative to BL fertilized soils with initial pH of 4.5 or 5.0. Biomass with BL + 10% Al-S application were not statistically different from those fertilized with BL. Fertilizing cotton or soybean with BL + Al-S decreased tissue Al, N and P concentration. BL and BL + 10% Al-S showed the potential to increase soil pH and reduce extractable soil Al in acid soils but need further field evaluation.

DEDICATION

I would like to dedicate this dissertation to my family who has supported me throughout the period of my study.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Dr Dennis E. Rowe, the committee chairman providing me the financial support to study at Mississippi State University. Special thanks to Dr Haile Tewolde who directed this research. His encouragement, inspiration, and guidance in conducting this research and in the preparation of the manuscript are highly appreciated. I also extend my appreciation to Drs Jack McCarty, Frank Matta, Teddy Wallace, Michael Cox and Mark Williams for their helpful suggestions.

I am deeply grateful to the staff at USDA-ARS, Waste Management and Forage Unit for their friendship and technical support during all stages of this work. I would like to thank Richard Switzer, Walter Woolfolk and Mary Hardy and Dr Tim Fairbrother for their assistance in laboratory work.

I would also like to thank my fellow graduate students, Mr. Takele Mojire, Vitallis Temu, and Peter Ampim for their friendship and encouragement during the course of study.

Above all, I would like to appreciate my wife Felisters, my kids for their patience and understanding.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The poultry and egg industry is one of the important livestock industries and leads Mississippi agricultural industries in gate receipts. Mississippi produces approximately 740 million broilers per year with an estimated farm production of poultry and eggs in 2001 of $1.54 billion (MSES, 2002). Approximately 1 million metric tonnes of poultry litter is produced every year (MSES, 2002) with the majority applied on agricultural fields to meet N requirement of the crops.

Poultry litter contains all essential plant nutrients but some nutrient ratios are higher than plant requirement. For example, the N to P ratio found in poultry litter ranges from 0.6 to 1.0 (Evanylo and Mullins, 2000), yet the ratio of N removed to P removed ranges from 2.0 in cotton *(Gossypium hirsutum* L.) to 9.0 in peanut (*Arachis hypogaea* L.) (Donahue, 2000). Long-term amendments of agricultural land with poultry manure based on N requirement of the crop have resulted in P accumulation in soils. Phosphorous is an essential plant nutrient of agronomic crops and not toxic to humans. The negative environmental effect of P is its role in the eutrophication of surface waters (Sims and Wolf, 1994). To address issues of environment, onsite poultry litter management using chemical amendments have been evaluated to reduce P release in soil and ammonia volatilization (Moore and Miller, 1994). Al-sulfate (alum) has been used, in addition to other chemical amendments such as Fe-sulfate ($FeSO_4.7H_2O$), calcium hydroxide

[$Ca(OH)_2$], and gypsum ($CaSO_4.2H_2O$), to change litter chemistry and reduce environmental impacts of land application of manure (Moore et al., 1995a). Sims and Luke-McCafferty (2002) found that poultry litter amended with Al-sulfate contained 73% lower water soluble P than untreated litter. The reductions in water soluble P have been attributed to adsorption of P to amorphous aluminum hydroxides in the reaction between poultry litter and Al-sulfate (Peak *et al.,* 2002).

Field studies to provide evidence that P runoff would be reduced with poultry litter amended with Al-sulfate have been conducted. Moore et al., (2000) found that soluble reactive phosphorous (SRP) concentrations in runoff from pastures fertilized with Al-sulfate-treated litter averaged 73% less than that from untreated litter throughout a three-year period. Shreve *et al.,* (1995) found that P runoff from tall fescue (*Festuca arundinacea* Shreb.) plots fertilized with Al-sulfate-amended litter was 87% lower than plots fertilized with untreated litter. Plots receiving Al-sulfate treated litter had significantly greater yields and higher nitrogen contents indicating that Al-sulfate had increased N availability in the litter. Moore *et al.,* (1998c) studied Al-sulfate-amended litter and unamended litter in tall fescue (*Festuca arundinacea Schreb*) with application rates of 0, 2.24, 4.49, 6.73 and 8.98 Mg ha^{-1}. Cumulative herbage yield with Al-sulfate treated litter was up to 6 and 16% higher than with untreated litter and ammonium nitrate respectively.

While environmental effects of poultry litter have been addressed with regard to soluble P and ammonia volatilization, concerns have been raised that long term application of litter amended with Al-sulfate may lead to accumulation of aluminum in soils to levels where it becomes toxic to plants (Sims and LukaMcCafferty, 2002). Current research on the use of Al-sulfate-amended litter has shown an increase in soil pH but those studies were conducted mostly on soils that were neutral and there is no available data on the use of Al-sulfate-amended litter on acidic soils. The potential adverse effect of Al accumulation in the soil should not only take into account the total metal concentration, but also the solubility and bioavailability of aluminum. Many soils in Mississippi and other southeastern states have a low pH and application of Al-sulfate-amended litter might increase extractable soil Al, increase its bioavailability, and reduce soil pH. The objectives of this study were to:

(1) Determine whether application of poultry litter amended with Al-sulfate to acid soils at different levels of pH further reduce soil pH, increase extractable soil Al, and affect plant performance

(2) Determine the influence of litter amended with Al-sulfate on the availability of Al to plants

CHAPTER II

LITERATURE REVIEW

Poultry Litter Production in Mississippi

Poultry is the first commodity in Mississippi to exceed $1.5 billions in sales at the farm gate (MSES, 2002). Mississippi produces 740 million broilers per year and is ranked 4th in the nation in 2000 based on number of broilers produced (USDA, ERC, 2000).

Chickens are raised in houses with a layer of bedding material such as sawdust or rice hulls covering the floor. At the end of the year after raising several bird flocks, the house is usually cleaned of wet or caked litter, which is now a mixture of mainly the bedding material and manure. A house may be completely cleaned out only every one or two years (Sims and Wolf, 1994). Once the litter is removed from the house, it is either applied to the field or stored under a roofed structure or tarpaulin

Table 1

Broiler Production, 2000

State	Number	Meat Produced (lb)
Georgia	1,229,700,000	6,148,500,000
Arkansas	1,191,700,000	5,839,300,000
Alabama	1,038,700,000	5,297,400,000
Mississippi	739,900,000	3,699,500,000
North Carolina	698,400,000	4,050,700,000
Texas	551,000,000	2,589,700,000
Maryland	283,300,000	1,359,800,000
Virginia	264,900,000	1,298,000,000
Delaware	247,700,000	1,461,400,000
Missouri	240,000,000	1,080,000,000

Source: Economic Research Service, USDA

Environmental Effects Associated with Poultry Litter

Poultry litter contains all essential plant nutrients (N, P, K, Ca, Mg, B, Cu, Fe, Mn, Mo, and Zn) and have been well documented to be excellent fertilizers (Bouldin et al., 1984; Edwards and Daniels, 1992; Hilemen, 1976b; Perkins et al., 1964; Simpson, 1990; Sims, 1987; Stephenson et al., 1990). A large database is available documenting the physical and chemical properties of poultry manures and litters (Barrington, 1991; Bomke and Lavkulich, 1975; Kunkle et al., 1981; Overcash et al., 1983b). As with other organic wastes, the moisture content, pH, soluble salt level, and chemical composition of poultry manures and litters vary widely as a function of genetics of poultry, diet, and dietary supplements, litter type, and handling and storage operations (Sims and Wolf, 1994). Several studies documenting the elemental composition of poultry manure and litters have indicated that total N and P contents are the highest among the nutrients (Overcash et al., 1983b; Stephenson et al., 1990; Malone, 1992).

Poultry litter is normally applied on N requirement of the crop and this has resulted in elevated concentrations of P in agricultural soils (Kingery et al., 1994) specifically in soils proximate to concentrated animal production facilities that have received long term applications of animal wastes. Phosphorous levels in soils amended with animal manures for many years are commonly well in excess of the critical values (Sims and Wolf, 1994). A survey of four regional soil testing committees representing 34 states found that the major environmental issue related to soil P was animal waste management, and poultry litter waste management in particular (Sims, 1987). In long term (15-28 yr) land application of broiler litter, Kingery et al., (1994) found that acid extractable P concentrations in littered soils were six times greater than in no littered soils to a depth of 60 cm.

Apart from buildup of P in the soil when amended with poultry litter, dissolved P in the runoff water can lead to accelerated eutrophication. McLeod and Hegg (1984) evaluated the quality of surface runoff water from a fescue pasture (Cecil clay, Typic Hapludults, 3-5% slope) that received surface applications of organic wastes (dairy manure, poultry manure, sewage sludge) and commercial fertilizer. The percentages of total P added in manure that was lost in the runoff were 2.4, 1.3, and 1.2% for poultry manure, dairy manure, and sewage sludge, respectively. The studies cited gives evidence to the importance of P management in areas where there is an influx of poultry industries.

Besides excess P in the soil from poultry litter application and runoff P that causes eutrophication, much of the N excreted from poultry manure is in the form of uric acid that can be rapidly converted to urea and NH_3-N if temperature, pH, and moisture are adequate for microbial activity (Siegel et al., 1975). The hydrolysis reactions result in elevated pH levels that facilitate NH_3-N volatilization (Reynolds and Wolf, 1987b).

Table 2

Summary of total elemental concentration in poultry litter from various studies

Element	Stephenson et al, 1990	Malone, 1992	Overcash et al., 1983b
N, %	4	3.9	3.5
NH_{4}, %		1.1	0.9
P, %	1.6	1.9	1.6
K, %	2.3	2.4	1.8
S, %	0.5	0.7	
Ca, %	2.3	2.4	3.1
Mg, %	0.5	0.7	0.4
B, mg/kg	54		
Cu, mg/kg	473	377	
Mn, mg/kg	348	355	
Zn, mg/kg	315	341	

All data reported on dry weight basis

Poultry Litter Amendment

One advance in manure management that has received considerable interest, particularly the poultry and swine industries is the use of litter amendments to stabilize P in manures in less soluble forms, thus decreasing the risk of soluble P losses by runoff and leaching (Sims and Luka-McCafferty, 2002). The main approach evaluated to date has been the addition of metal salts or by products containing Al, Fe, or Ca to solid or liquid manures, similar to the methods used in municipal wastewater treatment facilities to remove P from wastewaters (Codling et al., 2002; Dao, 1999; Moore and Miller, 1994; Smith et al., 2001).

Aluminum sulfate amendment of poultry litter is one management practice that reduces adverse environmental effects of poultry production. Aluminum sulfate is a dry acid salt that neutralizes alkalinity. When it is applied to poultry litter, it holds total litter pH below 5 or 6 for an extended time and litter pH is reduced to 3.5 for a short time (General Chemical, 2000). This dramatically retards generation of ammonia, which does not form in significant amounts until pH rises above 7. It also reduces available water in the litter through hydrolysis as it is activated (General Chemical, 2000).

Recent investigations into the use of aluminum sulfate as a poultry litter amendment have been documented. Shreve *et al*. (1995) examined the effects of aluminum sulfate and ferrous sulfate addition to poultry litter on P concentrations and load in runoff to evaluate the effects of amended litter on forage (*Fesuca arundinacea* Schreb) production. They observed decreased P runoff and increased forage yields with aluminum sulfate amended litter compared with non-amended poultry litter. Their results indicated that aluminum sulfate treatment amended litter can be a poultry manure management tool for limiting P inputs into surface waters and increase forage yields and fertilizer value of litter. In a separate study, Moore *et al*. (1995a) found that amending poultry manure with aluminum sulfate and ferrous sulfate also reduced ammonia volatilization, with aluminum sulfate producing a 99% reduction relative to unamended manure.

Sims and Luka-McCafferty (2002) conducted a large-scale on-farm evaluation of aluminum sulfate as poultry litter amendment utilizing 194 poultry houses, half of which received aluminum sulfate additions on the Delmarva Peninsula. They reported that aluminum sulfate treated litter contained 73% lower water soluble P in litter compared to unamended litter. Miles et al., (2003) found that the use of aluminum sulfate resulted in as much as a 60% reduction in water soluble P found in litter depending on dietary formulation. These reductions in water soluble P can be attributed to adsorption of P to amorphous aluminum hydroxides which form in poultry litter after the addition of aluminum sulfate (Peak et al., 2002).

One of the reasons aluminum sulfate was chosen for P control was because aluminum phosphates are stable under a wide range of soil physical and chemical conditions (Smith et al., 2001). In contrast, iron phosphates minerals are affected by redox reactions and can be reduced under wet conditions (Lindsay, 1979; Moore *et al.*, 1998c). Phosphorous bound to iron oxides is very insoluble under well-aerated conditions. However, prolonged anaerobic conditions reduces the iron in these complexes from Fe^{3+} to Fe^{2+}, making phosphate much more soluble and causing it to release P into solution (Brady and Weil, 2002).

