

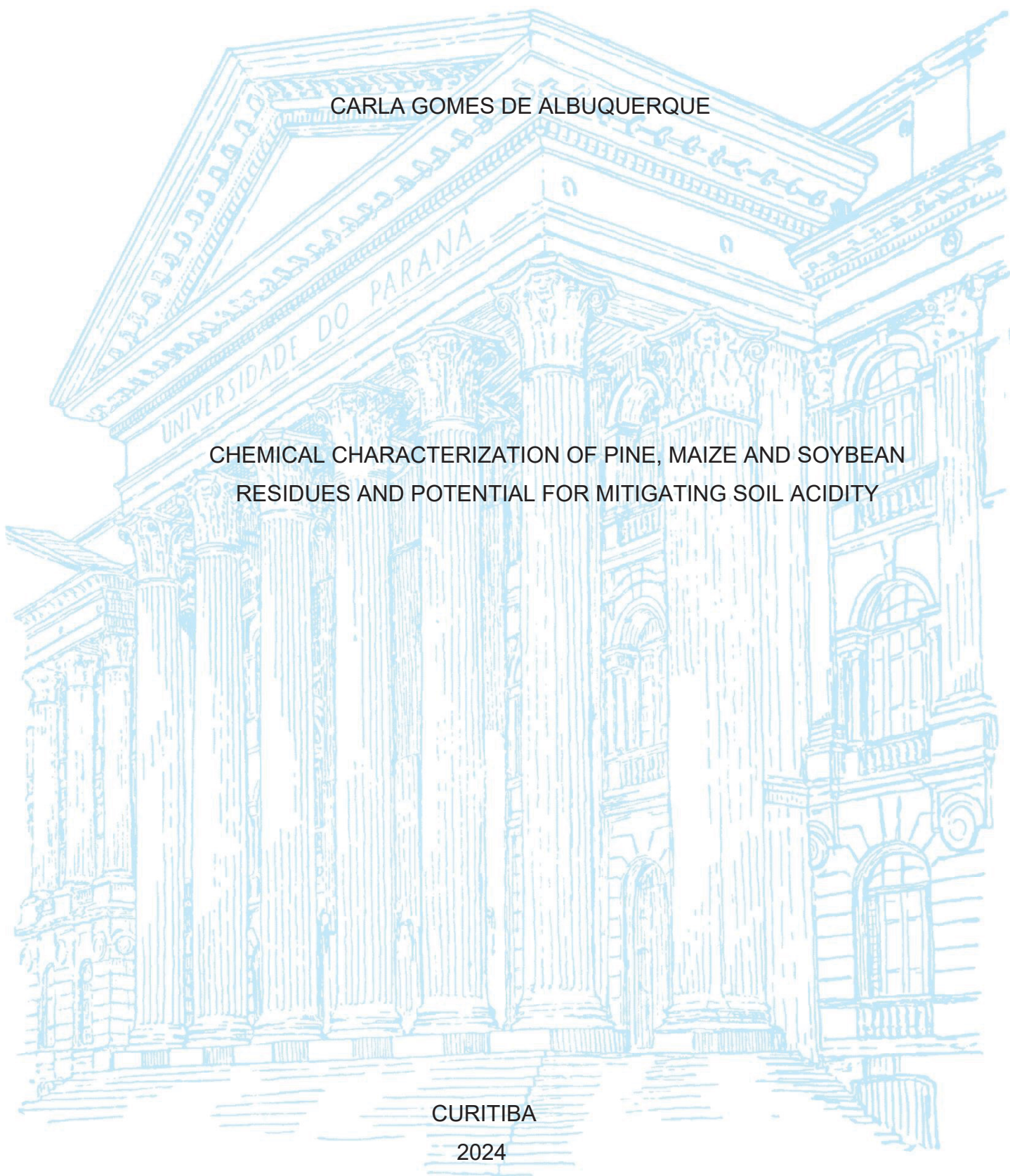
UNIVERSIDADE FEDERAL DO PARANÁ

CARLA GOMES DE ALBUQUERQUE

CHEMICAL CHARACTERIZATION OF PINE, MAIZE AND SOYBEAN
RESIDUES AND POTENTIAL FOR MITIGATING SOIL ACIDITY

CURITIBA

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CARLA GOMES DE ALBUQUERQUE

CHEMICAL CHARACTERIZATION OF PINE, MAIZE AND SOYBEAN RESIDUES
AND POTENTIAL FOR MITIGATING SOIL ACIDITY

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ANTONIO CARLOS VARGAS MOTTA

Presidente da Banca Examinadora

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DANIEL RENATO LAMMEL

Avaliador Externo (FREIE UNIVERSITÄT BERLIN_)

Assinatura Eletrônica

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JULIERME ZIMMER BARBOSA

Avaliador Externo (INSTITUTO FEDERAL SUDESTE DE MINAS
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"I don't even bother trying to picture a perfect world, because I don't think that perfection is something to strive for. I prefer imperfection. That's what makes things special. You know, things that change" (Anthony Kiedis).

RESUMO

Os benefícios dos resíduos da colheita são conhecidos, porém seu efeito na acidez do solo é pouco discutido. A soja é principal leguminosa cultivada no mundo, sendo o Brasil o maior produtor, o milho é a segunda lavoura mais abundante no país e o gênero pinus é conífera mais plantada em nível nacional e mundial. Tais características colocam o estudo de seus resíduos como fator relevante. Estudou-se a ação de resíduos sobre acidez de solos com poder tampão (Latossolo – baixo e Cambissolo – alto), horizontes (A e B) e acidez inicial (solo não corrigido e corrigido) distintos. Deste modo, foi possível verificar o efeito do tamponamento e da mineralogia, dos níveis preexistentes de matéria orgânica e da acidez inicial sobre as mudanças resultantes dos resíduos. Serapilheira de *Pinus taeda*, resíduos de milho (*Zea mays*) e soja (*Glycine max*) foram utilizadas proporcionando variação na relação C/N e de cátions. As doses 0, 6, 12, 24 e 48 t ha⁻¹ foram aplicadas e avaliados os parâmetros de acidez ativa (pH em CaCl₂ 0.01 M) e acidez potencial trocável (Al trocável) nos tempos de 18h, 30, 90, 180, 270 e 365 dias devido às prováveis diferenças na taxa de decomposição dos resíduos. Verificou-se que indiferente ao resíduo e solo utilizados ocorreu redução da acidez dos solos, sendo este efeito de até 30 dias e mais intenso para a soja e mais prolongado e menos intenso com milho e pinus. O efeito foi proporcional à dose e à abundância de cátions e inversamente proporcional à C/N. A diminuição da acidez foi maior nos solos não corrigidos, sendo que no horizonte B do Latossolo com a soja ocorreu o maior ΔpH (+1.35) e no horizonte B do Cambissolo o maior ΔAl (-2.87 cmol_c kg⁻¹). Mesmo o resíduo ácido e com baixo teor de cátions (*Pinus taeda*) diminuiu a acidez, mas o efeito de cada material vegetal depende do poder tampão e do pH inicial do solo e do tempo. Em segundo estudo foram caracterizadas palhadas de soja de duas regiões produtoras do Brasil e avaliou-se seu potencial em amenizar a acidez de um latossolo. Coletou-se amostras de palhada nos estados do Paraná e Rio Grande do Sul (clima subtropical), no sul do Brasil, e no oeste do estado da Bahia (clima tropical), no nordeste do Brasil. Foram quantificados C, N, Ca, Mg, S, P, Cu, Mn, Zn, V, Ni, Ba, K, Na, pH e alcalinidade disponível (OH⁻). A soja da região nordeste apresentou maior teor de Mg, K e P enquanto C, N, S, OH⁻, Cu, Mn, V, Ni e Ba foram maiores no resíduo do sul. Um latossolo foi incubado com as palhadas e analisou-se pH CaCl₂ e Al³⁺ após um mês. O pH aumentou e o Al³⁺ diminuiu no latossolo após incubação com as palhadas, sem diferença significativa entre as duas regiões. A qualidade química da palhada depende da região, variando principalmente quanto à adubação e calagem, porém adição de material vegetal ao solo, independente da composição, é benéfica pois ameniza a acidez.

Palavras-chave: Resíduo de plantas; Solos ácidos; *Glycine max*; Alcalinidade potencial; Relação C/N.

ABSTRACT

The benefits of crop residues are well known, but their effect on soil acidity is little discussed. Soybean is the main legume grown in the world, with Brazil being the largest producer, corn is the second most abundant crop in the country and pine is the most widely planted conifer at national and world level. These characteristics make the study of its residues a relevant factor. We studied the effect of residues on the acidity of soils with different buffering capacities (Oxisol - low and Inceptisol-high), horizons (A and B) and initial acidity (uncorrected and corrected soil). In this way, it was possible to verify the effect of buffering and mineralogy, pre-existing levels of organic matter and initial acidity on the changes resulting from the residues. *Pinus taeda* litter, maize (*Zea mays*) and soybean (*Glycine max*) residues were used, providing variation in the C/N ratio and cations. Doses of 0, 6, 12, 24 and 48 t ha⁻¹ were applied, and the parameters of active acidity (pH in 0.01 M CaCl₂) and exchangeable potential acidity (exchangeable Al) were evaluated at times of 18h, 30, 90, 180, 270 and 365 days due to the probable differences in the decomposition rate of the residues. It was found that regardless of the residue and soil used, there was a reduction in soil acidity, with this effect lasting up to 30 days and being more intense for soybeans and more prolonged and less intense with maize and pine. The effect was proportional to the dose and abundance of cations and inversely proportional to C/N. The decrease in acidity was greater in the uncorrected soils, with the greatest ΔpH (+1.35) occurring in the B horizon of the Oxisol with soybeans and the greatest ΔAl (-2.87 cmolc kg⁻¹) in the B horizon of the Inceptisol. Even the acidic residue with low cation content (*Pinus taeda*) reduced acidity, but the effect of each plant material depends on the buffering capacity and initial pH of the soil and time. In a second study, soybean straw from two producing regions in Brazil was characterized and its potential to mitigate the acidity of an Oxisol was assessed. Samples of straw were collected in the states of Paraná and Rio Grande do Sul (subtropical climate), in southern Brazil, and in the west of the state of Bahia (tropical climate), in northeastern Brazil. C, N, Ca, Mg, S, P, Cu, Mn, Zn, V, Ni, Ba, K, Na, pH and available alkalinity (OH⁻) were quantified. Soybeans from the northeast region had a higher content of Mg, K and P, while C, N, S, OH⁻, Cu, Mn, V, Ni and Ba were higher in the southern residue. An oxisol was incubated with the straw and pH CaCl₂ and Al³⁺ were analyzed after one month. The pH increased and Al³⁺ decreased in the oxisol after incubation with the straw, with no significant difference between the two regions. The chemical quality of the straw depends on the region, varying mainly in terms of fertilization and liming, but adding residues to the soil, regardless of its composition, is beneficial as it reduces acidity.

Keywords: Crop residue; acidic soils; *Glycine max*; potential alkalinity; C/N ratio.