Aluminum sulfate has been used in recent years in poultry litter houses to control NH_3 generation, typically at application rates of approximately 0.25 kg m^{-2} (General Chemical, 2000). Moore *et al.,* (1999a) recommended that higher aluminum sulfate application rates (approximately 1.0 kg m^{-2}, equivalent to approximately 10% aluminum sulfate concentration in the litter) to achieve the reduction in litter water-soluble phosphorus. Significant litter pH reduction during the first 3 to 4 weeks after the beginning of a growout has been reported, but as the amount of manure produced by birds increased, the pH of litter increased until the birds were 4 or 5 weeks old, when the litter pH levels off at 7.5 (Moore *et al.,* 1998b).

Treatment of Dairy Slurry with Al-Sulfate

Development of cost effective amendments for treating dairy slurry has become a critical problem as the number of cows on farms continues to grow and the acreage available for manure spreading shrinks. Lefcourt and Meisinger, (2001) listed three main nutrient issues for on-farm treatment of manure (1) nitrogen loss through ammonia volatilization (2) excess phosphorous, and (3) balance of N to P ratio. As a measure to reduce volatilization of ammonia and P, the authors conducted an incubation study to determine the effects of Al-sulfate or zeolite on dairy slurry at rates of 0.4, 1.0, 2.5, and 6.25% by weight. Zeolites are three-dimensional, microscoporous, crystalline solids with well-defined structures that contain aluminum, silicon, and oxygen in their framework;

cations and water are located in the pores. They reported that Al-sulfate reduced water soluble P by about 75% over the control at 1.0, 2.5, and 6.25 % which is consistent with research by Moore and Miller (1994) and Hsu (1976). They also reported significant increases in soluble Al for Al-sulfate treatments of 2.5 and 6.25% by weight. At the application rate of 6.25%, the pH of the slurry decreased by 0.1 units. However, zeolite addition at 6.25% resulted in a 50% reduction in ammonia volatilization and phosphorous but did not increase soluble aluminum because the zeolite is part of an alumina-silicate clay mineral structure, which is insoluble in aqueous extracts (Lefcourt and Meisinger, 2001).

Soil Chemical Changes with Manure

It is well established that crop production on acid soils can be improved when soil pH is adjusted to near neutral. Soil pH affects nutrient solubility, and influences the sorption or precipitation of nutrients with Al and Fe (Hue, 1992). Increasing the pH of acidic soils improves plant-availability of macronutrients while reducing the solubility and toxicity of elements such as Al and Mn (Hue and Licudine, 1999). In fact, whenever rainfall exceeds evapo-transpiration, bases (e.g. Ca, Mg, and K) and salts are leached from the soil profile, leaving behind materials rich in Al and Fe oxides, which render the soil more acid and less fertile. Thus acid soils are characterized by high levels of Al and deficient levels of Ca and possibly P. Phosphorus can be strongly absorbed on the sesqui-oxide surface and /or precipitated by highly soluble Al under acidic conditions.

Research has shown addition of green manures and animal manure reduces Al toxicity and increases crop yields (Ahmad and Tan, 1986; Hoyt and Turner, 1975; Hue and Amien, 1989 Ragland and Boonpuckdee, 1986). Complexation of Al in soil solution by decomposition products of organic residues has been implicated in Al detoxification (Hue and Amien 1989; Bartlett and Riego, 1972; Hue et al., 1986). Freshly added organic materials may inactivate soluble Al by adsorbing it on their surfaces (Hue and Amien 1989; Sposito, 1989) and/or precipitating Al with OH released from redox and/or ligand exchange reactions (Hue and Amien, 1989; Wahab and Lopez, 1980). Hue, (1992) reported that *Desmodium Intortum* grown on strongly acid subsoil of an Ultisol (Humoxic Tropohumults**,** Paaloa series) where soil acidity was corrected by either $Ca(OH)_2$ or organic manure additions. Both lime and manure raised soil pH and inactivated Al.

Recent research has shown that soil acidity can be corrected by cattle manure amendments for the short term (Whalen *et al.,* 2000). Whalen and his co-workers reported that manure amended soil had a significantly higher soil pH than unamended soil in an 8 week incubation study. They attributed higher pH in amended soils to buffering from bicarbonate in cattle manure. They also reported that concentrations of mineral N (NH_4–N + NO_3–N), available P, K, Ca and Mg increased immediately after manure application, and available P and K remained significantly higher in manure amended soil than unamended. Earlier, Kingery *et al.,* (1994) reported that long term application of poultry litter to tall fescue pastures provides benefits to pasture productivity such as higher soil pH and a more adequate supply of plant and animal nutrients. They reported that soil pH values were approximately 0.5 units higher in littered pastures than non-littered pastures. Other studies have shown similar effects on soil pH after application of fresh or composted animal manure (Warren and Fonteno, 1993; Iyamurenmye *et al*, 1996). It has been suggested that organic amendments such as manure may react similarly to $CaCO_3$ by precipitating Al and Fe (Iyamurenmye *et al.*, 1996).

In contrast, soil pH has also been shown to decline in some manure-amended soils. Soil pH in the top 15 cm of calcareous soils (pH 7.8) amended with cattle manure annually for 11 years declined by 0.3 to 0.7 units and the decline was greatest in soils receiving three times the recommended rates for manure application (Chang *et al.,* 1990). King *et al.,* (1990), reported that the pH of soils (pH 5.4 top 15cm) receiving low and medium application of swine lagoon effluent annually for 11 years reduced pH by 0.4 to 0.8 units, while the pH of soils receiving animal manure decreased by 0.3 units.

Poultry litter is normally an alkaline material, with pH values of 7.5 to 8.5 (Sims and Wolf, 1994). Its effects on soil pH can be significant but data has been contradictory. Sims (1986b) found that addition of three-broiler litters (pH from 8.5 to 8.9) raised the pH of an Evesboro loamy sand soil (Typic Hapludults) from 6.5 to 7.5 immediately after application, but the final soil pH after 20 weeks was about 5.5. The initial high pH could reduce micronutrient availability, particularly Mn and Zn and the final more acidic pH that resulted from the nitrification of added and mineralized NH_4-N could cause phytotoxicity from excessive Al and Mn in some soils.

Chemistry of Aluminum

Aluminum (Al) is one of the most abundant elements in soils, comprising approximately 7.1% by weight of the earth's crust (Lindsay, 1979). Al is released during weathering from primary minerals and precipitates largely as aluminosilicates. The dissolution of these primary and secondary minerals in acid soils ($pH<5.0$) releases soluble Al into soil water. The level of Al in soil solution will depend on the soil pH, amount and type of primary and secondary Al-containing minerals, exchange equilibra with inorganic surfaces and complexation reactions with organic constituents (Bell and Edwards, 1986). Aluminum has a high ionic charge and a small crystalline radius and is very reactive in solution. When an Al-containing mineral dissolves, the Al^{3+} released coordinates with six OH_2 groups. As pH increases each OH_2 group sequentially dissociates a H^+ to produce the mononuclear hydrolysis products $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_3^o$ and $Al(OH)_4^-$ over the pH range of interest in acid soils (Bell and Edwards, 1986). At elevated OH:Al ratios in solution, polynuclear hydroxyl-Al species, which are metastable intermediates in the precipitation of solid phase $Al(OH)_3$, may form. Various inorganic ligands including fluoride (F) and sulfate (SO_4) and a wide variety of organic form soluble complexes with Al. Different forms of aluminum occur in soil solution: $Al(OH)^{2+}$ and $Al(OH)_2^+$ at pH 5.7, Al^{3+} at pH 4.5, and $Al(OH)_4$ at pH 7.8. Other complex ions AlO_4Al_{12} $(OH)_{24}(H_2O)_{12}$ $^{7+}$ and Al^{3+} are almost certainly toxic to roots, but no rhizotoxicity has been detected for $AlSO_4^+$and $Al(SO_4)_2$ or Al-F (e.g. AlF_2+ and AlF^{2+}). The status of Al $(OH)^{2+}$ and $Al(OH)_2^+$ is uncertain although experimental results have indicate Al-OH toxicity (Kinraide, 1997). The following Al species are toxic for wheat roots in the following increasing order: $AlF_2{}^{+} < AlF^{2+} < Al^{3+} < Al_{13}$. According to Kochian, (1995) toxicity has been convincingly demonstrated only for Al^{3+}.

Soil Acidity and Plant Growth

Soil acidification is a natural process, which starts when a rock surface is first colonized by algae and lichens. In natural ecosystems, soils become gradually acidic with time. In general, superimposing agricultural production on an ecosystem results in faster rates of soil acidification. Acidity is one of the major yield limiting factors in soils because it restricts root growth (Toma et al., 1999). Soils naturally become more acidic over time with weathering. Minerals within the soil that buffer acidity can eventually become depleted and human activities can also influence soil reactions. Application of certain inorganic fertilizers such as $(NH_4)_2SO_4$ and NH_4NO_3 are oxidized by soil microbes to produce strong inorganic acids that provide H^+ ions that result in lower pH values. In humid regions, heavy rains can leach out most of base forming cations leaving the exchange complex dominated by aluminum and hydrogen ions.

Direct effects of the H ion on plant growth are difficult to assess because, at soil pH values where it is potentially harmful, Al, Mn, and other mineral elements may be present in toxic concentrations, and the availability of essential elements, particularly Ca, Mg, P, Mo, and Si, may be suboptimal. The H ion is probably most important in growth of legumes without nitrogen fertilizer (Andrew, 1978). It can affect rhizobial survival and multiplication in soils, root infection and nodule initiation, legume rhizobial efficiency, and nodulation of the host plant. The root infection process requires a higher pH than rhizobial survival (Munns, 1978; Carvalho *et al.,* 1981; Richardson et al., 1988a). Franco and Munns (1982) found that decreasing the pH of nutrient solutions from 5.5 to 5.0 decreased the number of nodules formed by beans (*Phaseolus vulgaris* L.), but variable pH between 4.5 and 5.5 did not affect nodule growth and nitrogenase activity. They emphasized the importance of low pH in the early nodulation of bean.

Aluminum Toxicity

Aluminum toxicity is a major factor that limits plant growth and development in many acid soils. The most easily recognized symptom of Al toxicity is the inhibition of root growth, and this has become a widely accepted measure of Al stress in plants (Delhaize and Ryan, 1995). Root cells plasma membrane, particularly of the root apex, seems to be a major target of Al toxicity. However, strong interaction of Al^{3+}, the main Al toxic form, with oxygen donor ligands (proteins, nucleic acids, polysaccharides) results in the inhibition of cell division, cell extension, and transport. Cytotoxicity of Al has been well documented in plants (Delhaize and Ryan, 1995; Horst *et al.,* 1999; Kollmeier *et al.,* 2000; Marienfeld *et al.,* 2000). It is generally known that plants grown in acid soils due to Al solubility at low pH have reduced root systems and exhibit a variety of nutrient-deficiency symptoms, with a consequent decrease in yield. In many countries with naturally acid soils, which constitute about 40% of world arable soil (LeNoble *et al.,* 1996), Al toxicity is a major agricultural problem, and is intensively studied in plant systems.

Aluminum is present in water, soil and air but most of it is incorporated into aluminosilicate soil minerals and only very small quantities appear in soluble forms capable of influencing biological systems (May and Nordstrom, 1991). Intensification of the process of Al compounds solubilization is connected with the degree of soil acidification caused by the washing of alkaline metals ions (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}) from the soil and a decrease in the pH of soil solutions. Aluminum ions translocate very slowly to the upper parts of plants (Ma *et al.,* 1997a). Most plants contain no more than 0.2 mg Al g^{-1} dry mass. However, some plants, known as Al accumulators, may contain over 10 times more Al without any injury.

Inhibition of root and shoot growth is a visible symptom of Al toxicity. The earliest symptoms concern roots. Root stunting is a consequence of Al-induced inhibition of root elongation. Roots are usually stubby and brittle and root tips and lateral roots become thick and may turn brown (Mossor-Pietraszewska *et al.,* 1997). Such roots are inefficient in absorbing both nutrients and water. Young seedlings are more susceptible than older plants. Aluminum apparently does not interfere with seed germination, but does impair the growth of new roots and seedling establishment (Nosko *et al.,* 1988). The common responses of shoots to Al include: cellular and ultrastructural changes in leaves, increased rates of diffusion resistance, reduction of stomatal aperture, decreased photosynthetic activity leading to chlorosis and necrosis of leaves, total decrease in leaf number and size, and a decrease in shoot biomass (Thornton *et al.,* 1986).