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1 GENERAL INTRODUCTION

Naturally, soil acidity is directly related to the degree of soil weathering, which intensifies over time (Rahman *et al.*, 2018). However, acidity is accentuated by factors such as the leaching of basic cations from the soil, the acid deposition of atmospheric components and even nitrogen fixation by plants (Cooper; Scherer, 2012). However, it can also be intensified by certain practices such as the use of ammoniacal fertilizers and the intensive cultivation of agricultural crops with the extraction of cations (Fageria; Nascente, 2014).

The pH value comes from acidic substances contained in the soil that release H^+ . The H^+ ions released by the dissociation of strong acidic groups in the soil are the active acidity of the soil. On the other hand, the H^+ not dissociated in weakly acidic substances in the soil is the potential acidity, and the total acidity of the soil is the sum of the soil's active and potential acidity (Tisdale *et al.*, 1993). The pH influences many soil variables and chemical processes and reactions, including the availability of P, activity of Al^{3+} , which is toxic to the plants, and micronutrients such as Mn, Cu, Fe and Zn (Sparks, 2003).

Correcting the surface and subsurface acidity of the soil is a necessary practice for plants to absorb nutrients and for good crop yields to be achieved (Sousa; Miranda; Oliveira, 2007). The materials commonly used for acidity correction are limestones which neutralize H^+ through the hydrolysis of H_2O by a strong base (CO_3^{2-} or OH^-) (Holland *et al.*, 2018; Sousa; Miranda; Oliveira, 2007). Some alternatives have been researched as organic soil acidity correctives, including crop residues, animal waste, poultry litter, compost products and biochar (Abewa *et al.* 2013; Arshad *et al.* 2012; Brassard *et al.* 2016; Butterly *et al.*, 2021; Cai *et al.* 2014; Lauricella *et al.*, 2020; Raboin *et al.* 2016; Wang *et al.* 2015; Xiao *et al.* 2013; Zhao *et al.* 2015). Plant residues generate alkalinity as they decompose, mitigating soil acidity (Butterly *et al.*, 2011; Xu *et al.*, 2006).

The decomposition of organic anions from plant residues by microorganisms contributes to the change in soil pH through: (1) decarboxylation, in which the organic anions consume a proton and release CO_2 , as described by Tang and Yu (1999). This reaction has already been attributed as responsible for pH changes that occurred in an experiment with the application of plant residues and correlated with CO_2 emissions by Yan, Schubert and Mengel (1996); (2) ligand exchange with hydroxylated groups ($-OH$) in iron and aluminum oxides, with the release of OH^- into the soil (Turmel *et al.*, 2015); (3) N mineralization, especially considering plant residues with a high content of this nutrient, such as legumes (Butterly *et al.*, 2021). The formation of ammonium increases the pH of the soil by consuming hydrogen (Sousa; Miranda; Oliveira, 2007). However, in the conversion of ammonium into nitrate, for 1 mol of ammonium oxidized, 2 mols of hydrogen are released, acidifying the soil at the end of the reaction. However, nitrification is greatly inhibited when the soil pH is low (Xiao *et al.*, 2013). Subsequently, denitrification reduces nitrate to N_2 , consuming 8 H^+ and alkalizing the soil (Shi *et al.*, 2020).

The H^+ consumption by N mineralization will be more evident in legumes residues, such as soybeans, because the C/N ratio is lower (Wang *et al.*, 2012; Xu; Tang; Chen, 2006). Legumes have

high alkalinity and mitigate soil acidity more easily than grasses like maize (Neina, 2019). The decomposition is affected in residues with a high lignin content and a high C/N ratio, such as pine residue, which inhibits consumption of H^+ through N mineralization (Priha; Smolander, 1999; Sánchez; DelPino; Hernández, 2018).

There are several studies in the literature showing that legumes have a higher capacity to correct soil acidity (Butterly *et al.*, 2021; Cai *et al.*, 2018; Sakala; Rowell; Pilbeam, 2004; Vanzolini *et al.*, 2017; Xiao *et al.*, 2014). Grasses, such as maize, have moderate correction potential, while there are few studies reporting soil incubation studies with pine residues, showing modest acidity correction potential (Noble; Zenneck; Randall, 1996; Sakala; Rowell; Pilbeam, 2004). Soybeans have good correction potential due to decarboxylation and ammonification reactions, the release of bases into the soil and the replacement of $H^+ + Al^{3+}$ in the exchange complexes (Xiao *et al.*, 2013).

The objectives of this work were to study the action of different crop residues (*Pinus taeda*, maize and soybean residues) on the acidity (pH and exchangeable Al) of soils with different buffering capacities (oxisol - low and inceptisol - high), diagnostic horizon (Horizon A and B) and initial soil acidity (uncorrected and corrected soil). In the second part, soybean straw from two soybean-producing regions in Brazil (Paraná and Rio Grande do Sul, and Bahia) was characterized and its potential to mitigate the acidity of an oxisol was discussed. The results of this work show that, in addition to the well-known benefits of crop residues to the soil, different types of organic material do not acidify the soil and that they have good alkalizing properties with the potential to mitigate soil acidification.

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CHAPTER 1: *POTENTIAL OF PINE, MAIZE, AND SOYBEAN RESIDUES TO ALTER ACIDITY OF SOILS WITH LOW AND HIGH BUFFERING CAPACITIES

Carla Gomes de Albuquerque, Antônio Carlos Vargas Motta, Fabiana Gavelaki, Grazielli da

Rocha, Stephen A. Prior, Tamires Maiara Ercole, Jeferson Dieckow

Abstract

Background and Aim Benefits of crop residues are well known, but their effects on soil acidity is poorly understood. This study evaluated the effect of three residue amendments on horizons (A and B) of two soils [Oxisol (low buffering capacity) and Inceptisol (high buffering capacity)] with and without liming. **Methods** Loblolly pine (*Pinus taeda*) litter, maize (*Zea mays*), and soybean (*Glycine max*) residues applied at equivalent rates of 0, 6, 12, 24, and 48 t ha⁻¹ were incubated with soils samples for 0.75, 30, 90, 180, 270, and 365 days. At incubation time intervals, pH and exchangeable Al were measured. **Results** Regardless of residue and soil type, there was a reduction in soil acidity according to pH and exchangeable Al; this effect lasted up to 30 days and was more intensive for soybean residue but more prolonged and less intensive with maize and loblolly pine residues. The influence on soil acidity was directly related to rate and residue cation abundance and inversely proportional to C/N. This was associated with residue composition in terms of lignin, cellulose, and hemicellulose. The decrease in acidity was greater in soils without lime; the greatest ΔpH (+1.35) occurred in the Oxisol B horizon with soybean, while the greatest ΔAl (-2.87 cmol_c kg⁻¹) occurred in the Inceptisol B horizon. **Conclusion** Even the acidic residue with low cation content (loblolly pine) reduced acidity, but the degree of effect of each plant material depends on soil buffering capacity, time, and soil pH.

Keywords: Crop residue; Potential alkalinity of residue; Soil acidity; C/N ratio; Infrared spectrometry.

1 INTRODUCTION

Soil acidification causes limitations to agricultural production in many soils worldwide. Acidic soils have high concentrations of toxic elements (e.g., Al), low availability of nutrients (Ca, Mg, K, and P), and high P fixation, especially in tropical climate areas (Hazarika et al. 2021; Latifah et al. 2018). The use of CaCO_3 and CaSO_4 mitigates toxic Al in soil, but use of animal manure, biochar, industrial sludge, and plant residues are alternatives for increasing soil pH and cation concentration, while decreasing exchangeable Al activity (Cai et al. 2018; Hazarika et al. 2021; Vanzolini et al. 2017; Wang et al. 2012; Yu et al. 2021).

Crop residues harvested for use in the landscape, animal production, and biomass energy may affect soil acidification. These residues could reduce Al^{3+} toxicity due to generated humic acids and low molecular weight organic acids released during decomposition processes (Haynes and Mokolobate, 2001). However, the ability of organic material to alleviate toxicity goes beyond the chelating power of organic acids since incorporation of these residues promotes acid-base reactions that increase pH and contribute to Al^{3+} reduction since the $\text{Al}(\text{OH})_3$ form predominates at $\text{pH H}_2\text{O} > 5.5$. (Haynes and Mokolobate, 2001; Sakala et al. 2004).

The ability of a plant residue to maintain soil acidity at adequate levels is associated with residue N content, alkalinity, and reactions such as the decarboxylation of anions derived from carboxylic acids released during decomposition (Yan et al. 1996; Tang and Yu, 1999). Residue N influences soil pH change since the ammonification reaction (NH_4^+ production) occurs as organic material is decomposed, which consumes protons and increases pH (Wang et al. 2012). The biological oxidation of N or nitrification (NO_3^- production) acidifies the soil as the reaction releases 2H^+ . While nitrification can be reduced under acidic environments that favor the rise in pH when plant residues are added to low pH soils, slightly alkaline soils tend to show a decrease in pH due to NO_3^- formation (Butterly et al. 2013; Wang et al. 2017). However, a hydroxyl is lost when nitrate is absorbed by the plant, neutralizing the reaction (Han et al. 2015; Sousa et al. 2007). Thus, it is necessary to consider soil and residue properties to clearly assess the effects on soil acidity.

Alkalinity of plant residues and other laboratory analyses can be measured and related to cations (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) bound to organic anions (R-CO-COO^-) derived from carboxylic acids. These anions are decomposed via decarboxylation reactions, consuming protons as well as releasing bound cations (Li et al. 2008; Wang et al. 2012). This alkalinity (also called excess cations) can be calculated as the difference between cation and inorganic anion contents (H_2PO_4^- , SO_4^{2-} , and Cl^-) and is equivalent to H^+ efflux resulting from plant absorption of these cations (Han et al. 2015; Vanzolini et al. 2017).

Low molecular weight carboxylic acids (e.g., oxalic, malic, citric, tartaric, acetic, lactic, ascorbic, and formic acids) can alter soil pH, and these have been quantified in some cultivated species to characterize residue decomposition for acidity amendments (Xu et al., 2006). If the initial soil pH is lower than the pK_a of organic acid carboxyl groups, pH increases due to the association of H^+ from the soil solution containing these functional groups (Rukshana et al. 2012). The use of acids and salts of organic anions as acidity correctors has been investigated under laboratory conditions and showed

potential when organic anions are incubated with soil resulting in organic acids decreasing soil pH in the short term due to deprotonation of carboxyls (Rukshana et al. 2014).

The Fabaceae and Poaceae plant families contain major agricultural crops with widely varying qualities and chemical compositions that can affect amelioration of soil acidity. In general, Fabaceae species have greater potential than other residue types (Xiao et al. 2014) and can easily decay due to low C/N ratios and the quick release of N and cations when incorporated into soil (Xiao et al. 2014). On the other hand, Poaceae species decay slowly over time as they have higher C/N ratios (Butterly et al. 2013).

Since rate of decay varies among residues, it is necessary to consider evaluation times to obtain both short term and residual effects of residue amendments. Evaluating residual effects of crop residue under field conditions, Butterly et al. (2013) found a maximum increase in soil pH around three months that persisted for 26 months. However, most laboratory studies average only three months (Cai et al. 2018; Vanzolini et al. 2017; Xiao et al. 2014), which may not adequately characterize slow decay residue. With bean and wheat residues, immediate (first day) changes in soil acidity (increasing soil pH that was initially at 6.0) have also been reported (Yan and Schubert, 2000). Decomposition of plant residues can also be affected by soil acidity where delays occurred between pH 4.3 and 5.3 due to low microbial activity (Kemmitt et al. 2006; Motavalli et al. 1995; Pietri and Brookes, 2008; Wang et al. 2017).

Neutralization of soil acidity is generally proportional to the quantity of residue applied (Cai et al. 2018; Xiao et al. 2014) highlighting the importance of the amount of residues incorporated into soil. Soil type and characteristics also influence variation in acidity. Depending on soil buffering capacity, mineralogy, and reactions between clay fractions and organic matter, the pH of a soil incubated with different plant residues can change by many units (Sakala et al. 2004; Wang et al. 2013; Xu et al. 2006). Soils with low buffering capacity tend to show greater pH variation when incubated with plant residues (Wang et al. 2013), while a soil with high buffering capacity requires greater application of the same residue. Exchange reactions between OH bonds in the mineral fraction and carboxylic or phenolic groups in organic matter tend to occur in acidic environments, which can increase pH by releasing OH⁻ into soil (Hue, 1992; Rukshana et al. 2012).

In a no-till system, crop residues helps cover the soil, which protects against erosion and leaching and favors maintenance of organic matter (Ramos et al. 2018). However, there is a lack of scientific studies reporting the benefits of plant residues in maintaining soil pH and exchangeable Al to prevent acidification. There are studies reporting the effects of incubating plant residues in combination with other types of acidity amendment (organic or mineral); however, to our knowledge, no studies have evaluated soil acidity amendment using plant residues on soil A and B horizons that were previously corrected with lime. This study aims to evaluate the variation in pH and exchangeable Al in the A and B horizons of two soils (Oxisol and Inceptisol) with different textures, organic matter content, degrees of weathering, and buffering capacities in response to incubation with contrasting crop residue. The main hypothesis was that the application of soybean and maize residue would reduce soil acidity (soybean > maize), while *Pinus taeda* residue would increase soil acidity. Greater effects were expected for B horizons of Oxisol without prior acidity amendment due to its lower organic matter

content and degree of weathering. Greater reduction in soil acidity was expected when residues were applied at higher rates, had lower C/N ratios, or had higher cation content.

2 MATERIALS AND METHODS

2.1 COLLECTION AND CHARACTERIZATION OF SOIL AND PLANT RESIDUES

2.1.1 Soils

Two acidic soils of contrasting buffering capacity, textures and degree of weathering were selected for collection: an Inceptisol with high activity minerals (clay CEC > 27 cmol_c kg⁻¹) located in the municipality of Pinhais, Paraná state (Pires et al. 2007); and an Oxisol from the Campos Gerais region in Paraná state, both in southern Brazil. A and B horizons were collected from each soil, air-dried, sieved (< 2 mm), and analyzed for: pH CaCl₂ 0.01 M (1:2.5 m/v); Ca, Mg, and Al extracted with KCl 1 M and determined by flame atomic absorption spectroscopy (Ca and Mg) and titration with NaOH 0.025 M and bromothymol blue indicator (Al); and P and K extracted with Mehlich-I and determined by colorimetry and flame photometry, respectively (Table 1). Particle size determinations of sand, silt, and clay fractions were conducted using the pipette method, and total C and N were determined using an elemental analyzer (ELEMENTAR -Vario EL III) (Teixeira et al. 2017).

Table 1 Chemical and granulometry analyses of A and B soil horizons used to evaluate the effect of residue amendment on soil acidity.

Soil and horizon	pH	Al ³⁺	H+Al	K ⁺	Ca ²⁺	Mg ²⁺	P	C	N	Sand	Silt	Clay
	CaCl ₂			cmol _c kg ⁻¹			mg kg ⁻¹	g kg ⁻¹	g kg ⁻¹		g kg ⁻¹	
Oxisol A	3.76	1.37	9.0	0.08	0.66	0.28	2.40	19.8	1.2	600	50	350
Oxisol B	3.94	0.82	6.7	0.06	0.50	0.11	2.10	8.7	0.53	563	50	387
Inceptisol A	3.89	3.48	19.0	0.29	3.39	1.96	5.20	59.5	3.52	312	354	334
Inceptisol B	3.83	3.94	15.2	0.07	0.61	0.31	0.40	9.2	0.55	198	257	488

2.1.2 Plant residues

Plant residues used were loblolly pine (*Pinus taeda*) needle litter, maize (*Zea mays*) residue (leaves, straw from cob, cobs, and stalks), and soybean (*Glycine max*) residue (leaves, branches, and stalks). *Pinus taeda* litter was collected from a 10-year-old commercial plantation in a low-fertility area in the municipality of Pirai do Sul, Paraná state. Soybean and maize residues were collected from field farms just after harvesting in Paraná state, southern Brazil. Each residue type was dried at 65°C, ground, and homogenized (< 1 mm for characterization; < 4 mm for incubation).

Samples of each residue were digested using ~200 mg of ground residue with 4 mL of HNO₃ (65%) P.A., 1 mL of H₂O₂, and 3 mL of Milli-Q water in a Microwave (Mars Xpress 6, CEM) at 1300 W for 20 min at a maximum temperature of 180° C for 15 min (Magri et al. 2022). Extracts were then used to determine levels of Ca, Mg, P, and S using inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian 720-ES), and K and Na were determined using a flame photometer (Table 2). Total C and N were determined using an elemental analyzer (ELEMENTAR-Vario EL III), and pH was determined in reverse osmosis H₂O in a 1:10 (m/v) ratio (Teixeira et al. 2017). Available alkalinity was determined by titration using 0.5 g of each residue and adding 25 mL of 0.015 M CaCl₂ solution, followed by stirring for 15 min. pH was determined and titrated with 5mM H₂SO₄ until pH 4 was attained. Potential alkalinity (ash alkalinity) was determined using 0.25 g of plant residue ashed in a muffle furnace with a temperature ramp for 30 min up to 500°C, followed by 1 hour at 500°C. 10 mL of 1 M HCl was added to the residue ash, followed by titration with 0.25 M NaOH (Sakala et al. 2004).

Residues were analyzed by Fourier-transform infrared spectrometry (FTIR) to characterize constitution of lignin, cellulose, and hemicellulose on a BRUKER alpha II spectrometer (absorbance mode) in the spectral range of 4000 to 400 cm⁻¹ with a resolution of 4 cm⁻¹ and 32 scans. Measurements were made on pellets prepared from each grounded residue mixed with spectroscopic grade KBr in a ratio of 1 mg of sample to 100 mg of KBr. Spectra were acquired with baseline correction and deconvolution (a mathematical treatment that resolve overlapping of broad bands from functional groups that mask narrower bands at nearby frequencies) using Fast Fourier Transform (FFT) mathematical processing algorithm with a Lorentzian band distribution adjustment using Bruker's OPUS 8.5 software (Alemdar and Sain 2008; Báder et al. 2020). Characterization of pH at the point of zero charge (pH_{pzc}) was conducted with 0.2 g of each plant residue with 50 mL of 0.01 M NaCl with pH adjusted to 2, 4, 6, 8, and 10, which were called the initial pH. Samples were stirred for 48 hours, followed by a final pH reading. The relationship curve between initial pH and final pH was used to determine pH_{pzc} by calculating the average of the final pH results at points where there was stabilization in the curve (Bhan et al. 2021; Mishra et al. 2019).

Table 2 Chemical analysis of loblolly pine, maize, and soybean residue used in incubation experiments.

Plant residue*	pH H ₂ O	Σ cations	SO ₄ ²⁻	H ₂ PO ₄ ²⁻	C	N	C/N	Available alkalinity mmolc OH ⁻ kg ⁻¹	Potential alkalinity	pH _{pzc}
Loblolly pine	3.91	3.5	1.4	1.0	391.1	6.2	62.9	0	1413.22	4.65
Maize	6.29	14.5	2.9	4.9	375.1	15.8	23.7	158.44	1826.50	5.95
Soybean	6.09	26.3	7.5	5.1	425.4	43.3	9.8	541.35	1990.76	6.35

$$\Sigma \text{ cations} = [\text{Ca}^{2+}] + [\text{Mg}^{2+}] + [\text{K}^{+}] + [\text{Na}^{+}]$$

*All values correspond to the average of triplicates.

2.2 INCUBATION PROCEDURES

After being dried and sieved ($< 2\text{mm}$), horizon samples of Inceptisols and Oxisols were separated into two equal portions. To observe initial soil pH and residual effects of residue incubation, a portion of soil samples received soil acidity corrective to increase soil pH and were evaluated over 12 months. One portion was weighed and given a rate of acidity corrective to raise the base saturation to 70%. Analytic sources of Ca and Mg oxides were used as amendments, keeping the Ca/Mg ratio at 4/1 ($\text{cmol}_c \text{kg}^{-1}$). Oxides were added to the soil and homogenized. After homogenization, purified water was gradually added and homogenized until 80% of field capacity was reached. The soil was kept with the Ca and Mg oxides for 7 days before the incubation with the plant residues.

1 kg of air-dried soil samples were weighed into plastic bags and mixed with quantities of loblolly pine, maize or soybean residues equivalent to 0, 6, 12, 24, and 48 t ha^{-1} , considering a soil depth of 0.2 m. High rates were used to simulate a possible cumulative effect occurring over several years or the influence of residue on surficial soil of no-till systems. For soil that had been mixed with residue, the water content in the mixture was adjusted to 80% of field capacity and was maintained by adding reverse osmosis water to compensate for evaporative loss during the course of the experiment. All bags were closed using an elastic band and aerated using a plastic tube to maintain aerobic conditions at $\sim 25^\circ\text{C}$ in a greenhouse, without direct sunlight.

Approximately 50 g of soil were sampled at 0.75, 30, 90, 180, 270, and 365 days after incubation with loblolly pine, maize, and soybean residue. This material was homogenized before each collection. The pH (1:2.5 m/v, CaCl_2 0.01 M) and Al^{3+} (KCl 1 M) was analyzed by titration in a digital burette with 0.025 M NaOH and bromothymol blue indicator (Teixeira et al. 2017).

2.3 EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

The incubation experiment was conducted with three replicates using a completely randomized experimental design. Five application rates (0, 6, 12, 24, and 48 t ha^{-1}) of three plant residues (loblolly pine, maize, and soybean) were used in A and B horizons from two soil types (Inceptisol and Oxisol) with or without prior liming; this resulted in 360 experimental units. Results of pH and Al^{3+} were subjected to the Shapiro-Wilk normality test and Bartlett's homogeneity of variance test, both at a 5% significance level. Once normality and homogeneity of variance were obtained, analysis of variance (ANOVA) was carried out and when there was an effect of residue rate (F test), these were evaluated by regression. All statistics were conducted with R software using the ExpDes package and graphs were composed using OriginLab software.