Tests for Aluminum Toxicity in Soils

Aluminum concentration can be sufficiently high in acid soils and toxic to plants. The Al species which are responsible for the phytotoxic effect appear to be a small fraction of the total Al in the soil solution. It is important to know which Al species in the soil are responsible for the toxicity, and to understand plant response to toxicity. Different methods have been compared to determine if any consistent relationship exists between soil Al and plant growth (Foy, 1988). Methods have been compared by their ability to predict lime requirements and plant yield (Soon et al, 1978). In this case, the assumption is that they extract aluminum from biologically active pools only. Conventional tests for Al toxicity in soil (pH, exchangeable Al, percentage Al saturation of CEC, and salt extractable Al) are not useful in predicting Al toxicity problems across a wide range of soils (Adams and Lund, 1966; Wright, 1989). However, for soils having similar parent materials and clay minerals, pH alone or absolute levels of Al extracted by KCl or other salts may be useful in predicting Al toxicity for a given plant (Blamey and Nathanson, 1977; McCormick and Amendale, 1983; Manrique, 1986). In general, a more useful predictor of Al toxicity is the percentage of cation exchange capacity (CEC) occupied by Al (Evans and Kamprath, 1970; Blamey and Nathanson, 1977; Farina and Channon, 1980; Kamprath and Foy, 1985). The Al saturation is determined by displacing soil Al with 1 N KCl or other neutral, unbuffered salts and expressing the Al as a percentage of the 1 N NH_4Oac at pH 7 or as a percentage of the total exchangeable Ca, Mg, K, and Na plus Al. Extraction of aluminum by calcium, barium, lanthanum and copper chlorides have received a lot of attention (Hoyt and Nyborg, 1971; Khalid and

Silva, 1979) Exchangeable aluminum extracted with 0.01M $CaCl_2$ has shown a significant relationship with plant growth (Bromfield *et al.,* 1983; Hoyt and Nyborg, 1971). The amount of Al extracted by 0.01M $CaCl_2$ represents soluble plus some exchangeable Al and would be more closely related to concentration of Al in soil solution than Al extracted by high ionic strength extractants such as 1M KCl (Baligar *et al.,* 1990). Khalid and Silva (1979) reported a strong correlation between soil Al extracted with 0.01M $CaCl_2$ to plant aluminum using maize (*Zea mays* L.), desmodium (*Desmodium aparines* L.) and Louisiana white clover (*Trifolium repens* L) as test crops. One problem arising from soil tests for aluminum is inability to predict plant growth or lime requirements even when plant growth is not confounded by concomitant toxicities of manganese or hydrogen ions or deficiencies of calcium and phosphorous. Exchangeable Al and percentage aluminum saturation of ECEC has been found to be better predictors of crop response to liming than pH measurements (Kamprath, 1970; Reeve and Sumner, 1970).

CHAPTER III

MATERIALS AND METHODS

This research was conducted in a glasshouse at the Crop Science Research Laboratory of the USDA-ARS at Mississippi State, MS in a Ruston soil (Fine-loamy, siliceous, semiactive, thermic Typic Paleudults) collected from Mississippi Agricultural and Forestry Experiment Station, Coastal Plain Experiment Station, Newton, Mississippi. The soil was collected from the upper 0.20 m soil profile of a site that was cropped with bermudagrass (*Cynodon dactylon* L Pers.). The Ruston series consists of very deep well drained, moderately permeable soils formed in loamy marine or stream deposits. This soil has dark grayish brown fine sandy loam layer underlain by pale brown, red clay loam. Slopes range from 0 to 8 percent (NRCS, 2005). The soil is acidic (pH 4.5, 1:1 soil-water extract) and it occurs widely in Mississippi. Before being utilized in this experiment, the pH was raised to 4.5, 5.0, 5.5, or 6.5. Litter treatments were (1) unamended litter (BL), (2) litter amended with 10% (w/w) Al-sulfate (BL + 10% Al-S) (3) litter amended with 20% (w/w) Al-sulfate (BL + 20% Al-S). These treatments were applied to soil with initial soil pH of 4.5, 5.0, 5.5 and 6.5 in a full factorial combination. The initial soil of pH of 5.0, 5.5, or 6.5 was prepared by raising the 4.5 pH of the field soil.

Soil pH Adjustments

The bulk soil sample was air-dried in a glasshouse, crushed, and sieved to pass through a 2-mm screen and then mixed in a cement mixer to ensure homogeneity. Soil from the field had a pH of 4.5. The pH of this soil was adjusted to pH of 5.0, 5.5 and 6.5 using a modified procedure by Islam *et al.,* (2004) using $Ca(OH)_2$. To determine the amount of $Ca(OH)_2$ application needed to raise the pH to a desired level, 200 g aliquots of the ground and dry soil were mixed with 0, 20, 40, 60, 80, 100 or 120 mg $Ca(OH)_2$ (CCE = 135) in 200-mL plastic cups. This was replicated four times. To each mix, 50 mL of tap water was added to dissolve the $Ca(OH)_2$ for reaction with the soil and left on a glasshouse bench for 60 days. Water was maintained at approximately field capacity in the cups. Soil pH was measured in 1:1 soil to water (v/v) mixture using a glass electrode (Hanna pH/EC/TDS meter model H19813-0, Woonsochet, RI) 2, 5, 8, 10-d after mixing and every 5 d thereafter until pH stabilized. Regressing $Ca(OH)_2$ amount on soil pH resulted in a curvilinear relationship (Figure 1).

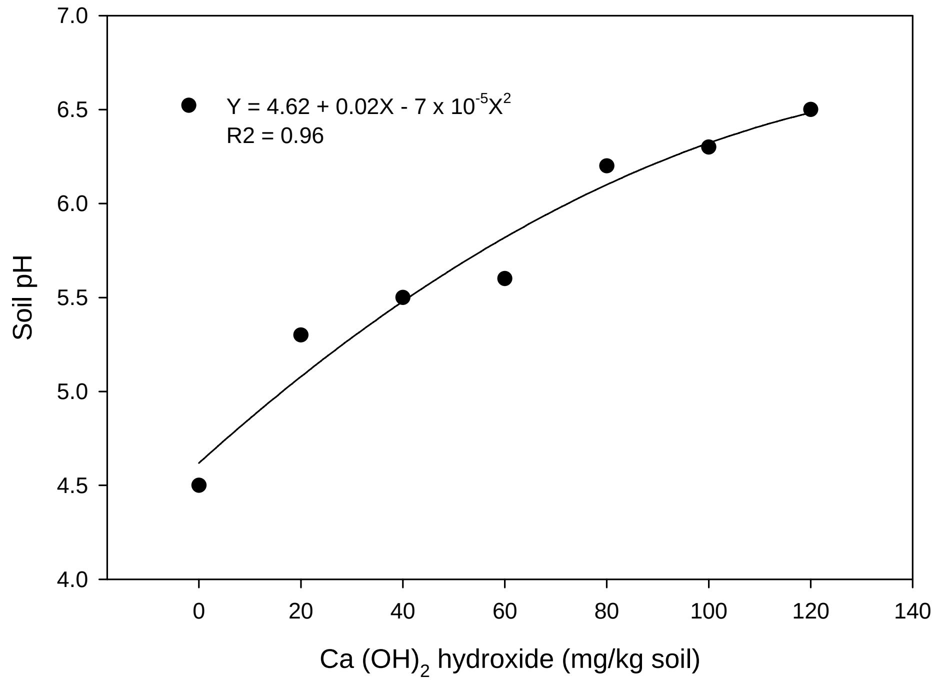

Figure 1

Soil pH with application of $(Ca(OH)_2$ to a Ruston Soil.

The fitted equation was used to estimate the quantity of $Ca(OH)_2$ required to adjust the pH of the potting soil from 4.5 to 5.0, 5.5, or 6.5. The pH stabilization time gave an estimate of time to reach desired pH following $Ca(OH)_2$ application (Fig.2). Soil chemical properties (Table 3) were determined prior to planting using the procedure described in soil analysis.

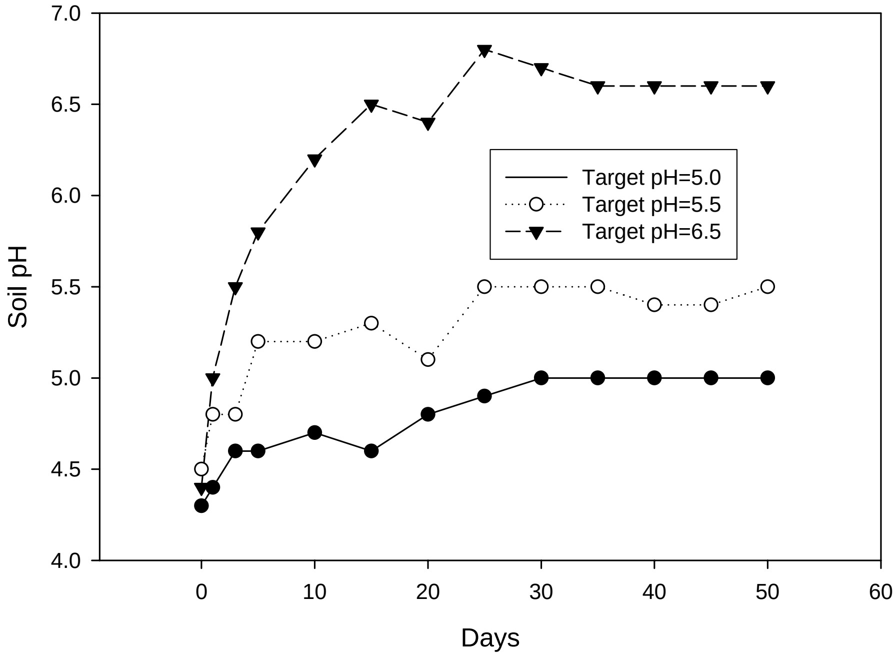

Figure 2

Changes in soil pH over 50 days after addition of calcium hydroxide

Table 3

Chemical properties of the soil after pH adjustment and prior to planting

Soil pH	P	K	Ca	Mg	Al	Cu	Fe	Mn	Zn
	g kg^{-1}				mg kg^{-1}				
4.5	0.11	0.16	1.1	0.15	13	1.9	341	22.4	7.8
5.0	0.09	0.24	2.6	0.23	10	4.6	216	33.9	7.6
5.5	0.17	0.24	3.6	0.29	<1	4.2	208	18.4	7.3
6.5	0.19	0.28	3.7	0.31	<1	4.2	199	14.8	6.9

Poultry Litter Amendment

Two hundred kilograms (kg) of fresh poultry litter was obtained from a commercial broiler chicken production house near Carthage, Mississippi and stored immediately in a refrigerator at a approximate temperature of 3^0 C. Three kg of the fresh litter was weighed into three 15 L containers, ground prior to amendment. The 3 kg of litter in two containers were amended with 300 g $Al_2(SO_4)_3.18H_2O$ or 600 g $Al_2(SO_4)_3.18H_2O$ (Al-S), for the 10 or 20% (w/w) while one container was not amended. After amending the litter, each treatment was well homogenized using a cement mixer. The chemical were reagent grade materials. After the amendments were added, the mixtures were stirred and incubated at 25^oC and 80% relative humidity for six weeks. A 6-wk equilibration time was chosen to mimic the time span between Al-S application in poultry houses and final growout of the birds. The litter amendment procedure described above was executed four times for each experiment with a new randomization each time.

After incubation, 20g of a sub-sample was collected from amended and unamended litter for chemical analysis (Table 4). The sub-samples were air dried and ground (<1.0 mm) before chemical analysis. Total Al, Ca, P, K, Mg, Fe, Mn, Zn and Cu were measured in duplicate samples by dry ashing a 0.2 g sub-sample of manure in a ceramic crucible at 500^o C for 4 hours. The ash was dissolved in 10.0 mL of 6 M HCl for 1 hour and then an additional 40 mL of a double-acid solution of 0.0125 M H_2SO_4 and 0.05 M HCl was added for another hour before filtering through Whatman paper (Southern Coop. Ser. 1983). The filtrate was measured by emission spectroscopy on an inductively coupled plasma spectrophotometer (ICP) (Spectro Instruments, Fitchburg, MA). Total N in poultry litter was determined with an automated dry-combustion analyzer (Model NA 1500 NC, Carlo Erba, Milan, Italy).