3 RESULTS

3.1 FTIR OF LOBLOLLY PINE, MAIZE, AND SOYBEAN RESIDUES

Deconvoluted FTIR spectra showed that pine, maize, and soybean residues differed in terms of lignin, cellulose, and hemicellulose (Figure 1). Only pine residue showed a band at 1271 cm^{-1} attributed to the C-O bond stretching mode vibration in phenol groups and present in the three-dimensional structure of lignin, corroborating with high composition of lignin in this residue (Pavia et al. 2010; Silverstein et al. 2019). The band representing stretching of the carbon of the aromatic ring to the hydroxyl oxygen has low intensity and can be superimposed on nearby bands that are more intense. No bands were observed in the 1420 cm^{-1} region for pine, which is a vibration mode characteristic of folding of CH_2 groups present in monomeric cellobiose units that form cellulose (Lima et al. 2019; Pavia et al. 2010; Silverstein et al. 2019). In the region of aromatic carbons (C=C stretching vibrations; at $\sim 1514\text{ cm}^{-1}$), it is possible to observe a greater signal intensity for pine, as well as an intense signal in the 1735 cm^{-1} region (C=O carbonyl stretching vibration of carboxylic acids and esters). This set of bands indicates a higher concentration of hemicellulose and lignin in pine (especially lignin), which is signaled by the aromatic bands whose three-dimensional aromatic structure is made up of phenylpropane units joined by C-O-C and C-C bonds (Pavia et al. 2010; Silverstein et al. 2019; Suota et al. 2021). The band at 1162 cm^{-1} of the β -1,4 glycosidic bond of the cellulose pyranose rings has comparable intensity to the soybean spectra, but much lower than maize. This lower intensity can be inferred from the lower concentration of cellulose present in pine residue (Pavia et al. 2010; Prabhu et al. 2017; Silverstein et al. 2019).

Maize showed lower intensity bands in the aromatic and vinyl carbon vibration regions (between 1514 cm^{-1} and 1650 cm^{-1}) as well as the C=O stretching vibration (at 1735 cm^{-1}) of hemicellulose and lignin (Pavia et al. 2010; Silverstein et al. 2019). On the other hand, maize showed the most intense bands in the characteristic region of cellulose and starch, especially the band at 1031 cm^{-1} referring to the C-O stretching of primary alcohols and the stretching vibrations of the C-O-C of glycosidic bonds (β -1,4) of pyranose rings of cellulose, branched glycosidic bonds (β -1,6) of amylopectin, and glycosidic bonds β -1,4 of amylose. The shoulder at 993 cm^{-1} suggests the deformation vibration of CH_2 groups of amylose (Pavia et al. 2010; Silverstein et al. 2019; Socrates, 2004).

All band characteristics of cellulose, hemicellulose, and lignin from the other residues were observed in the soybean residue. However, the region of vinyl carbons of lignin and hemicellulose (at 1608 and 1657 cm^{-1}) showed the highest signal intensity compared to others, which indicates a high percentage of hemicellulose in soybean, since vinyl carbons are more present in this structure.

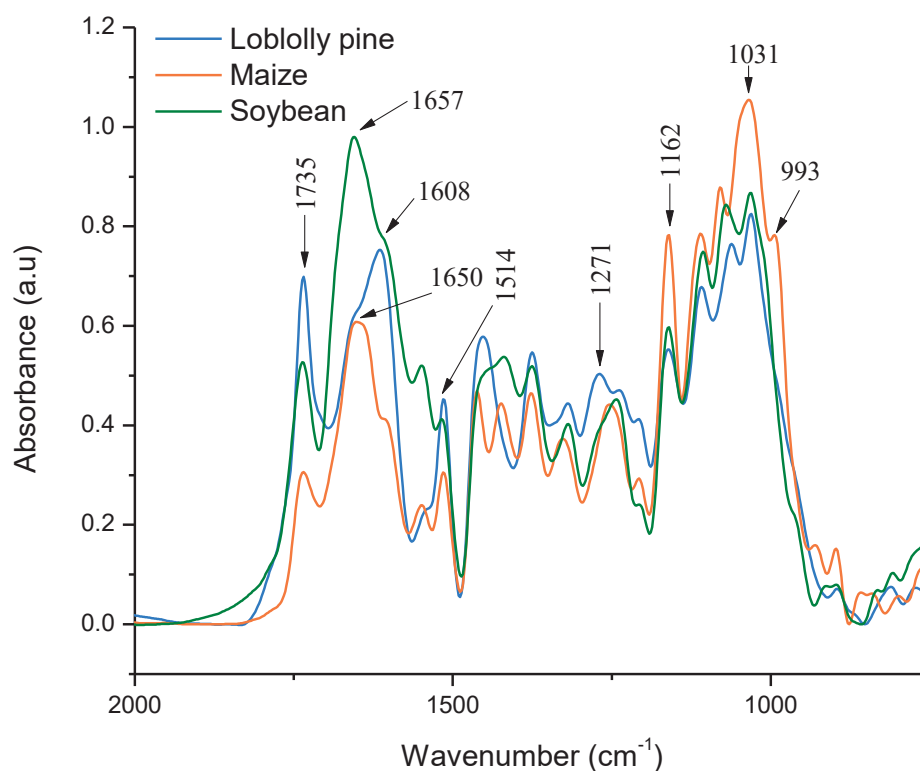


Fig.1 Deconvoluted FTIR spectra of loblolly pine litter (blue), maize (orange), and soybean (green) residues.

3.2 pH

Soybean residue promoted the largest increase in pH ($\Delta\text{pH} = +1.35$) in Oxisol B horizon without liming after 30 days of incubation at the maximum rate (48 t ha^{-1}) (Supplementary Information – Figure 1e). The reduction in soil acidity was greater in soils without liming than in soils with liming (Figures 2, 3, 4, and 5 and Supplementary Information – Figures 1, 2, 3 and 4). At the end of the incubation period (365 days), the pH of Oxisol A and B horizons without liming increased (Figure 2 and Supplementary Information – Figure 1), with the ΔpH being proportional to the rates applied. However, loblolly pine caused a decrease in pH at the end of the study (365 days) when lime was applied to Oxisol A horizon ($\Delta\text{pH} < 0$ – Figure 3a). ΔpH was higher in Oxisol A horizon without liming compared to the other soils incubated with loblolly pine and maize (Figures 2a, c and 4a, c and Supplementary Information – Figures 1a, c and 3a, c).

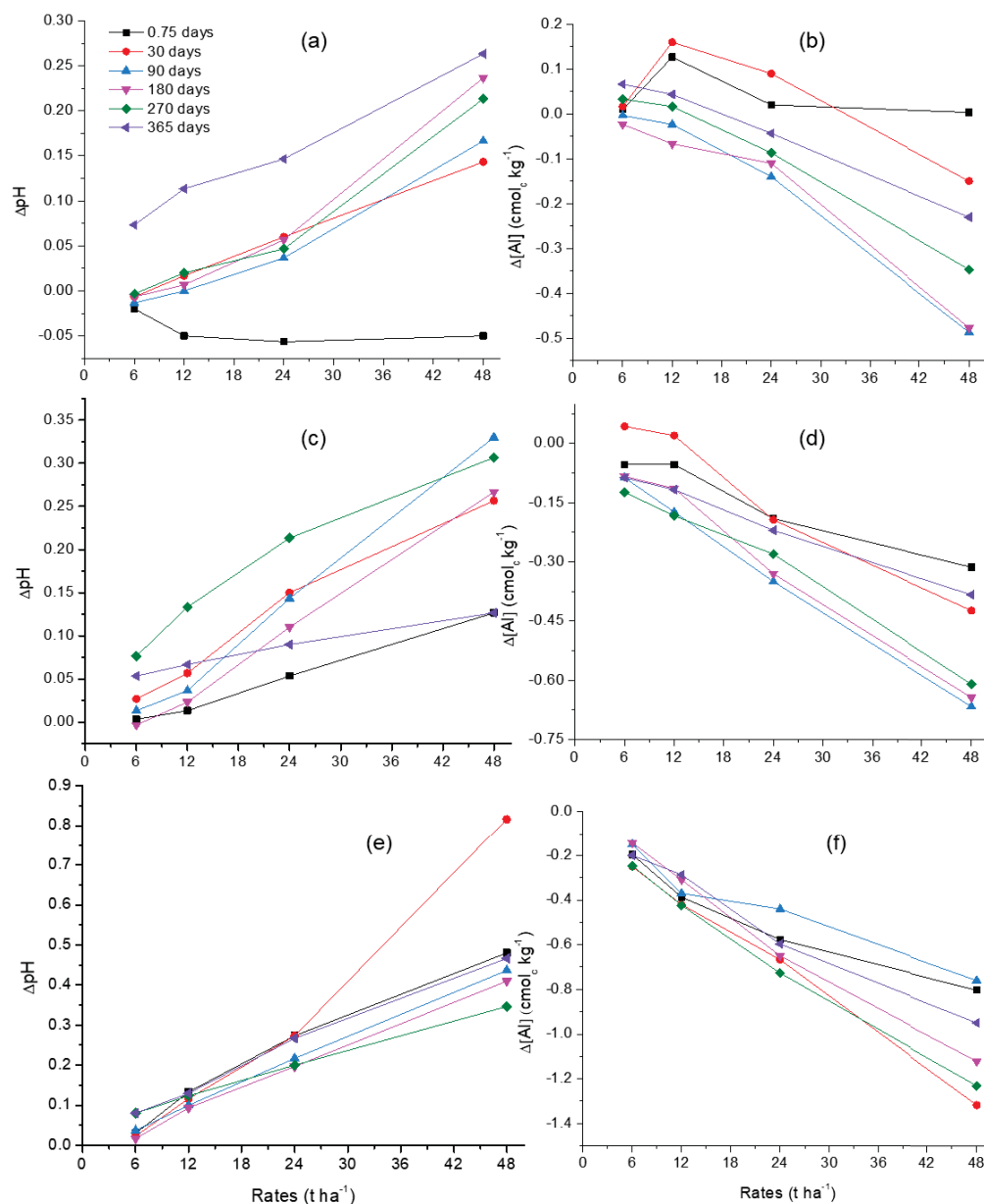


Fig.2 pH variation (ΔpH - a, c, and e) and Al concentration (cmol_c kg⁻¹) (ΔAl - b, d, and f) of Oxisol A horizon according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha⁻¹) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

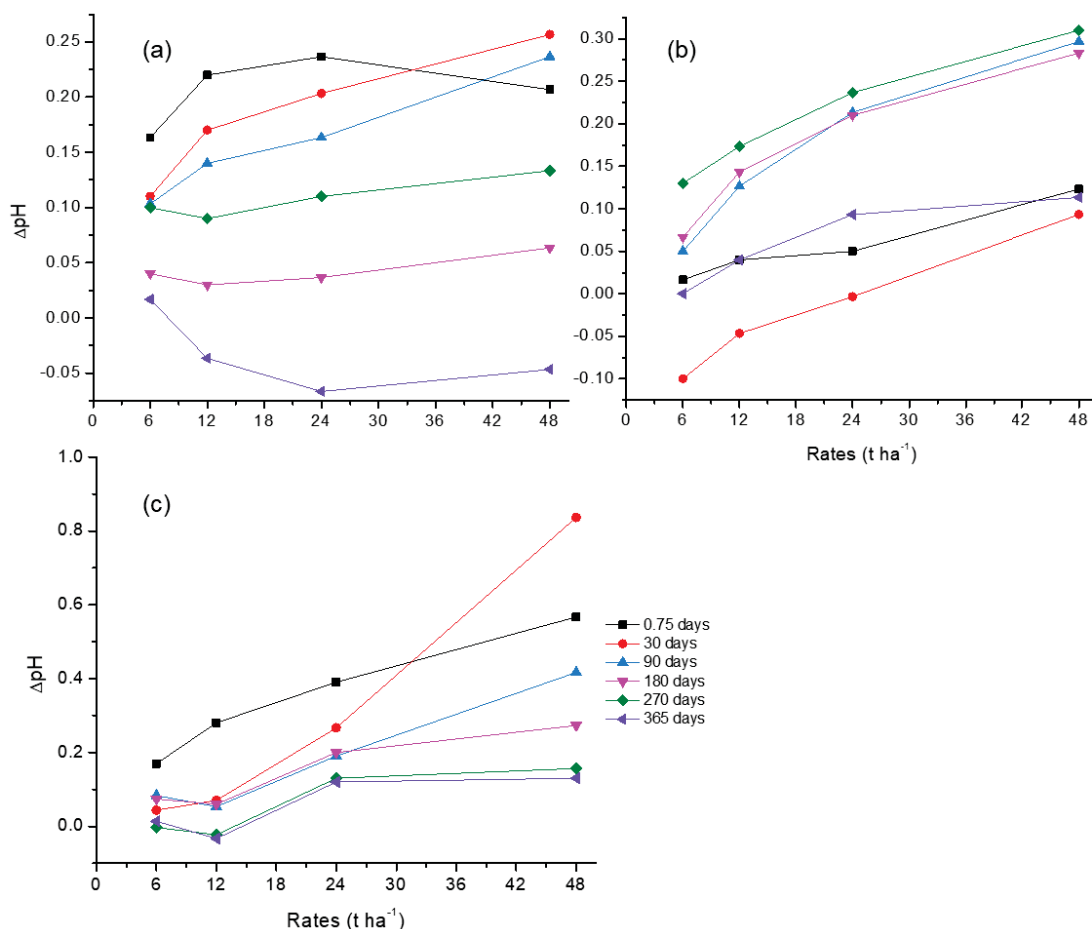


Fig.3 pH variation (ΔpH) of Oxisol A horizon amended with lime according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha^{-1}) minus the control treatment (0)]; Plant residues: Loblolly pine (a), Maize (b), and Soybean (c); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))]; Al^{3+} remained equal zero in all of incubation times.

Values of ΔpH were lower in Inceptisol A (Figures 4 and 5) and B (Supplementary Information – Figures 3 and 4) in relation to ΔpH of residues observed when residues were incubated with A horizon Oxisol (Figures 2 and 3) and B (Supplementary Information – Figures 1 and 2); that is, the three residues were more efficient at increasing the pH of more weathered soils with less buffering capacity. In A horizon Inceptisol without and with liming (Figures 4a and 5a and Supplementary Information – Tables 5 and 6) there was no significant variation in pH ($P > 0.05$) according to the increase in loblolly pine rates at the end of the incubation period (365 days). On the other hand, when liming was carried out on B horizon Inceptisol (Supplementary Information – Figure 4), neither loblolly pine nor soybean caused any variation in pH with increased rates at 365 days of incubation ($P > 0.05$). Soybean was the most efficient residue to raise soil pH in the initial phase, followed by maize and loblolly pine.

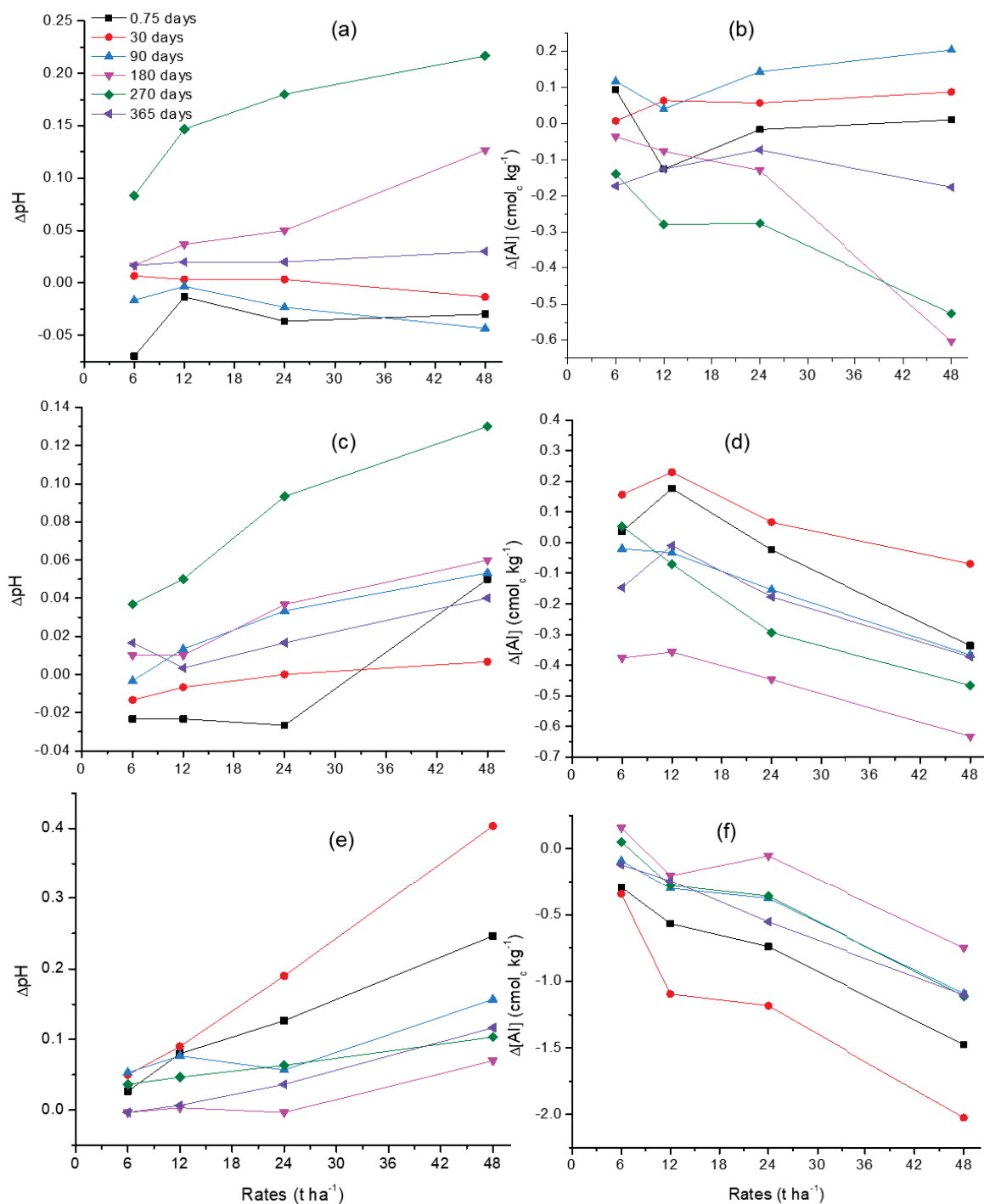


Fig.4 pH variation (ΔpH - a, c, and e) and Al concentration ($\text{cmol}_c \text{ kg}^{-1}$) ($\Delta[\text{Al}]$ - b, d, and f) of A horizon Inceptisol according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha^{-1}) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

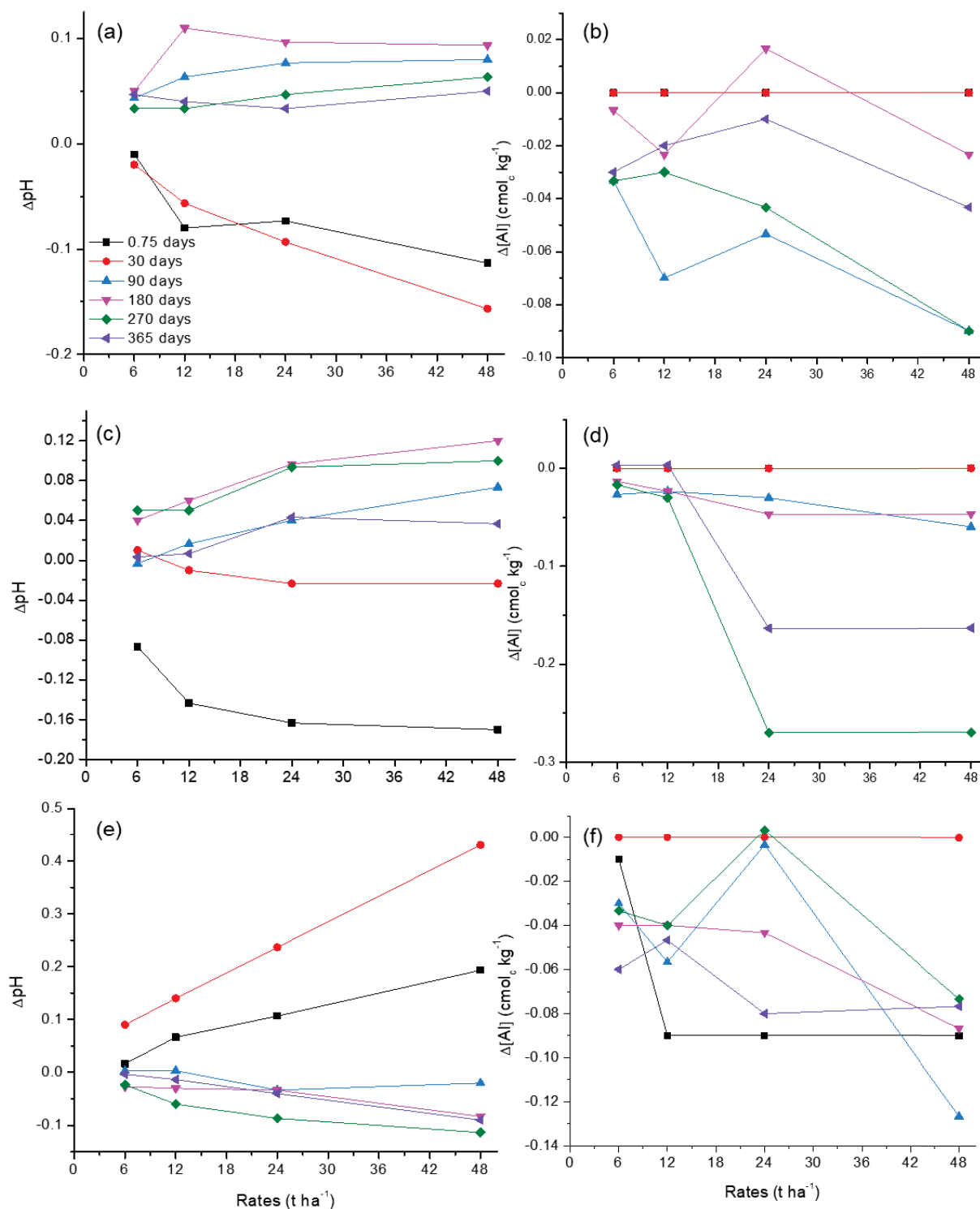


Fig.5 pH variation (ΔpH - a, c, and e) and Al concentration ($\text{cmol}_c \text{ kg}^{-1}$) (ΔAl - b, d, and f) of A horizon Inceptisol, amended with lime, according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha^{-1}) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

The effect of incubation times on pH was diffuse, although longer incubation times seemed to have greater corrective effect in unamended soils when loblolly pine or maize residues were applied.