Table 4

Chemical characteristics of dried poultry litter used in the glasshouse experiments

Constituent	BL	BL + 10% Al-S	BL + 20% Al-S
Moisture (%)	26	28	28
C, %	28	24	22
N, %	3.1	2.7	2.5
C/N	8.6	5.5	5.4
Al, g/kg	1.52	9.24	13.97
Ca, g/kg	15.2	13.0	10.9
K, g/kg	24.3	22.1	18.4
Mg, g/kg	4.6	4.4	4.1
Na, g/kg	12.7	11.8	10.5
P, g/kg (Mehlich 3)	9.4	8.4	7.7
Cu, mg/kg	353.2	326	312
Fe, mg/kg	511	528	415
Mn, mg/kg	478	425	369
Zn, mg/kg	344	320	289

Plant Culture

Ten kg of air-dried soil, which had been adjusted to a pH of 4.5, 5.0, 5.5, or 6.5, using $Ca(OH)_2$ was placed into 80 plastic containers with diameters of 30 cm and depth of 20 cm. The five litter treatments (BL, BL + 10% Al-S, BL + 20% Al-S) were mixed with each soil pH making 12 treatment combinations. The 12 treatment combinations were placed on a glasshouse bench in a randomized complete block design with four replications. These 12 treatments combinations were maintained in all four experiments such that each pot received the same litter amendment in each experiment. In experiment 1, litter amendments treatments were applied at 90 g pot^{-1}. In experiment 2 to 4, litter amendment treatments were applied at 110 g pot^{-1}. The litter applied was thoroughly mixed with soil before adding water. Water was applied to bring the soil moisture to near field capacity following blending. The pots were not planted for 21d to avoid seedling damage due to initial release of ammonia (Siegel et al., 1975). In experiment 1, five seeds of soybean (*Glycine max* L.) var. AG 4603/RR was planted without an inoculant on 26 June 2004. Three days after germination, the plants were thinned to two uniform plants per pot. Soybean was harvested at early flowering stage on 28 August, 2004. Cotton (*Gossypium hirsutum* L) var. DP 555 BG/RR was used as an indicator crop in Exp. 2 to 4. Five cotton seeds were planted on 10 February, 2005 in experiment 2, and harvested on 13 April, 2005. In experiment 3 and 4, cotton was planted on 10 June, 2005 and 10 December 2005 and harvested on 11 August 2005 and 15 February 2006 respectively. Cotton was thinned to two uniform seedlings three days after emergence.

Measurements

Biomass and Nutrient Analyses

Following each of the experiments, plants were harvested at early flowering stage from each pot at the same time. Plants in each pot were harvested by cutting at soil level after washing with tap water and drying at 80^0 C to constant dry weight. The roots were not weighed because of the difficulty in completely removing the soil particles from the roots. The dried aboveground biomass from each pot was ground in a Wiley mill to pass through a 2-mm sieve.

After grinding the samples from each pot, concentrations of Al, P, Ca, K, Mg, Fe, Cu, Mn and Zn were analyzed in duplicate samples by dry ashing a 0.2 g sub-sample in a ceramic crucible at 500^o C for 4 hours. The ash was dissolved in 10.0 mL of 6 M HCl for 1 hour and an additional 40 mL of a double-acid solution of 0.0125 M H_2SO_4 and 0.05 M HCl for another hour, and then filtering through a Whatman No.2 paper (Southern Coop. Ser. 1983). The filtrate was measured by emission spectroscopy on an inductively coupled plasma spectrophotometer (ICP) for Al, Ca, P, K, Mg, Fe, Mn, Zn and Cu.

Soil Analysis

Soil samples were collected from each pot after the plants were harvested to measure soil pH and extractable soil Al. Soil pH was measured in 1:1 soil to water (v/v) mixture using a glass electrode (Hanna pH/EC/TDS meter model H19813-0, Woonsochet, RI)

The soil samples were analyzed for extractable soil Al using 5 g of soil mixed with 10 mL of 0.01M $CaCl_2$ (Hoyt and Nyborg, 1971), and filtered with a pre-washed Whatman No. 42 filter paper. Aluminum in the filtrate was measured by emission spectroscopy on an inductively coupled plasma spectrophotometer (ICP) (Spectro Instruments, Fitchburg, MA).

Soil P, Ca, Mg, K, Cu, Fe, Mn and Zn were measured following extraction with Mehlich-3 extractant (Mehlich, 1984). Two gram soil sample from each pot were put into 125 mL flask and 20 mL Mehlich-3 extractant solution were added. The solution was then shaked for 30 minutes and centrifuged at 200 r.p.m. It was filtered and the filtrate measured with an ICP.

Statistical Analysis

All the data were analyzed as a randomized complete block design in a factorial arrangement of treatments using PROC ANOVA procedure of SAS (SAS Institute, 1999). An analysis of variance (ANOVA) was performed to determine the effects of the initial soil pH, litter amendments, experiment and any interaction on the soil pH, extractable soil Al, Mehlich-3 extractable soil P, K, Ca, Mg, Cu, Fe, M, and Zn. When there was no experiment effect, data analysis was combined over the four Exp..

Biomass and tissue N, P, K, Ca, Mg, Cu, Fe, Mn and Zn concentrations of soybean were analyzed using PROC ANOVA separately. In Exp. 2, 3, and 4 where cotton was used as a test crop, cotton biomass and tissue N, P, K, Ca, Cu, Fe, Mn and Zn concentrations were analyzed using PROC ANOVA combined over three experiments. When there was a experiment effect, data was analyzed for each experiment.

When there was no significant interaction of the factors on the response variables, comparisons of means was made on the marginal means of the main effects. Fishers Protected Least Significant Difference (LSD) procedure (p=0.05) was used to compare treatment means on all the response variables.

CHAPTER IV

RESULTS AND DISCUSSION

Soil pH

Soil pH measured after plant harvest was significantly influenced by litter amendment, initial soil pH, experiment by litter amendment interaction, and initial soil pH by litter amendment interaction (Table 5).

Table 5

Statistical tests of the initial soil pH, litter amendment, experiment and their interactions on final soil pH in a glasshouse study

Source	**DF**	**P>F**
Exp.	3	0.001
Initial Soil pH	3	0.0412
Exp. x Initial Soil pH	9	0.5709
Litter amendment	2	0.001
Exp. x Litter amendment	6	0.0445
Initial Soil pH x Litter amendment	6	0.0001
Exp. x Initial soil pH x Litter amendment	18	0.5194

Because of the significant litter amendment by initial soil pH interaction, the effect of litter amendments was analyzed for each initial soil pH treatment (Table 6).

Table 6

Final soil pH after applying selected litter amendments with different soil pH in four experiments

Litter amendment	Initial Soil pH 4.5	5.0	5.5	6.5
	Final Soil pH			
BL	5.00a[12]	5.60a	6.04a	6.94a
BL + 10% Al-S	4.86a	5.32b	5.88a	6.83a
BL + 20% Al-S	4.13b	4.69c	5.47b	6.46b

[1]Means followed by the same letter in columns are not significantly different at P = 05
[2]Each value is averaged across four experiments

The results in Table 6 show that BL and BL + 10 or 20% Al-S effects to the Ruston soil pH were dependent on the initial soil pH. Variation in soil pH due to BL and BL + 10 or 20% Al-S at different soil pH may be associated with solubility of Al compounds. Some of the Al containing compounds are more soluble at higher pH while others are more insoluble at low soil pH.

The final soil pH resulting from BL and BL + 10% Al-S application show that the initial soil pH levels were increased (Table 6). The increase in soil pH was higher from BL application than BL + 10% Al-S although they are not statistically different. The increase in soil pH due to BL and BL + 10% Al-S application may be due to fact that poultry litter contains large amounts of $CaCO_3$ which originate from the diet of the birds (Egball, 1999; Moore and Edwards, 2005). Although BL and BL + 10% Al-S has large amounts of ammoniacal N (Moore and Edwards, 2005), the acidity produced by nitrification and Al from Al-S may have been buffered by the $CaCO_3$ in the litter. It appears that the potential acidity due to nitrification of ammoniacal N did not exceed the bases content of the litter to cause soil acidification. These results agree with the findings of Warren et al., (2006a) who reported an increase in soil pH from BL and BL + 10% Al-S application in a cornfield study that had an initial soil pH of 5.6.

Application of BL + 20% Al-S significantly decreased the initial soil pH of 4.5 and 5.0 compared to BL application (Table 6). It has been assumed that phosphate anions in poultry liter react with Al^{3+} from Al-S to form solid aluminum phosphate (Moore and Miller, 1994), which is insoluble in the pH range for agricultural soils (Lindsay, 1979). This data suggest that some of Al in BL + 20% Al-S did not form solid aluminum phosphate as suggested by Moore and Miller (1994). Had the entire Al reacted with the phosphate anions, there would be little effect on soil pH because aluminum phosphate may not be soluble in the pH levels in which this study was done. Aluminum that did not react with the phosphate anions was soluble in soil solution and with its subsequent hydrolysis generated H^+ ions, which decrease the soil pH. In addition to acidity from Al, the other source of acidity may be from nitrification of ammoniacal N. Although poultry litter contains $CaCO_3$ and other basic cations, these results suggest that the acidity produced by nitrification and Al in BL + 20% Al-S were not neutralized.

Table 7

Final soil pH following litter amendment treatments in a four-crop glasshouse study

	Final Soil pH			
Litter amendment	Experiment			
	1	2	3	4
BL	5.64a	5.66a	6.05a	6.22a
BL + 10% Al-S	5.46b	5.57a	5.96a	5.89b
BL + 20% Al-S	5.08c	5.16b	5.17b	5.34c

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across soil pH treatments

Application of BL and BL + 10 or 20% Al-S elevated soil pH at the end of each experiment Table 7). The increases in the final soil pH were much higher in soils receiving BL than those receiving BL + 20% Al-S (Table 7). This was followed by BL + 10% Al-S.

These results show that application of BL and BL + 10 or 20% Al-S had a different effect in each experiment. The effects of these treatments were different in each experiment probably because of differences in the concentrations of acid and base cations (Table 4). It appears that BL application had a higher effect on the soil pH because concentrations of bases cations were higher and had the lowest Al concentrations. Increase in soil pH from BL application has been reported by a lot of researchers (Moore and Edwards, 2006; Warren et al., 2006a; Tang et al., 2007). On the other hand, adding litter with 10% Al-S increased Al concentration (Table 4), which has an acidifying effect. Although Al has an acidifying effect on the soil pH, the data suggest that amendment rate of 10% had a similar effect on the pH in experiments 2 and 3 as BL. Increasing the amendment rate to 20% Al-S resulted in significant lower soil pH compared to BL application in all experiments. Although BL + 20% Al-S increased soil pH in each experiment, it was always significantly lower than BL and BL + 10% Al-S in each experiment.

Extractable Soil Aluminum

Extractable soil Al concentrations were significantly influenced by the initial soil pH, litter amendment, initial soil pH by litter amendment interaction, experiment by initial soil pH interaction, and experiment by litter amendment interaction (Table 8).

Table 8

Statistical tests of initial soil pH, litter amendment, experiment and their interactions on extractable soil Al

Source	DF	P>F
Exp.	3	0.0621
Initial Soil pH	3	<0.0001
Exp.x Initial Soil pH	9	0.0221
Litter amendment	2	<0.0001
Exp. x Litter amendment	6	0.001
Initial soil pH x Litter amendment	6	0.0413
Exp. x Initial Soil pH x Litter amendment	18	0.5362

Table 9

Extractable soil Al following litter amendment treatments to soils with different pH levels in a four crop glasshouse study

	Extractable Soil Al mg kg^{-1}			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	8.89c[12]	8.69b	3.67a	2.87a
BL + 10% Al-S	10.62b	9.75b	3.78a	2.82a
BL + 20% Al-S	19.45a	15.98a	3.98a	2.94a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across experiments.

Results in Table 9 indicate that BL + 20% Al-S application tended to increase extractable soil Al but the effect of the treatment were significant only on soils with pH of 4.5 or 5.0. Extractable soil Al could have been increased at low soil pH due to solubility of the native Al-compounds because soil pH decreased with application of BL + 20% Al-S. Fertilization with BL gave the lowest extractable soil Al compared to BL + 10 or 20% Al-S at initial soil pH of 4.5 or 5.0 (Table 9).

Extractable soil Al concentrations at the beginning of the study were 13 mg kg^{-1} and 10 mg kg^{-1} at the soil pH of 4.5 and 5.0, respectively (Table 3). In soils with pH 5.5 or 6.5, it was not detectable. Application of BL and BL + 10% Al-S decreased extractable Al by 3.28 and 4.11 mg kg^{-1} respectively over the initial Al concentration at pH 4.5. The decrease in extractable soil Al from soils receiving BL + 10% Al-S was significantly less than soil receiving BL. At pH 5.0, BL and BL + 10% Al-S application decreased extractable Al by 0.25 and 1.31 mg kg^{-1} respectively (Table 9). Although extractable Al was significantly higher in soils receiving BL + 10% Al-S compared to BL at pH 4.5, there were no significant differences at soil pH of 5.0, 5.5 and 6.5. The mechanism by which Al decreases with manure addition to the soils has been controversial (Tang et al., 2007). Haynes and Mokolobate (2001) reviewed the mechanisms involved in the amelioration of Al by manure addition to the soil. In their review, they suggested the possible mechanism for amelioration of Al was increase in soil pH by organic matter decomposition, complexation of Al in soil solution by soluble organic matter, and the reduction of exchangeable Al due to solid-phase organic matter. Wong and Swift (2003) suggested that activity of Al in soil solution decreases due to significant amounts of inorganic and organic P, which may complex Al. Since, BL and BL + 10% Al-S application increased the soil pH (Table 6), this may have decreased Al^{3+} by forming the hydroxyl forms of Al which are not exchangeable. The decrease in extractable soil Al may have been from reaction between water soluble P that is high in poultry litter (Moore and Edwards, 2005) with Al in the soil and from Al-S.

Extractable soil Al significantly increased with the application of BL + 20% Al-S to soils with pH 4.5 and 5.0 compared to BL (Table 9). Significant increases in extractable soil Al due to BL + 20% Al-S application to soils with pH 4.5 or 5.0 suggests dissolution of Al from BL + 20% Al-S. Since BL + 20% Al-S application reduced the initial soil pH, some of the Al might have come from the solubility of the native Al-compounds because Al concentration in soils is about 7% by weight (Lindsay, 1979). In acid soils, the native Al-compounds dissolve to produce Al^{3+}, which can then be adsorbed to the cation exchange capacity (CEC).

On the other hand, minimal extractable soil Al in soils with pH of 5.5 and 6.5 may be associated with insolubility of aluminum phosphate (Moore and Miller, 1994) and the reduction in concentration of Al^{3+} (Havlin et al., 2002). At the soil pH of 6.5, there is a decrease in Al^{3+} in soil solution because the Al-compounds precipitate (Havlin et al., 2002). Although extractable Al was not significantly different between BL and BL + 20% Al-S at pH 5.5 or 6.5, there was slight increase from the initial extractable soil Al. The initial extractable soil Al was not detected on the ICP but it was 4 mg kg^{-1} after four experiments.

Arguments in support of amending litter with alum have been that "additional Al will not increase extractable soil Al because $Al(PO_4)_3$ and $Al(OH)_3$, compounds formed between the reaction of Al and the phosphate anions or hydroxyl ions are stable in a wide range of conditions" (Moore et al., 2000). Contrary to this proposition, it is evident that application of BL + 20% Al-S to the acidic Ruston soil can increase extractable soil Al. Although BL + 20% Al-S increased extractable soil Al especially at the soil pH of 4.5 or 5.0, it appears that not all of the Al in the litter went into soil solution because the total Al content in the litter was higher than the extractions obtained.

Due to litter amendment by experiment interaction, the effects of litter amendments on extractable soil Al were analyzed for each experiment (Table 10).

Table 10

Extractable soil Al following litter amendment treatments in a four crop glasshouse study

Litter amendment	Extractable Soil Al mg kg^{-1} — Experiment 1	2	3	4
BL	8.52b[1,2]	7.35bc	5.72b	1.86bc
BL + 10% Al-S	9.77b	8.62b	5.57b	2.48b
BL + 20% Al-S	14.82a	12.99a	11.59a	4.55a

[1]Means followed by the same letter in a column are not significantly different at P = .05
[2]Each value is averaged across soil pH treatments

The concentration of extractable soil Al due to BL and BL + 10 or 20% Al-S application varied in each experiment (Table 10). Differences in extractable soil Al among the experiments may be explained in terms of soil pH changes (Table 7). The increase in soil pH from BL and BL + 10% Al-S application may have decreased extractable soil Al in soil solution. In fact, extractable soil Al decreased to less than 5 mg kg^{-1} over the four experiments from BL and BL + 10 or 20% Al-S. It is not known if the similar results can be obtained in the field considering that the soil was well mixed with litter in the pots and plants were only grown for a short period in each experiment.

There was initial soil pH by experiment interaction on extractable soil Al (Table 8) and the results of the analysis are in Table 11.

Table 11

Extractable soil Al following from different soil pH treatments in four experiments

	Extractable Soil Al mg kg^{-1}			
Initial Soil pH	Experiment			
	1	2	3	4
4.5	19.59a[12]	16.22a	11.59a	4.27a
5.0	18.02a	15.93a	9.51b	2.72a
5.5	5.25b	4.49b	3.73c	1.75b
6.5	4.27b	3.09b	2.53c	1.61b

[1] Means followed by the same letter in columns are not significantly different at P = .05
[2] Each value is averaged across litter amendments

The initial soil pH of 4.5 or 5.0 had significant higher extractable soil Al compared to soils with pH 5.5 or 6.5 in the first three experiments. Significant higher extractable soil Al in soil pH levels of 4.5 or 5.0 may be related to dissolution of Al-compounds, which add Al^{3+} into soil solution. Similar to the results in Table 10, extractable soil Al decreased in each experiment. Although this study was a short term, the results suggest that there is potential in BL and BL + 10% Al-S in decreasing extractable soil Al.

Mehlich-3 Soil Extractable Nutrients

The analysis of variance for the initial soil pH, litter amendment, experiment and their interactions effect on Mehlich-3 extractable soil nutrients are in Table 12.

Table 12

Statistical tests of initial soil pH, litter amendment, experiment, and their interactions on Mehlich-3 extractable soil nutrients

Source	**DF**	**P**	**K**	**Ca**	**Mg**	**Cu**	**Fe**	**Mn**	**Zn**
		P>F							
Exp.	3	0.0001	0.0001	0.5564	0.0031	0.0001	0.0001	0.8864	0.4521
Initial Soil pH	3	0.0107	0.1197	0.0001	0.0009	0.4076	0.0713	0.0184	0.2014
Exp. x Initial soil pH	9	0.3884	0.0565	0.0021	0.3850	0.0001	0.4084	0.0061	0.1463
Litter amendment	2	0.0010	0.7273	0.0343	0.0018	0.1111	0.4345	0.2215	0.4521
Exp. x Litter amendment	6	0.6617	0.3068	0.5986	0.3146	0.9866	0.9809	0.8547	0.7124
Initial soil pH x Litter amendment	6	0.1102	0.3090	0.0357	0.4298	0.0355	0.9808	0.1238	0.8048
Exp. x Initial soil pH x Litter amendment	18	09215	0.6220	0.9690	0.2152	0.6421	0.9306	0.8349	0.9573

Phosphorous

Averaged across litter amendments and experiments, Mehlich-3 extractable P increased with the raise in soil pH (Table 13).

Table 13

Mehlich-3 extractable soil P after applying litter amendments to soil at four different pH levels

Initial Soil pH	Extractable soil P
	g kg^{-1}
4.5	0.23b
5.0	0.24b
5.5	0.24b
6.5	0.26a

[1]Means followed by the same letter are not significantly different at P = .05
[2]Each value is averaged across litter amendments and experiments

Significantly lower extractable P in soils at pH 4.5 or 5.0 compared to pH 5.5 or 6.5 may be associated with high extractable soil Al (Table 13) that may have adsorbed or precipitated some of the P. At low pH values, P fixation is largely from reaction with Al oxides and precipitation as $AlPO_4$. Havlin et al., (1999) reported that P adsorption by gibbsite (FeOOH) or goethite ($Al(OH)_3$ is greatest at pH 4 to 5 and that maximum P concentration is at pH 6.5 in most soils. As the pH increases, the activity of Fe and Al decreases, this results in lower P adsorption/precipitation and higher P concentration in solution.

Calcium

Significant differences in Mehlich-3 extractable Ca due to BL and BL + 10 or 20% Al-S application were observed at each soil pH level (Table 14).

Table 14

Extractable soil Ca following litter amendment treatments to soils with different pH levels in four experiments

	Extractable Soil Ca			
	$g\ kg^{-1}$			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	2.79a[12]	2.71a	2.89a	3.20a
BL + 10% Al-S	2.54a	2.59a	2.80a	2.79b
BL + 20% Al-S	2.07b	2.25b	2.63a	2.76b

[1]Means followed by the same letter in columns are not significantly different at P = .05.
[2]Each value is averaged across experiments

Differences in extractable soil Ca due to BL and BL + 10 or 20% Al-S application among the initial soil pH treatments reflect variation in cations that dominate the cation exchange capacity (CEC) in soils that are slightly acidic and those that are more acidic. In acidic soils, Ca and Al dominate the CEC while in neutral to calcareous soils Ca occupies the majority of the exchange sites (Havlin et al, 2002).

Soils receiving BL had the highest extractable soil Ca compared with BL + 10 or 20% Al-S. However, extractable soil Ca from soils receiving BL + 10% Al-S was not significantly different from soils receiving BL (Table 14). Insignificant differences in extractable soil Ca between soils receiving BL compared to BL + 10% Al-S may be related to elevation in the soil pH (Table 6) and decrease in extractable soil Al (Table 10). Calcium is a base cation that has a higher concentration as the pH increases and exchangeable soil Al decreases. Since application of BL and BL + 10% Al-S increased the initial soil pH (Table 6), this may have increased the availability of Ca^{2+} in soil solution. In addition, poultry litter contains a lot of Ca^{2+} (Table 3), which may have increased the concentration. Mitchell and Tu (2006) reported that application of BL resulted in an accumulation of extractable Ca in surface soils increasing by 28% compared with the untreated control.

Application of BL + 20% Al-S significantly decreased extractable soil Ca relative to BL at initial soil pH of 4.5 and 5.0. Significant decreases in extractable soil Ca from BL + 20% Al-S application relative to BL at pH 4.5 or 5.0 reflect soil acidification (Table 6) and the increase in extractable soil Al concentration (Table 10). In strong acid soils, the tightly held H^+ and hydroxyl Al^{3+} prevent Ca from being closely associated with the colloidal surfaces that reduces it in soil solution (Havlin et al., 2002). Although BL + 20% Al-S contain a lot of Ca (Table 4), it appears that Al^{3+} was more dominant at the initial soil pH of 4.5 and 5.0.

Due to the interactions between initial soil pH and experiment, Mehlich-3 extractable soils Ca due to soil pH are presented for each experiment (Table 15).

Table 15

Extractable soil Ca from different soil pH levels in four experiments

	Extractable Soil Ca			
	$g\ kg^{-1}$			
	Experiment			
Initial soil pH	1	2	3	4
4.5	2.09c[12]	2.15b	2.52ab	2.31a
5.0	2.45bc	2.55a	2.36b	2.58a
5.5	2.65b	2.61a	2.56ab	2.72a
6.5	3.47a	2.74a	2.81a	3.03a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across litter amendments.

Extractable soil Ca differences among the experiments may be related to changes in extractable soil Al (Table 11). Extractable soil Ca from different soil pH levels was significantly different only in experiment 1 in which the initial soil pH of 6.5 resulted in significant greater extractable soil Ca compared to the other pH levels (Table 15). Although there were no significant differences in soil Ca among the soil pH treatments in experiment 2, 3 and 4, soils with pH 5.5 or 6.5 contained high Ca concentrations. At the beginning of the study, Ca concentrations was higher at the initial soil pH of 5.5 and 6.5

and contained lower extractable soil Al concentrations (Table 3). Therefore, it is not surprising that soil pH levels of 5.5 and 6.5 had higher Ca concentrations than pH of 4.5 and 5.0.

Potassium

Extractable soil K response to the initial soil pH resulted in different concentrations among the experiments (Table 16).

Table 16

Extractable soil K with different soil pH levels in four experiments

	Extractable Soil K g kg^{-1}			
	Experiment			
Initial soil pH	1	2	3	4
4.5	0.43a[12]	0.57b	0.66a	0.60b
5.0	0.45a	0.63a	0.67a	0.68ab
5.5	0.46a	0.63a	0.68a	0.75a
6.5	0.48a	0.63a	0.69a	0.82a

[1]Means in the table followed by the same letter are not significantly different at P = .05
[2]Each value is averaged across litter amendments.

Statistical differences in extractable soil K among the soil pH treatments were only in experiments 2 and 4 (Table 16). Although there were no differences in soil K among the soil pH levels, initial pH of 6.5 had the highest soil K concentrations. Like other basic cations, K in the soil is affected by soil pH with low concentrations in more acidic soils. This data also show that extractable K increased in each experiment. For example, soil K changed from 0.43 in experiment 1 to 0.61 g kg^{-1} in experiment 4 at initial soil pH level of 4.5. The increase in soil K may be associated with buildup of soil K due to litter amendment fertilization because litter has a higher amount of K (Table 4).

Magnesium

Extractable soil Mg from experiment by initial soil pH interactions are in Table 17.