On the other hand, ΔpH was greater in the first 30 days with the application of soybean residue. After 365 days of incubation, the effect of residues appeared to stabilize and decrease.

3.3 EXCHANGEABLE Al

The decrease in exchangeable Al^{3+} concentration and the ΔAl value was inversely proportional to increased residue rates when soils were not limed (Figures 2 and 4 and Supplementary Information – Figures 1 and 3). In A and B horizon Oxisol with previous liming, Al^{3+} remained at 0 until the end of incubation (365 days) since the pH CaCl_2 remained over 5.0 (Supplementary Information – Tables 15 and 16). Maize and soybean decreased exchangeable Al in Oxisols A and B at the end of the incubation period (365 days) (Figures 2 d and f and and Supplementary Information – Figure 1 d and f); this pattern was inversely proportional to increased residue rates.

Proportionally, the decrease in Al^{3+} was less significant in Inceptisols A and B (Figures 4 and 5 and Supplementary Information – Figures 3 and 4) compared to the decrease in Al^{3+} caused by residues in Oxisols A and B (Figure 2 and Supplementary Information – Figure 1). The exception was Inceptisol B without liming at the maximum soybean residue rate at 180 days, where ΔAl reached - 2.87 $\text{cmol}_\text{c} \text{ kg}^{-1}$ (Supplementary Information – Figure 3). The most effective residue for reducing the concentration of exchangeable Al in all the soils was soybean, followed by maize and loblolly pine.

It seems that residues reduce exchangeable Al in soil more effectively with the passage of incubation time, especially when loblolly pine or maize residues were applied. Similar to observations of pH, after 365 days of incubation there seems to be a decrease in the ability of residues to reduce Al^{3+} .

4 DISCUSSION

Through FTIR analysis it was possible to characterize biopolymers within plant residues and infer their reactivity in the soil (Figure 1). Maize is mostly composed of cellulose and starch, loblolly pine is mostly composed of lignin and soybean residue is largely composed of hemicellulose, as well as lignin and cellulose. Lignin is a heteropolymer whose three-dimensional and amorphous structure is made up of phenylpropane unit (aromatic) groups linked randomly and repetitively by carbon-oxygen (ether) bonds. This structure gives lignin high stability, low reactivity, and resistance to decomposition by microorganisms (De Bhowmick et al. 2018; Lima et al. 2019; Pulronik 2009). Hemicellulose is a branched heteropolymer made up of hexoses, pentoses, uronic acids, and deoxyhexoses linked to very labile groups such as carboxylic acids, esters, and ethers. The amorphous and hydrophilic structure of hemicellulose makes it easily accessible to microbial degradation in soil (De Bhowmick et al. 2018; Lima et al. 2019; Pulronik 2009). Cellulose is a linear homopolymer with crystalline and amorphous components. The ordered and unbranched structure of cellulose provides more resistance to microbial attack than hemicellulose, but less resistant than lignin (Brigham 2018; Zhao et al. 2022). Starch is primarily composed of the polysaccharides amylose and amylopectin (less water-soluble structures), which lessens susceptibility to microbial attack in soil (De Bhowmick et al.

2018; Lima et al. 2019; Pultronik 2009). Soil acidity correction occurs more quickly with soybean due to faster degradation of hemicellulose, more slowly with loblolly pine due to slower degradation of lignin in soil, and at an intermediate rate with maize due to the cellulose and starch composition, which has some resistance to degradation.

In general, the increase in pH was proportional to residue rate applied (with linear, quadratic or exponential responses), which depended on the residue or analysis time (Supplementary Information – Tables 1 to 14). In cases where there were quadratic responses, indications were that proton consumption reactions (e.g., decarboxylation, ligand exchange, denitrification and ammonification) overlapped with proton release reactions (nitrification), which would predominate at high residue rates (Butterly et al. 2021; Shi et al. 2020, Tang and Yu 1999; Turmel et al. 2015; Yan et al. 1996). In similar studies, amendment potential was often attributed to release of basic cations into soil and replacement of $H^+ + Al^{3+}$ in exchange complexes, but primarily to decarboxylation reactions as measured by emitted CO_2 concentration and ammonification (production of NH_4^+) (Xiao et al. 2013). However, these parameters were not quantified in our study.

Soybean residue had the greatest potential to increase soil pH and decrease Al^{3+} , followed by maize and loblolly pine. This result confirms the hypothesis that residue quality (based on chemical attributes such as cation content, available and potential alkalinity) defines the corrective potential of plant residues. Thus, soybean residue increased soil pH to levels higher than incubation with maize in the short term (Sakala et al. 2004). Several studies in the literature showed that legumes are more effective at alleviating soil acidity (Butterly et al. 2021; Cai et al. 2018; Vanzolini et al. 2017; Xiao et al. 2014).

Soybean residue had higher available and potential alkalinity than maize (Table 2). Loblolly pine had no available alkalinity since pH was less than 4 (Table 2). However, loblolly pine ash had potential alkalinity ($1413 \text{ mmol}_c \text{ kg}^{-1}$) (Table 2), which was much higher than the alkalinity of *Pinus radiata* ash ($450 \text{ mmol}_c \text{ kg}^{-1}$) as reported by Noble et al. (1996). Potential alkalinity may explain the longer time to achieve the maximum pH increase when loblolly pine residue is applied to soils without liming since this form of alkalinity is not readily available. Available alkalinity of soybean residue in our study ($541.3 \text{ mmol}_c \text{ kg}^{-1}$) was close to values reported by Sakala et al. (2004) ($577 \text{ mmol}_c \text{ kg}^{-1}$), while the potential alkalinity in our study ($1991 \text{ mmol}_c \text{ kg}^{-1}$) was higher ($1264 \text{ mmol}_c \text{ kg}^{-1}$). Maize available alkalinity ($158.4 \text{ mmol}_c \text{ kg}^{-1}$) was slightly lower than reported by Sakala et al. (2004) ($181 \text{ mmol}_c \text{ kg}^{-1}$), while potential alkalinity was much higher in our study ($1826 \text{ mmol}_c \text{ kg}^{-1}$ vs $373 \text{ mmol}_c \text{ kg}^{-1}$). Available alkalinity appears to be directly involved in short-term pH increases (as observed with soybean) since it can readily neutralize H^+ .

Soybean had the highest pH_{pzc} of the three residues evaluated, followed by maize then loblolly pine (Table 2). Values obtained for residues in our study were close to the pH_{pzc} of *Pinus radiata* (4.8), *Pinus caribea* (4.6), maize (6.0), and soybean (6.7) reported in other studies (Honorio et al. 2016; Petrovic et al. 2016; Pimentel et al. 2023; Sinyeue et al. 2022). These data were indicative of the pH at which protonation or deprotonation of each material occurred, since at conditions where $pH < pH_{pzc}$ material is protonated (adsorbs H^+) and where $pH > pH_{pzc}$ deprotonation of organic functional groups releases H^+ . Loblolly pine tends to release H^+ above $pH = 4.65$ (loblolly pine pH_{pzc} - Table 2), which

may explain the acidification of limed Oxisol A horizon after 365 days of incubation. On the other hand, maize and soybean deprotonated (release H^+) only when pH was raised above 5.95 and 6.35, respectively (Table 2). At pH below these values, maize and soybean can contribute to increasing the pH, since they decrease the H^+ activity of soil to keep functional groups protonated (Sinyue et al. 2022).

Despite the low pH (Table 2) of loblolly pine residue, the decrease in acidity of soils incubated with this residue was in line with studies incubating acidic soils using *Pinus radiata* residues where a small increase in pH and a decrease in exchangeable Al concentration was observed with increasing residue rate (Noble et al. 1996). In comparison, proportional responses to residue rates in our study were similar. Application of loblolly pine residue to soils can be compared to application of vinasse since an increase in soil pH has been reported in previous studies using this acidic organic residue. Vinasse, like plant residues, is rich in basic cations such as K, Ca, Mg, and organic compounds that reduce the activity of H^+ and Al^{3+} by exchange reactions with cations in the soil solution and by complexation (Cardoso et al. 2022; Possignolo-Vitti et al. 2017). Maize and soybean applied at high rate (42 t ha^{-1}) to acidic soil increased pH by 0.30 and 0.89 units, respectively, after 100 days in a study reported by Sakala et al. (2004), similar to our results with the same residues.

Regarding to exchangeable Al, soybean also decreased Al^{3+} more efficiently compared to maize with increasing residue rate (Cai et al. 2018). Increase in pH caused by proton consumption reactions in plant residue decomposition can reduce Al toxicity (attenuates Al^{3+} activity) while adding other less toxic forms of Al such as $AlOH^{2+}$, $Al(OH)_2^+$, $Al(OH)_3$ and $Al(OH)_4^-$ (Abdulaha-Al Baquy et al. 2017). Furthermore, Al^{3+} concentration in soils can be reduced by adding organic material since this can increase organic matter content and fulvic and humic acids that complex Al^{3+} (Shetty et al. 2021). Carboxyl ($-COOH$) or phenolic ($-OH$) groups of short-chain carboxylic acids in organic matter such as citric, oxalic, salicylic, lactic, and formic acids complex Al^{3+} and reduces toxicity (Hue et al. 1986).

There were immediate responses in soil acidity due to residue addition (0.75 days), with variations observed according to analysis time, however there was no optimum reaction time pattern observed for residues and soils used in our study. However, the high soybean rate increased pH and decreased exchangeable Al as early as 30 days after incubation and can be attributed to higher alkalinity, cation content, and low C/N (Table 2), as well as higher hemicellulose composition of residue (Figure 1). These characteristics provide for faster decomposition of soybean residue and quicker soil acidity decreases (Wang et al., 2012; Xu et al. 2006). The maximum short-term potential of soybean residue observed in our study is in line with results of applying increasing rates of vetch, where there was an increase in pH and a decrease in exchangeable Al in less than 30 days, which was proportional to applied residue rates (Vanzolini et al. 2017; Xiao et al. 2014). The high lignin content (Figure 1) and high C/N ratio of loblolly pine residue hinders decomposition and slows down proton consumption (or release) reactions, which explains the greater effect of this residue over longer incubation periods (Sánchez et al. 2018).