Table 17

Extractable soil Mg with different soil pH levels in four experiments

	Extractable Soil Mg g kg^{-1}			
	Experiment			
Initial soil pH	1	2	3	4
4.5	0.19c	0.29a	0.35b	0.38a
5.0	0.23bc	0.28a	0.34b	0.38a
5.5	0.27ab	0.31a	0.38b	0.34a
6.5	0.30a	0.32a	0.51a	0.40a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across litter amendments

Differences in extractable soil Mg among the experiments may be related to changes in extractable soil Al (Table 11). Higher concentrations of extractable soil Al may affect exchangeable soil Mg because it competes for exchange sites on the CEC (Havlin et al., 2002). Extractable soil Mg among the soil pH treatments was significantly different in experiments 1 and 3 only (Table 17). Although there were no significant differences in the other experiments, extractable soil Mg was higher at the soil pH of 6.5. Like Ca^{2+}, Mg^{2+} concentration in the soil depends on the soil pH with a lower concentration in more acidic soils. Higher Ca^{2+} concentration at initial soil pH of 6.5 though not significantly different in some experiments is likely from relative higher Mg at the beginning of the study (Table 3). Adding BL and BL + 10 or 20% Al-S increased Mg in each experiment because of poultry litter has high Mg concentrations. Mitchell and Tu (2005) reported that BL application increased Mehlich3- extractable soil Mg by 23% compared to the untreated control. Similar results were obtained by Kingery et al., (1994) in long term field trials who reported that Mg increased with BL applications.

Copper

Mehlich-3 soil extractable Cu response from application of BL and BL + 10 or 20% Al-S was different among the initial soil pH levels (Table 18).

Table 18

Extractable soil Cu following litter treatments to soils with different initial pH levels in four experiments

	Extractable Soil Cu			
	$mg\ kg^{-1}$			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	9.98a[1,2]	10.20a	9.88a	9.84a
BL + 10% Al-S	9.41a	9.65a	9.13b	9.45a
BL + 20% Al-S	8.04b	8.64b	9.10b	9.43a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across four experiments

Differences in Mehlich-3 soil Cu from BL and BL + 10 or 20% Al-S applications among the soil pH levels may be attributed to decreased mineral solubility and increased adsorption with increasing soil pH (Havlin et al, 2002). Extractable soil Cu was higher in more acidic soil than less acidic soil. For example Cu concentrations in soils receiving BL was 9.98 and 10.20 mg kg^{-1} at pH of 4.5 and 5.0 respectively (Table 18). At the soil pH of 5.5 and 6.5, extractable Cu from BL application was 9.88 and 9.84 mg kg^{-1}.

Soils receiving BL had the highest extractable soil Cu compared to BL + 10 or 20% Al-S (Table 18). Higher extractable Cu from BL may be related to greater water solubility of Cu (Toor et al., 2007). Mehlich-3 extractable soil Cu response to BL + 10% Al-S application did not shown any significant differences from BL except at initial soil pH of 5.5 but it was consistently lower than BL (Table 18). Application of BL + 20% Al-

S significantly decreased extractable Cu compared to BL at pH 4.5, 5.0 and 5.5 (Table 18). The decrease in soil Cu in soils receiving BL + 10 or 20% Al-S has been attributed to the dilution of litter with Al-S (Moore et al., 2000; Tor et al., 2007).

Copper is an element of great concern in poultry litter because it is extremely toxic to algae, and it poses the greatest threat to aquatic organisms of all the metals (Moore et al., 1998). Amending poultry litter with Al-S at either 10 or 20% rate appears to be of great benefit in decreasing Cu in the soil and toxicity to algae.

Results for the initial soil pH by experiment interaction effects on extractable soil Cu are in Table 19.

Table 19

Extractable soil Cu with different soil pH levels in four experiments

	Extractable Soil Cu $g\ kg^{-1}$			
	Experiment			
Initial soil pH	1	2	3	4
4.5	9.88a	10.37a	11.51a	11.90a
5.0	8.22ab	9.77a	9.96ab	11.20a
5.5	8.02b	9.76a	8.80b	10.98a
6.5	6.43c	6.75b	8.69b	10.20a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across litter amendments.

Extractable soil Cu from different soil pH levels showed different concentration among the experiments. Differences in soil Cu among the experiments may be due to soil pH changes (Table 7) because the magnitude of pH decrease was not the same among the experiments. These results show that Cu concentrations in the soil were greater in low pH soils than high pH soils (Table 19). This may be due to the fact that Cu in the soil usually precipitates as cupric hydroxide at soil pH greater than 6 (McBride, 1994).

Manganese

Extractable soil Mn response to the initial soil pH varied among the experiments (Table 20).

Table 20

Extractable soil Mn from different soil pH levels in four experiments

	Extractable Soil Mn			
	mg kg^{-1}			
	Experiment			
Initial soil pH	1	2	3	4
4.5	34.73a[12]	33.07a	28.41a	23.71a
5.0	27.91ab	28.05ab	26.64a	20.84ab
5.5	25.93b	25.87b	25.87a	20.01ab
6.5	21.20b	24.69b	24.18a	17.98b

[1] Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across litter amendments

Extractable soil Mn response to soil pH was different in each experiment (Table 20). These results also show that Mn was significantly greater at soil pH level of 4.5 than pH levels of 5.5 and 5.6 in experiment 1. Higher soil Mn at pH 4.5 may be due to the fact that Mn^{2+} can be released from solid phase by spontaneous dissolution under acidic conditions (McBride, 1994). At high soil pH, Mn is in solid phase where they form insoluble oxide and hydroxide minerals.

These results also show that extractable soil Mn decreased in each experiment. The mechanism by which Mn in the soil decreases with manure additions is unknown but it may be the complexation with organic matter like Al. Although the mechanism of Mn decrease due to application of manure is not known, this is a great benefit because higher concentrations of Mn in the soil can affect crop growth and development.

Soybean Biomass

The effect of initial soil pH and litter amendment on soybean biomass and tissue nutrients concentrations are in Table 21.

Table 21

Statistical tests of the initial soil pH, litter amendment, experiment and their interactions on soybean biomass and concentrations of 10 elements

			Soybean Nutrient Concentrations									
Effect	DF	Biomass	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn	Al
		P>F										
Initial soil pH	3	0.0001	0.0217	0.0011	0.0065	0.0001	0.0104	0.1402	0.0776	0.1976	0.3137	0.0001
Litter amendment	2	0.0001	0.0325	0.0001	0.0030	0.0410	0.0001	0.2223	0.1056	0.1246	0.5018	0.0524
Initial Soil pH x Litter amendment	6	0.0650	0.5460	0.5221	0.5315	0.1480	0.7210	0.5680	0.2914	0.4901	0.7550	0.5460

In general, soybean biomass in plants fertilized with BL and BL + 10 or 20% Al-S increased with increasing soil pH (Table 22). The impact of applying BL + 10 or 20% Al-S on soybean biomass was greater for low pH soils. The decrease in biomass in more acidic soils when fertilized with BL + 10 or 20% Al-S may be attributed to increased extractable soil Al and reduction in soil pH.

Table 22

Effect of poultry litter amendments application to different soil pH levels on soybean biomass

	Biomass			
	g plant^{-1}			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	22.1a	23.12a	23.65a	24.21a
BL + 10% Al-S	21.25a	21.98a	23.56a	24.21a
BL + 20% Al-S	13.59b	16.50b	22.50a	23.58a

Means each column followed by the same letter are not significantly different at P =. 05

Soybean biomass response to BL and BL + 10% Al-S fertilization in soils with pH of 4.5 and 5.0 were not significantly different. Lack of significant differences in biomass between BL and BL + 10% Al-S may be probably because these treatments had the similar effect on the soil pH (Table 6), extractable soil Al (Table 7), and some extractable soil nutrients (Table 18). Although there are no significant differences in biomass production between BL and BL + 10% Al-S fertilized plants, BL has the highest biomass. This is similar to the findings of Warren et al (2006b) who reported higher non significant yields of tall fescue from BL compared to BL + 10% Al-S. Soybean biomass with BL + 20% Al-S fertilization were significantly less than BL fertilization at initial soil pH of 4.5 and 5.0 (Table 22). It is evident from these findings that the decrease in soybean biomass due to BL + 20% Al-S fertilization was severe in lower pH soils probably because solubility of Al-compounds occurs on acid soils with pH of 5.0 or below (Foy, 1988) and the susceptibility of soybean to Al toxicity. Above pH 5.2, hydroxyl aluminum species are formed which are less toxic to plants. In addition to soil pH and extractable soil Al, lower biomass in plants fertilized with BL + 20% Al-S at the soil pH of 4.5 may be due to reduced tissue N concentrations.

Soybean Nutrient Concentrations

Since mineral availability in soil and acquisition by plants are so dependent on soil pH, tissue nutrient concentrations were measured to determine BL and BL + 10 or 20% Al-S effects on uptake of nutrients.

Nitrogen

Nitrogen tissue concentration in soybean varied according to the type of the litter applied. Nitrogen tissue concentration in plants fertilized with BL + 10 or 20% Al-S was often significantly lower than that of BL (Table 23).

Table 23

Effect of poultry litter amendments on soybean tissue nutrient concentration

	Nutrient				
Litter Amendment	N	P	K	Ca	Mg
	g kg^{-1}				
BL	45.02a[12]	3.7a	22.7a	21.4a	9.1a
BL + 10% Al-S	39.25b	3.3b	22.5a	19.4b	7.6b
BL + 20% Al-S	38.46b	3.2b	20.0b	17.8b	7.4b

[1] Means followed by the same letter in columns are not significantly different at P = .05
[2] Each value is an average across soil pH treatments

The concentration of tissue N in plants fertilized with BL + 10 or 20% Al-S was below the sufficiency range of 45 -55 g kg^{-1} in soybean (Jones et al., 1991). Insufficient tissue N concentration in plants is expected to reduce biomass production. Tissue N concentration may have been insufficient in plants fertilized with BL + 10 or 20% Al-S presumably because of reduced mineralization of the organic N because most bacteria perform well under neutral soil pH conditions (Havlin et al., 2000). Reduced organic N transformations in BL + 10% Al-S have been reported by Karthikeyan et al., (2005). However, other studies have reported no significant differences in mineralization between BL + 10% Al-S and BL (Gilmour et al., 2004).

Table 24

Effects of initial soil pH on soybean tissue nutrient concentrations

	Nutrient				
Initial Soil pH	N	P	K	Ca	Mg
	g kg^{-1}				
4.5	32.9b[12]	2.8b	37.1b	18.11b	4.42b
5.0	33.5b	3.2a	33.4c	18.45b	4.46b
5.5	44.6a	3.3a	42.1a	18.62b	4.85a
6.5	47.6a	3.3a	43.3a	22.69a	5.03a

[1] Means followed by the same letter in columns are not significantly different at P = .05
[2] Each value is an averaged across litter amendment

Phosphorous

As observed with tissue N concentration, significantly higher P concentrations occurred with BL fertilization (Table 23). The reduced tissue P concentrations with BL + 10 or 20% Al-S fertilizations may be due to the inactivation of P by Al. Al-sulfate is amended with litter to reduce water soluble P (Moore et al., 2000) and tissue P concentration from plants fertilized with BL + 10 or 20% Al-S suggest that BL + 10 or 20% Al-S decreases plant uptake of P. These findings are similar to those reported by Warren et al., (2006b) who found significant differences between plants fertilized with BL and BL + 10% Al-S in tissue P of tall fescue grown on Davidson loam that had an initial soil pH of 5.6. Smith et al., (2004) found no significant differences in forage P removal by fescue treated with BL + 10% Al-S compared to that treated with BL.

Potassium, Calcium and Magnesium

Tissue Ca, K, and Mg concentrations decreased with BL + 10 or 20% Al-S fertilizations compared to BL fertilization. Plants fertilized with BL had significantly higher tissue Ca, K and Mg concentrations compared with BL + 20% Al-S (Table 23). Lower tissue Ca, K and Mg in plants fertilized with BL + 20% Al-S may be related to extractable soil Al increases in the soil which may have affected crop uptake.

Aluminum

Although Al is not a nutrient required for plant growth it was measured to determine how Al-sulfate-amended litter affected the uptake of Al by plants. The data in Table 27 indicate that soybean tissue Al concentration significantly increased in plants receiving BL+ 10 or 20% Al-S compared to BL.

Table 25

Effects of litter amendments fertilization on soybean tissue Al concentration

Litter amendment	Plant Tissue Al Concentration
	mg kg^{-1}
BL	30.7b[12]
BL + 10% Al-S	35.5a
BL + 20% Al-S	38.6a

[1] Means followed by the same letter are not significantly different at P =.05
[2] Each value is averaged across soil pH treatments

These findings on tissue Al concentrations do not show any differences between plants fertilized with BL + 10% Al-S compared to BL + 20% Al-S (Table 27). Although there were significant differences in extractable soil Al between BL + 10% Al-S and BL + 20% Al-S (Table 9), tissue Al concentrations did not reflect. These results suggest that high soil Al concentrations may probably affected root growth and development. Higher concentrations of extractable soil Al have been reported to affect root development and uptake of essential elements (Foy, 1988).

Averaged over the litter amendments, Al tissue concentrations decreased with an increase in soil pH (Table 26).

Table 26

Effects of initial soil pH on soybean tissue Al concentrations

Initial Soil pH	Tissue Al Concentration
	$mg\ kg^{-1}$
4.5	52.47a[12]
5.0	50.51a
5.5	40.15b
6.5	39.83b

[1] Means followed by the same letter are not significantly different at P = .05
[2] Each value is averaged across litter amendments

Tissue Al concentration was significantly higher at pH 4.5 or 5.0 than at pH 5.5 or 6.5 probably because exchangeable and soluble Al^{3+} is high at pH 4.5 or 5.0. In this study, extractable soil Al was 13 and 10 mg kg^{-1} at pH 4.5 and 5.0 respectively at the beginning of the study while it was not detectable at pH 5.5 or 6.5 (Table 4). Therefore, significantly greater tissue Al concentrations at pH levels of 4.5 and 5.0 were due to higher levels of extractable soil Al to begin with. The other source of extractable soil Al might have been from BL + 10 or 20% Al-S (Table 10).

Cotton Biomass

The analysis of variance shows that cotton biomass was significantly affected by the initial soil pH, litter amendment, and the initial soil pH by litter amendment interaction (Table 27).

Table 27

Statistical test of initial soil pH, litter amendment, experiment and their interaction on cotton biomass in a glasshouse study

Source	DF	P>F
Exp.	2	0.1692
Initial Soil pH	3	0.0060
Exp. x Initial soil pH	6	0.7558
Litter amendment	2	0.0466
Exp. x Litter amendment	6	0.9986
Initial soil pH x Litter amendment	6	0.0001
Exp. x Initial soil pH x Litter amendment	18	0.3091

Table 28

Cotton biomass from litter amendments fertilization at different soil pH levels

	Biomass g $plant^{-1}$			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	26.07a	27.00a	27.26a	30.12a
BL + 10% Al-S	24.94a	25.17a	27.71a	28.33a
BL + 20% Al-S	20.6b	20.9b	27.92a	29.33a

[1]Means followed by the same letter in columns are not significantly different at P=.05
[2]Each value is averaged across experiments

The biomass of cotton fertilized with BL and BL + 10 or 20% Al-S was dependent on the initial soil pH (Table 28). Soil acidification due to BL + 20% Al-S fertilization may have reduced cotton growth.

The biomass of cotton fertilized with BL was the highest among the three litter treatments. Cotton biomass with BL + 10% Al-S application was not significantly different from BL (Table 28). Lack of significant differences in biomass produced between BL and BL + 10% Al-S fertilized plants may be due to increases in the initial soil pH from these treatments (Table 6). Besides increasing the initial soil pH, BL and BL + 10% Al-S application also decreased the initial extractable soil Al (Table 7). These findings are in agreement with the results of Warren et al., (2006a) who reported non-significant differences in corn yields between BL + 10% Al-S and BL in a Davidson loam soil that had an initial soil pH of 5.6. These findings contrast the findings of Moore and Edwards (2005) who reported higher tall fescue yields from BL + 10% Al-S compared to BL fertilization.

Biomass yields from BL + 20% Al-S application was significantly lower than BL at pH 4.5 and 5.0 (Table 30). The decrease in cotton biomass fertilized with BL + 20% Al-S may be related to reduced soil pH and increased extractable soil Al at the initial soil pH of 4.5 and 5.0. Besides the effect of the initial soil pH and extractable soil Al, biomass production may have been affected by reduced N supply to the plants. This can be supported by the lower tissue N concentrations in plants fertilized with BL + 20% Al-S compared to BL fertilized plants (Table 32).

Tissue Nutrient Concentrations

The analyses of variance for initial soil pH, litter amendment, experiment and their interactions effects on cotton tissue nutrient concentrations are in Table 29.

Table 29

Statistical tests of the initial soil pH, litter amendment, experiment and their interactions on cotton tissue concentrations of 9 elements

Source	DF	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
						P>F				
Exp.	2	0.3146	0.7124	0.0001	0.0001	0.0001	0.3546	0.0819	0.7966	0.0824
Initial Soil pH	3	0.1457	0.0001	0.0147	0.1614	0.0640	0.1602	0.2072	0.2654	0.3759
Exp. x Initial soil pH	6	0.3850	0.2852	0.0427	0.0032	0.0011	0.1487	0.7814	0.8771	0.3059
Litter amendment	2	0.0018	0.0010	0.0001	0.5845	0.0428	0.2540	0.2492	0.3214	0.5555
Exp. x Litter amendment	4	0.9942	0.3124	0.0591	0.7538	0.0012	0.8616	0.9708	0.9891	0.9497
Initial soil pH x Litter amendment	6	0.0431	0.0250	0.7795	0.9101	0.7075	0.8769	0.4200	0.8269	0.4894
Exp. x Initial soil pH x Litter amendment	12	0.2152	0.4110	0.6408	0.9482	0.9571	0.4784	0.8799	0.7495	0.3057

Nitrogen

Tissue N concentrations in cotton fertilized with BL and BL + 10 or 20% Al-S showed differences among initial soil pH treatments (Table 30).

Table 30

Cotton tissue N concentration from litter amendments fertilization at different soil pH levels

	Tissue N Concentration			
	g kg^{-1}			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	41.90a[12]	42.20a	42.80a	42.20a
BL + 10% Al-S	39.80a	40.60a	41.90a	41.50a
BL + 20% Al-S	36.70b	38.60b	39.30a	38.00a

[1]Means followed by the same letter in columns are not significantly different at P=.05
[2]Each value is averaged across experiments

Results in Table 32 show that tissue N concentration response to BL and BL + Al-S depends on the percentage Al-S in BL and initial soil pH. Lower tissue N concentrations in low pH soils may be attributed to the reduced mineralization of organic N because most microbial activities are reduced in low pH soils.

Significant differences in tissue N concentrations among the litter treatments were only at the initial soil pH of 4.5 and 5.0 (Table 30). Significant lower tissue N concentrations in plants fertilized with BL + 20% Al-S compared with BL may attributed to decreased the initial pH (Table 6) and this could have affected N uptake by the plants.

Despite significantly reduced tissue N concentration in plants receiving BL + 20% Al-S at initial soil pH of 4.5 and 5.0 relative to BL, tissue N concentrations was consistently lower although not statistically lower relative to BL fertilized plants at initial soil pH of 5.5 and 6.5. This demonstrates that BL + 20% Al-S does not suppress tissue N concentrations when applied to soils with soil pH levels of 5.5 and above. It appears that N supply to plant at soil pH of 5.5 and above was similar for all the liter amendment treatments. These findings are similar to those reported by Warren et al., (2006) who found no significance difference in the tissue N status of corn grown on a Davidson loam when BL and BL + 10% Al-S were applied.

Phosphorous

The effects of applying BL or BL + 10 or 20% Al-S on tissue P concentration were proportional to the initial soil pH (Table 31) and experiment (Table 32).

Table 31

Cotton tissue P concentration from litter amendments fertilization at different soil pH levels

Litter amendment	Tissue P Concentration g kg $^{-1}$ Initial Soil pH 4.5	5.0	5.5	6.5
BL	2.40a[1,2]	2.24a	2.52a	2.38a
BL + 10% Al-S	2.16a	2.10a	2.29a	2.26a
BL + 20% Al-S	1.40b	1.63b	2.03b	2.31a

[1]Means followed by the same letter in columns are not significantly different at P=.05
[2]Each value is averaged across experiments

Variations in tissue P concentration due to BL or BL + 10 or 20% Al-S fertilization at each soil pH may be due to the fact that soil P bioavailability is affected by soil pH (Codling et al., 2000). The reduction in the bioavailability of P can reduce root proliferation (Havlin et al., 2002) and affect nutrient uptake.

Fertilizing cotton with BL + 10% Al-S reduced tissue P concentrations relative to BL but the reductions were not statistically significant except at initial soil pH of 5.5 (Table 33). Tissue P concentration significantly decreased with increased Al-S concentration in BL at initial soil of pH 4.5 and 5.0 (Table 31). For example, application of BL + 20% Al-S at initial soil pH of 4.5 decreased tissue P concentration by 35% relative to BL + 10% Al-S (1.40 vs. 2.16 g kg $^{-1}$). The significant reductions in tissue P concentration with BL + 20% Al-S at pH 4.5 and 5.0 most likely resulted from fixation of water soluble P by additional Al. In more acid soils, exchangeable soil Al can react with the phosphate anions to form variscite, which are stable and insoluble (Brady and Weil, 2000). The fixation of P by Al reduces root proliferation and decreases the uptake of P and other nutrients from the soil. However, solubility of variscite increases with an in soil pH and P is more available in soil solution. Therefore crop uptake of P is expected to increase in high pH soils.

Table 32

Cotton tissue P concentrations fertilized with selected litter amendments in three experiments

	Tissue P Concentration		
	g kg $^{-1}$		
Litter amendments	Experiment		
	2	3	4
BL	2.74a	2.13a	2.24a
BL + 10% Al-S	2.54ab	2.11a	2.16ab
BL + 20% Al-S	2.19b	1.95a	1.92b

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across the initial soil pH treatments

Application of BL and BL+ 10 or 20% Al-S showed significant effects on tissue P concentrations in experiment 2 but few effects was significant in experiments 3 and 4 (Table 34). Differences in tissue P concentration among experiments may be linked to changes in the initial soil pH from BL and BL + 10 or 20% Al-S applications in each experiment (Table 7). Plant available P in the soil is related to the soil pH because PO_4^{2-} anions can react with Fe^{3+} and Al^{3+} in acid soils forming water insoluble compounds (Weil and Brady), which cannot be taken up by the plant. Since each litter treatment had different effect on the final soil pH in each experiment, this may have affected plant available P. Similar to tissue N concentration, plants fertilized with BL had the highest tissue P concentration compared to BL + 10 or 20% Al-S fertilized plants. Tissue P concentrations may have been higher in BL fertilized plants because it contains greater water soluble P compared to BL + 10 or 20% Al-S (Moore and Miller, 1994).

Potassium

Cotton tissue K concentrations with BL, and BL + Al-S fertilization varied among the three experiments (Table 33).

Table 33

Plant tissue K concentrations fertilized with selected litter amendments in three experiments

	Tissue K Concentration		
	g kg $^{-1}$		
	Experiment		
Litter amendment	2	3	4
BL	39.48a[1,2]	39.19a	50.19a
BL + 10% Al-S	36.83b	38.37a	48.24a
BL + 20% Al-S	31.56c	36.19b	47.37a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across the initial soil pH treatments

The differences in tissue K concentration from BL and BL + 10 or 20% Al-S fertilization in each experiment may be related to soil pH changes (Table 7). These changes in the soil pH due to BL or BL + 10 or 20% Al-S applications may have affected plant available K because exchangeable soil K is affected by soil pH and exchangeable soil Al like other exchangeable base cations.

Application of BL resulted in the highest tissue K concentrations among the litter amendments (Table 33). Higher tissue K concentrations in plants fertilized with BL may be related to increase in extractable soil K from BL applications which may have enhanced plant available K in soil solution. Application of BL has shown to increase tissue K concentration in cotton leaf blades (Mitchell and Tu, 2005). Fertilizing plants with BL + 10% Al-S resulted in non-significant tissue K concentrations compared to BL in experiment 1 while BL + 20% Al-S significantly decreased tissue K concentration in experiments 2 and 3 (Table 33). Reduced tissue K concentrations in plants fertilized with BL + 10 or 20% Al-S may due to magnitude of soil pH changes that could have affected K in soil solution. Decreased tissue K concentrations in plants fertilized with BL + 10 or 20% Al-S are in contrast with the findings of Sistani et al., (2002) who reported higher non significant tissue K in plants fertilized with BL + low or high alum compared to BL.

Because of the significant initial soil pH by experiment interaction, tissue K concentrations due to soil pH were analyzed for each experiment (Table 34).

Table 34

Plant tissue K concentrations in cotton grown at different soil pH in three experiments

	Tissue K Concentration		
	$g\ kg^{-1}$		
	Experiment		
Soil pH	2	3	4
4.5	33.72b[12]	35.33a	48.05a
5.0	35.18ab	37.91a	48.24a
5.5	37.60a	38.38a	48.51a
6.5	37.31a	40.05a	49.57a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across litter amendments

Cotton tissue K response to the initial soil pH showed different concentrations in each experiment (Table 34). Most tissue K concentration differences among the soil pH treatments were only in the second experiment. Despite lack of significant differences in tissue K concentration among the soil pH treatments in experiment 3 and 4, tissue K concentrations were always higher at soil pH of 6.5. Higher tissue K concentration at soil pH of 6.5 than the other pH levels may be due increased K availability in the soil. Like other exchangeable cations, K in the soil increases with an increase in soil pH. Potassium might have been higher in soil solution at pH level of 6.5 than the lower soil pH levels that led to higher uptake by the plants. Tissue K concentration also shows an increase in experiment. The increase in tissue K concentration in each experiment may be to the residual effect of K from BL and BL + 10 or 20% applications because of higher K concentrations (Table 4).