Prior liming reduced the effectiveness of plant residue amendment. That is, soil pH increase and exchangeable Al decrease through the direct effect of residues was more efficient in soils that had not received prior liming. This was due to soil buffering capacity, which means that soil pH changes only

slightly when an acid or base is added (Troech and Thompson, 1993). Considering that soil pH consists of the H^+ contribution to active acidity and that this is the portion of acidity neutralized by liming, H^+ from soil potential acidity (from organic matter and minerals in the clay fraction) tends to dissociate to maintain chemical balance. This process continues until all soil potential acidity is dissociated and neutralized (Tisdale and Nelson 1961). Alkalizing reactions from plant residue decomposition shift the soil balance in the direction of releasing more H^+ from potential acidity, which makes it difficult to increase pH further.

There was a more discreet variation in pH and Al^{3+} in Inceptisols with residue application, which was in line with our hypothesis. Due to higher buffering capacities, variation in pH tends to be lower in Inceptisols compared to other acidic soils in plant residue application studies (Wang et al. 2017). The high buffering capacity was due to organic matter in Inceptisol A and due to the presence of permanently charged minerals in the clay fraction in Inceptisol B (Wang et al. 2013). However, there was no great variation in buffering capacity between A and B horizons (both Oxisol and Inceptisol) (Table 1), which contradicts our hypothesis about a greater decrease in acidity in subsurface horizons. In addition to similar buffering capacity, low microbial activity may have hindered the degradation of residues in the B horizons, which slowed down or reduced acid-base reactions (Bhattarai 2015; Taylor et al. 2002).

5 CONCLUSIONS

The ability of residues to decrease active acidity (pH) and Al^{3+} (exchangeable Al) was associated with the sum of cations, C/N ratio, and plant residue alkalinity and followed the descending order of soybean > maize > loblolly pine. The effect of the three residues was proportional to rates applied.

Residue activity varied with time due to the decomposition of lignin, cellulose, hemicellulose and starch (characterized by FTIR) being faster and more intense (~30 days) in the case of soybean (high hemicellulose composition) and slower, less intense, and apparently more stable in the case of maize residues (high cellulose and starch composition) and loblolly pine residues (high lignin composition).

Results indicated that the three residues have good potential to reduce soil acidity, especially in terms of reducing Al^{3+} availability in soil. The action of soybean residue was intense and fast, which may indicate that residue supply to soil should be constant. Loblolly pine residue caused a reduction in pH when applied to lime amended soil and an increase when applied to unamended soil, indicating the importance of initial soil pH on residue application effects.

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SUPPLEMENTARY INFORMATION

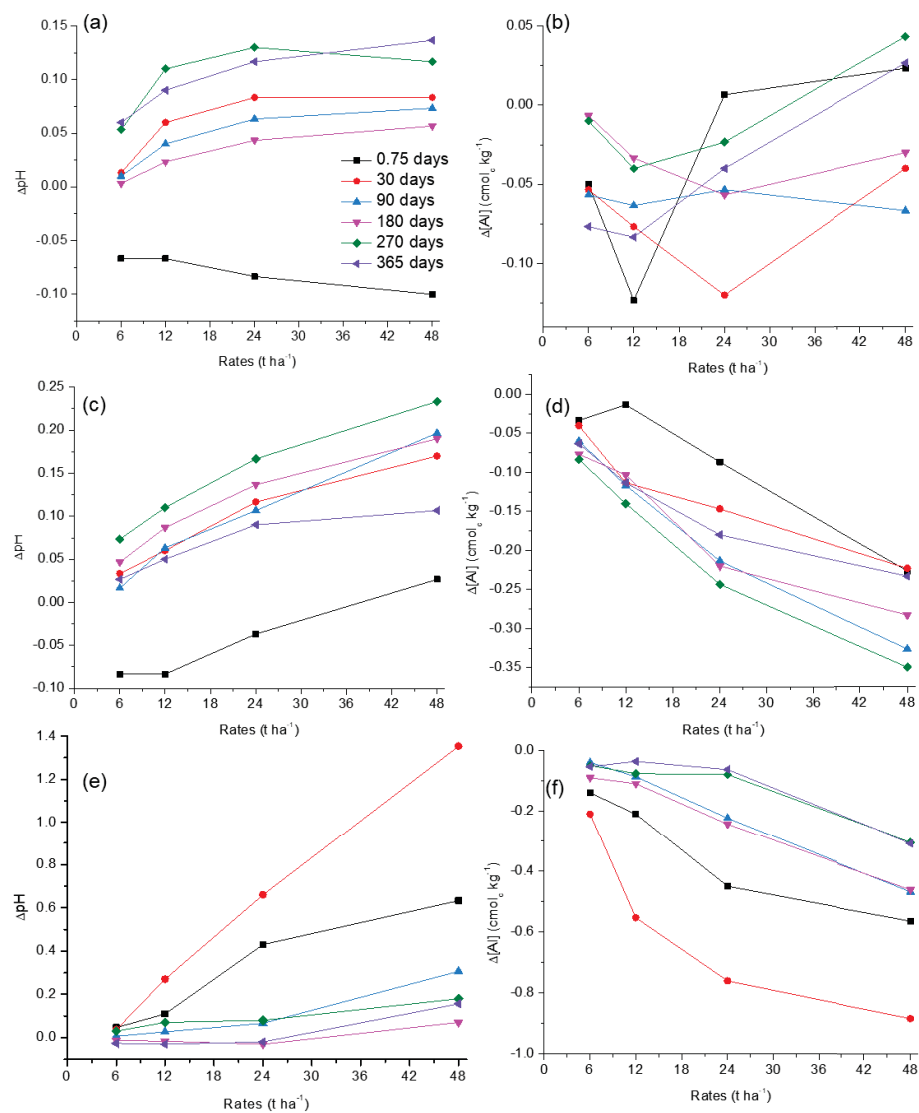


Fig.1 pH variation (ΔpH - a, c, and e) and Al concentration ($\text{cmol}_c \text{kg}^{-1}$) (ΔAl - b, d, and f) of Oxisol B horizon according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha⁻¹) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

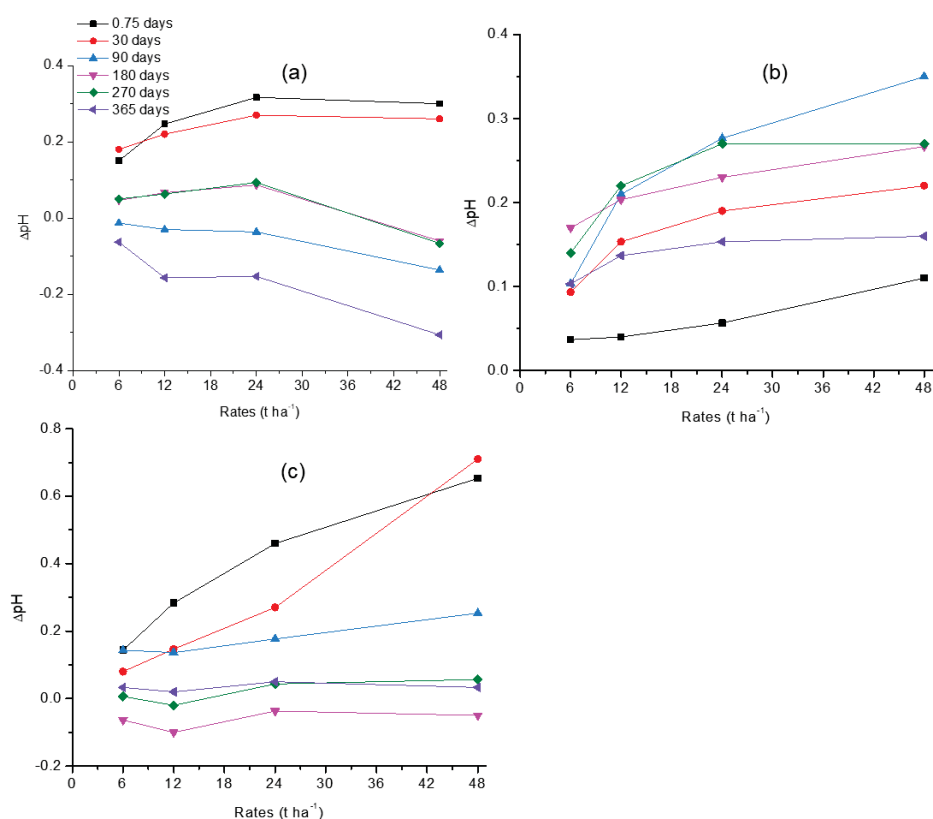


Fig.2 pH variation of Oxisol B horizon, corrected with liming, according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha⁻¹) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

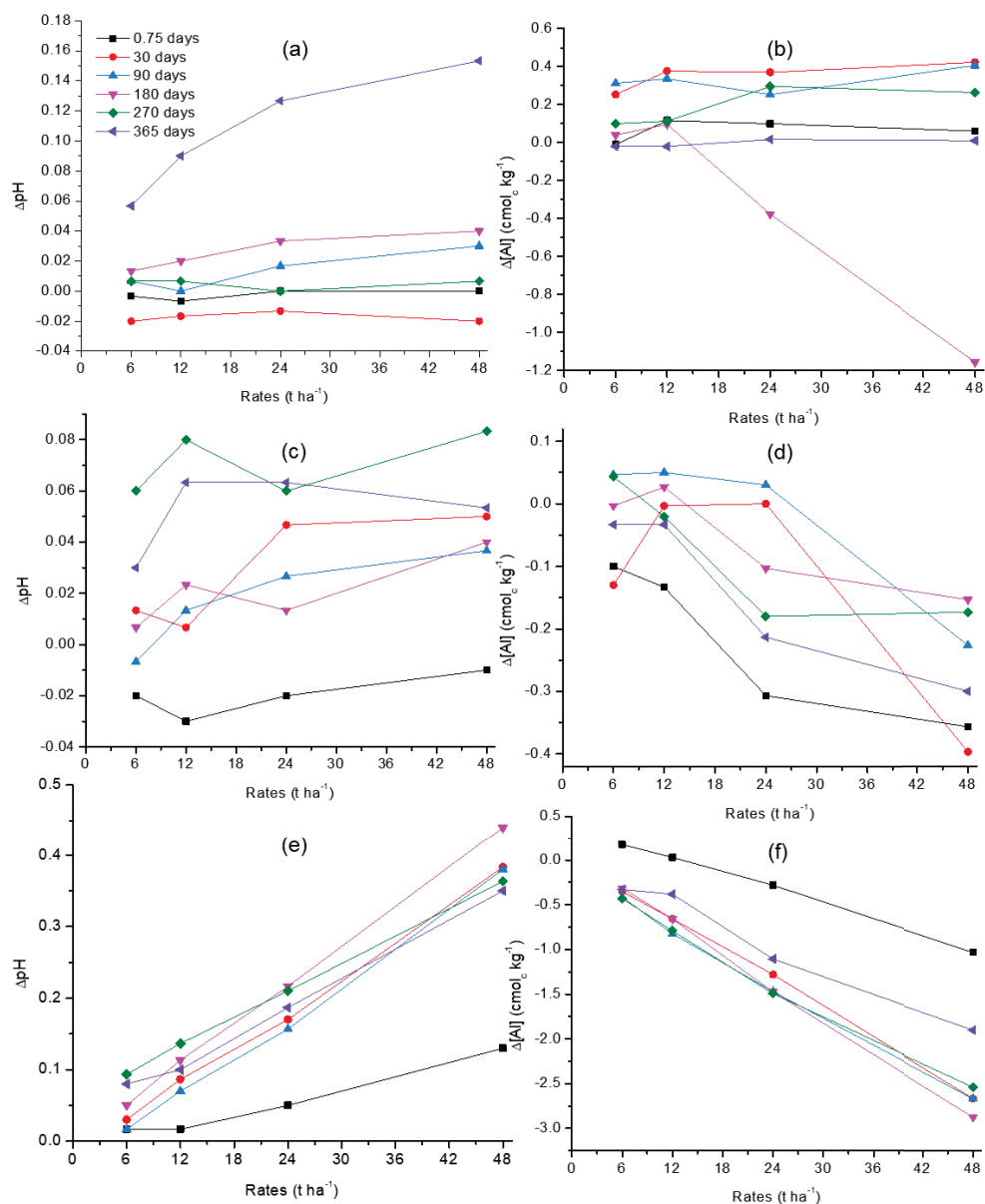


Fig.3 pH variation (ΔpH - a, c, and e) and Al concentration ($\text{cmol}_e \text{kg}^{-1}$) ($\Delta[\text{Al}]$ - b, d, and f) of Inceptisol B horizon according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha^{-1}) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