Calcium

Fertilizing cotton with BL and BL + 10 or 20% Al-S resulted in different tissue Ca concentrations among the initial soil pH treatments (Table 35) and, experiments (Table 36).

Table 35

Plant tissue Ca concentrations in cotton fertilized with selected litter amendments with different initial soil pH levels

	Tissue Ca Concentration			
	g kg $^{-1}$			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	33.13a[12]	34.66a	33.78a	31.59a
BL + 10% Al-S	28.73a	32.17a	33.57a	32.34a
BL + 20% Al-S	26.33b	23.84b	31.89a	30.00a

[1]Means followed by the same letter in columns are not significantly different at P =.05
[2]Each value is averaged across experiments.

Tissue Ca concentration in plants receiving BL and BL + 10 or 20% Al-S were different among the initial soil pH treatments because available soil Ca^{2+} is low in acidic soils. Since some of these treatments decreased the initial soil pH (Table 6), plant available Ca may have decreased. In addition, low soil pH contains higher concentrations of Al^{3+} and H^{+} that impedes Ca^{2+} uptake (Brady and Weil, 2000).

Plants fertilized with BL had the highest tissue Ca concentration (Table 35). Higher tissue Ca concentrations in plants fertilized with BL may be attributed to its effects on extractable soil Ca (Table 14). Soils receiving BL had the highest extractable soil Ca compared to soil receiving BL + 10 or 20% Al-S suggesting that there was an increase of Ca in soil solution. The increase in Ca in soil solution may have enhanced uptake by the plants.

Tissue Ca concentrations in plants receiving BL + 10% Al-S were not significantly different from BL (Table 35). Similar to the results on biomass, BL + 20% Al-S fertilization significantly decreased tissue Ca concentrations relative to BL at the initial soil pH of 4.5 or 5.0 (Table 35). Significant low tissue Ca concentrations with BL + 20% Al-S at pH 4.5 and 5.0 may be associated with Al^{3+}, which dominates the exchange complex and decreases Ca in soil solution. Meanwhile at the soil pH of 5.5 and 6.5, tissue Ca concentrations are not significantly different among the litter treatments. Despite lack of significant differences in tissue Ca concentration among BL and BL + 10 or 20% Al-S fertilization at initial soil pH of 5.5 and 6.5, plants fertilized with BL contained the highest tissue Ca Concentrations. This is in agreement with the findings of Shreve et al., (1995) who reported non significant differences in tissue Ca concentrations between tall fescue fertilized with BL and BL + 10% Al-S.

Table 36

Plant tissue Ca concentrations with selected litter amendments fertilization in three experiments

	Tissue Ca Concentration		
	$g\ kg^{-1}$		
Litter amendments	Experiment		
	2	3	4
BL	31.73a[1,2]	31.15a	26.48a
BL + 10% Al-S	31.90a	27.58b	26.70a
BL + 20% Al-S	28.49b	23.67c	27.69a

[1] Means followed by the same letter in columns are not significantly different at P =.05
[2]Each value is averaged across soil pH treatments

The effect of BL and BL + 10 or 20% Al-S on tissue Ca concentrations was different among the experiments (Table 36). One possibility for the differences in BL and BL + 10 or 20% Al-S effects on tissue Ca concentrations among the experiments may be related to extractable soil Al because plant available Ca is affected by Al concentration and soil pH. Since applications of BL and BL + 10 or 20% Al-S had different effects on the soil pH and extractable soil Al in each experiment (Table 7), this may have created variation in plant available Ca and plant uptake. Significant differences in tissue Ca concentration were found only in experiment 2 and 3 among the sources of litter.

Magnesium

Due to significant litter amendment by experiment interaction and soil pH by experiment interaction, tissue Mg concentration response to BL or BL + 10 or 20% Al-S was analyzed for each experiment (Table 37) and each soil pH treatment (Table 38).

Table 37

Plant tissue Mg concentrations fertilized with selected litter amendments in three experiments

	Tissue Mg Concentration		
	$g\ kg^{-1}$		
	Experiment		
Litter amendment	2	3	4
BL	7.36a[12]	7.77a	10.51a
BL + 10% Al-S	7.11a	7.76a	10.08a
BL + 20% Al-S	6.79a	5.91b	9.87a

[1]Means followed by the same letter in columns are not significantly different at P=.05.
[2]Each value is averaged across soil pH treatments

Statistical differences in Mg concentrations among the five litters were only in experiment 2 (Table 37). Magnesium in the soil occurs predominantly as exchangeable and solution Mg and adsorption by plants depends on soil pH, Mg on the CEC and quantity of other exchangeable cations (Havlin et al., 2002). Since BL and BL + 10 or 20% Al-S applications had different effects on soil pH and exchangeable cations in each experiment, this may have contributed to differences in tissue Mg concentrations.

These results show that there are no differences in tissue Mg concentration among the experiments except experiment 3. Lack of significant differences in tissue Mg concentration between plants fertilized with BL and those fertilized with BL + 10% Al-S consistent with the findings of Shreve et al., (1995) who found no differences in tissue Mg concentrations in tall fescue between BL and BL + 10% Al-S fertilization. Although no differences in tissue Mg concentrations in experiments 3 and 4, cotton-receiving BL had the highest tissue Mg concentrations among the treatments (Table 3). Higher tissue Mg concentrations in cotton fertilized with BL than BL + 10% Al-S is likely from elevated soil pH levels (Table 7) and subsequent lower extractable soil Al concentrations which increases Mg^{2+} uptake.

Table 38

Plant tissue Mg concentrations in cotton grown at different soil pH levels in three experiments

	Tissue Mg Concentration		
	g kg $^{-1}$		
	Experiment		
Initial Soil pH	2	3	4
4.5	6.41b[12]	6.34b	9..07b
5.0	6.82b	7.02ab	10.49a
5.5	6.89ab	7.47a	10.62a
6.5	7.56a	7.53a	10.68a

[1]Means followed by the same letter in columns are not significantly different at P=.05
[2]Each value is averaged across litter amendments

In general, plant tissue Mg concentrations increased with an increase in pH in all experiments (Table 38). Statistical differences in tissue Mg concentrations were only in experiment 1. Tissue Mg concentrations showed an increase in each experiment. For example, tissue Mg at pH 4.5 increased from 6.58 g kg^{-1} in experiment 1 to 7.13 g kg^{-1} in experiment 2 and to 9.86 g kg^{-1} in experiment 3. Increase in tissue Mg concentrations in each experiment may be from elevated exchangeable soil Mg from litter amendments (Table 17).

Tissue Aluminum Concentration

The analysis of variance shows that the tissue concentrations of Al in cotton were significantly affected by initial soil pH, litter amendment, initial soil pH by litter amendment interaction and, experiment by initial soil pH interaction (Table 39).

Table 39

Statistical tests of initial soil pH, litter amendment, experiment and their interactions effect on plant tissue Al concentration in a glasshouse experiment

Source	DF	P>F
Exp.	2	0.1193
Soil pH	3	0.0001
Exp. x Soil pH	6	0.0027
Litter amendment	2	0.0349
Exp. x Litter amendment	4	0.0672
Soil pH x Litter amendment	6	0.0351
Exp. x Soil pH x Litter amendment	12	0.2996

Results show that plant tissue Al concentration due BL and BL + 10 or 20% Al-S fertilization varied according to the initial soil pH (Table 40).

Table 40

Plant tissue Al concentration from selected litter amendments to different soil pH levels

	Plant tissue Al concentration			
	mg kg^{-1}			
Litter amendment	Initial Soil pH			
	4.5	5.0	5.5	6.5
BL	22.06c[12]	22.77b	18.59b	19.35a
BL + 10% Al-S	27.49b	30.61a	24.97a	23.08a
BL + 20% Al-S	37.30a	33.96a	27.34a	23.36a

[1]Means followed by the same letter in columns are not significantly different at P = .05
[2]Each value is averaged across experiments

Cotton fertilized with BL + 10 or 20% Al-S contained significantly higher tissue Al compared to BL fertilization at pH 4.5. The significant increase in tissue Al in plants fertilized with BL + 20% Al-S relative to BL may be due to the decrease in soil pH and an increase in extractable soil Al with these treatments. The acidification of the soil due to BL + 20% Al-S increased the dissolution kinetics of Al and placed some of the Al into solution where it was bioavailable to the plants. It appears that the dissolution kinetics of Al was higher with BL + 20% Al-S than BL + 10% Al-S. Significant differences in tissue Al concentrations are between BL compared with BL + 10% Al-S are inconsistent with the findings of Moore and Edwards (2005) who reported non significant differences in tissue Al between tall fescue fertilized with BL and BL + 10% Al-S. The findings from this study may be different probably because the soils used were more acidic than those used by Moore and Edwards (2005). However, Shreve et al., (1995) reported significantly higher tissue Al concentrations in tall fescue treated BL + 10% Al-S compared with BL. Although plant tissue Al concentration increased in plants fertilized with BL + 10 or 20% Al-S, Al toxicity were not observed. It is likely that dissolved compounds such as PO_3^{3-} and SO_4^{2-} in the litter can ameliorate toxicity by reducing bioavailability (Sparling and Lowe, 1996).

Since there was a significant soil pH by experiment interaction, plant tissue Al due to soil pH were analyzed for each experiment (Table 41)

Table 41

Plant tissue Al concentrations in cotton at different soil pH in three experiments

	Tissue Al Concentration		
	mg kg $^{-1}$		
	Experiment		
Initial Soil pH	2	3	4
4.5	38.03a	30.28a	14.71a
5.0	39.55a	29.68a	14.81a
5.5	28.85b	26.19b	14.21a
6.5	27.11b	25.27b	12.43b

[1]Means followed by the same letter in columns are not significantly different at P=.05
[2]Each value is averaged across litter amendments

Tissue Al concentration response to the initial soil pH showed differences in each experiment (Table 41). The differences in tissue Al concentrations may be related to extractable soil Al variations in each experiment (Table 11). The data in Table 11 show that extractable soil Al varied in each experiment and this may have affected Al uptake by the plants.

Tissue Al concentrations decreased in each experiment (Table 41). For example, tissue Al concentration decreased by 7 mg kg^{-1} from experiment 1 to experiment 2 at soil pH 4.5 and decreased further by 14 mg kg^{-1} in experiment 3 (Table 41). The decrease in tissue Al concentrations in each experiment suggest that BL and BL + 10 or 20% Al-S additions to the soil may reduce tissue Al concentrations in the short term.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Repeated application of BL and BL + 10 Al-S to pots growing soybean and cotton increased the soil pH but applications of BL + 20% Al-S decreased soil pH.

Application of BL + 10 or 20% Al-S increased extractable soil Al and the effect were soil pH dependent with highest concentrations of extractable soil Al at the pH 4.5 and 5.0 These results show that use of BL + 20% Al-S should be of environmental concern in acid soils.

Application of BL + 20% Al-S significantly decreased extractable soil Ca. Mehlich-3 extractable P was affected by the initial soil pH with low values in more acidic soil. Mehlich-3 extractable soil Cu decreased over time with BL + 10 or 20% Al-S with significantly lower values from BL + 20% Al-S at pH 4.5 or 5.0. The initial soil pH significantly affected extractable Mn with higher numbers in more acidic soils.

The impacts of BL + 10 or 20% Al-S on cotton or soybean biomass were dependent on the initial soil pH and to an extent the amendment rate. Plant receiving BL had the highest biomass and those fertilized with BL + 20% Al-S had the lowest biomass. The reduction in biomass may be attributed to a combination of soil pH decrease and increase in extractable soil Al. In addition, inadequate N and P due to 20% Al-S may have limited biomass. Conclusions drawn from this study are that application of BL + 20% Al-S reduces biomass in acid soils.

Soils receiving BL + 10 or 20% Al-S elevated tissue Al concentrations and it was soil pH dependent with higher values at soil pH $\leq$ 5.0 and lower values at $\geq$ 5.5. Although plant tissue Al concentration was higher in plants fertilized with BL + 10 or 20% Al-S, it is inconclusive as to whether the higher levels of Al affected biomass. Fertilization cotton or soybean with BL + 20% Al-S had similar effects on soil pH, extractable soil Al, biomass and tissue concentrations of N, P, Ca, K, and Mg.

In conclusion, the results of this study show that BL and BL + 10% Al-S can be used as a fertilizers in acid soils without applying lime to increase the soil pH but increasing the amendment rate of Al-S to 20% may not a good fertilizer in acidic soils. It is unclear if the soil pH increase from BL and BL + 10% Al-S may be a short-term effect lasting several months or it may be a long term in nature. Nonetheless, such an effect creates a short-term window of opportunity for crop production in acid soils.

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