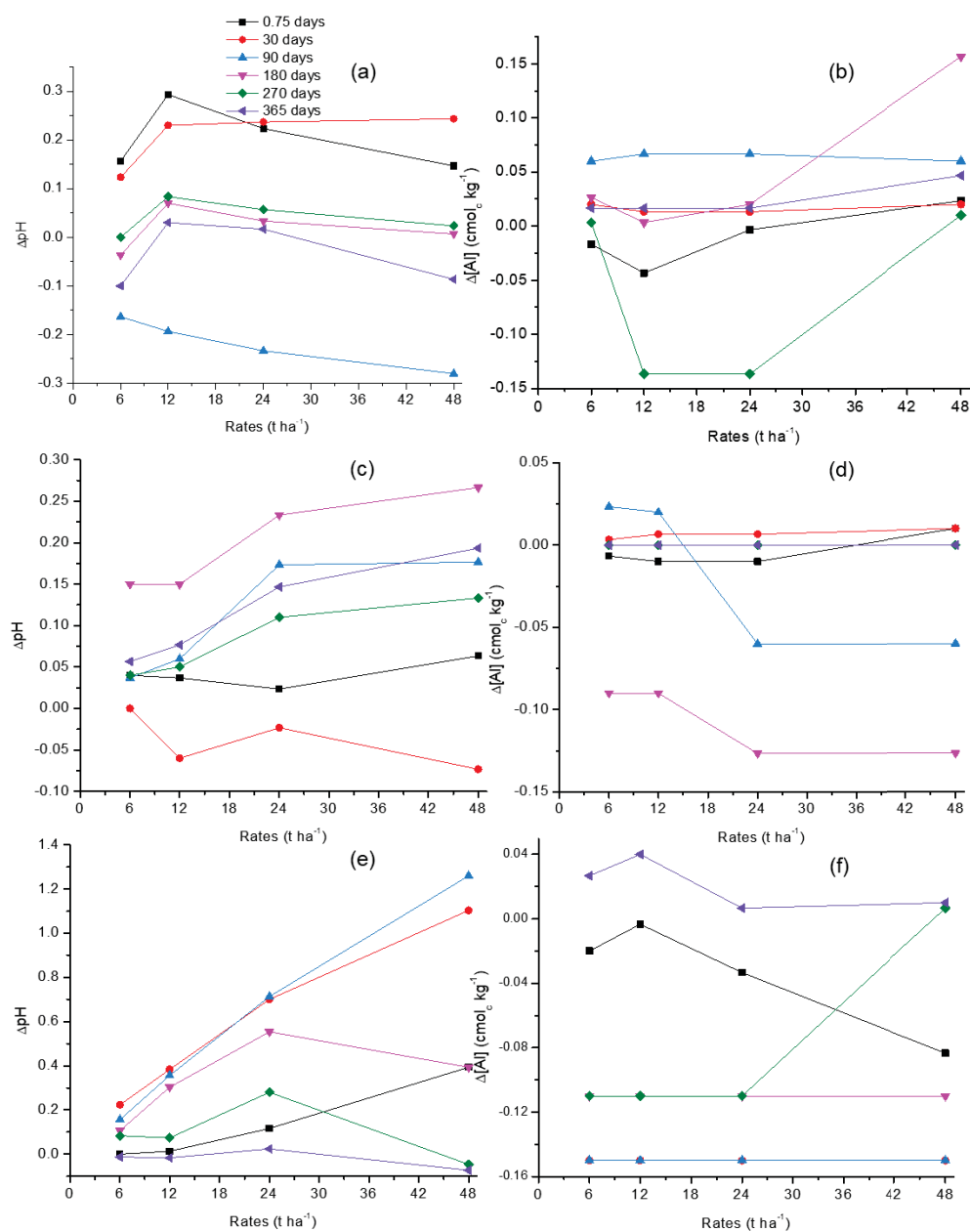


Fig.4 pH variation (ΔpH - a, c, and e) and Al concentration ($\text{cmol}_e \text{ kg}^{-1}$) (ΔAl - b, d, and f) of Inceptisol B horizon, corrected with liming, according to plant residue rates (x axis) and time. Rates: [(6, 12, 24, and 48 t ha^{-1}) minus the control treatment (0)]; Plant residues: Loblolly pine (a and b), Maize (c and d), and Soybean (e and f); Incubation time: [(0.75 (black), 30 (red), 90 (blue), 180 (pink), 270 (green), and 365 (purple))].

Table 1 - Equations from analysis of variance of regressions, correlation coefficient (R^2), P -value, and coefficient of variation (CV) for effects on pH after incubation of Oxisol A horizon with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 3.5454 - 0.0041x + 0.0001x^2$	0.95	<0.01	0.32
	30 days	$y = 3.5985 - 0.0019x + 0.00003x^2$	0.98	<0.01	0.21
	90 days	$y = 3.5243 - 0.0001x^2$	0.99	<0.01	0.31
	180 days	$y = 3.6260 + 0.0001x^2$	0.99	<0.01	0.19
	270 days	$y = 3.7130 - 0.0002x + 0.0001x^2$	0.99	<0.01	0.27
	365 days	$y = 3.8558 + 0.005x$	0.95	0	0.82
Maize	0.75 days	$y = 3.4793 + 0.0028x$	0.98	<0.01	0.41
	30 days	$y = 3.5972 + 0.0055x$	0.99	<0.01	0.18
	90 days	$y = 3.55087 + 0.0049x - 0.00004x^2$	0.99	<0.01	0.34
	180 days	$y = 3.5757 + 0.0036x + 0.00005x^2$	0.99	<0.01	0.29
	270 days	$y = 3.7614 + 0.006x$	0.90	0	0.43
	365 days	$y = 3.8409 + 0.0023x$	0.88	<0.01	0.58
Soybean	0.75 days	$y = 3.7140 + 0.0103x$	0.98	<0.01	0.64
	30 days	$y = 3.4940 + 0.0064x + 0.0002x^2$	0.99	<0.01	0.58
	90 days	$y = 3.5977 + 0.0093x$	0.99	<0.01	0.55
	180 days	$y = 3.5343 + 0.0088x$	0.99	0	0.42
	270 days	$y = 3.9296 + 0.0069x$	0.98	0	0.46
	365 days	$y = 3.6254 + 0.0096x$	0.99	0	0.28

Table 2 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Oxisol A, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24 and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270 and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 5.2655 + 0.0164x - 0.0003x^2$	0.87	<0.01	0.87
	30 days	$y = 5.0179 + 0.0125x - 0.0002x^2$	0.94	<0.01	0.71
	90 days	$y = 5.0676 + 0.0094x - 0.0001x^2$	0.92	<0.01	0.34
	180 days	-	-	0.06	0.42
	270 days	$y = 5.1893 + 0.0063x - 0.0001x^2$	0.76	0.01	0.47
	365 days	-	-	0.052	0.62
Maize	0.75 days	$y = 5.5615 + 0.0025x$	0.98	<0.01	0.34
	30 days	$y = 5.3038 - 0.0021x + 0.0001x^2$	0.76	<0.01	0.25
	90 days	$y = 5.1213 + 0.00119x - 0.0001x^2$	0.99	<0.01	0.34
	180 days	$y = 5.2025 + 0.0122x - 0.0001x^2$	0.99	<0.01	0.60
	270 days	$y = 5.1937 + 0.0136x - 0.0002x^2$	0.96	<0.01	0.58
	365 days	$y = 5.0562 + 0.0026x$	0.87	<0.01	0.58
Soybean	0.75 days	$y = 5.3781 + 0.0217x - 0.0002x^2$	0.98	<0.01	0.83
	30 days	$y = 5.1595 + 0.0040x + 0.0003x^2$	0.99	<0.01	0.75
	90 days	$y = 5.3147 + 0.0086x$	0.97	<0.01	1.09
	180 days	$y = 5.1693 + 0.0057x$	0.92	<0.01	1.12
	270 days	$y = 5.3046 + 0.0039x$	0.78	<0.01	0.95
	365 days	$y = 5.2778 + 0.0032x$	0.68	<0.01	1.05

Table 3 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Oxisol B horizon with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 3.7905 - 0.0049x + 0.0001x^2$	0.83	<0.01	0.59
	30 days	$y = 3.9151 + 0.0056x - 0.0001x^2$	0.96	<0.01	0.36
	90 days	$y = 3.8529 + 0.0015x$	0.83	<0.01	0.36
	180 days	$y = 3.9598 + 0.0012x$	0.90	<0.01	0.33
	270 days	$y = 3.9386 + 0.0091x - 0.0001x^2$	0.96	<0.01	0.36
	365 days	$y = 3.9638 + 0.0072x - 0.0001x^2$	0.97	<0.01	0.59
Maize	0.75 days	-	-	0.07	1.29
	30 days	$y = 3.8921 + 0.006x - 0.0001x^2$	0.99	<0.01	0.31
	90 days	$y = 3.8488 + 0.0041x$	0.99	<0.01	0.42
	180 days	$y = 4.0025 + 0.0076x - 0.0001x^2$	0.99	<0.01	0.19
	270 days	$y = 4.2259 + 0.0045x$	0.91	0	0.45
	365 days	$y = 4.1823 + 0.0022x$	0.87	<0.01	0.42
Soybean	0.75 days	$y = 3.8207 + 0.0198x - 0.0001x^2$	0.96	<0.01	0.62
	30 days	$y = 3.8761 + 0.0295x$	0.99	<0.01	1.59
	90 days	$y = 4.0037 + 0.0001x^2$	0.99	<0.01	0.70
	180 days	$y = 4.0237 - 0.0036x + 0.0001x^2$	0.98	<0.01	0.36
	270 days	$y = 4.0382 + 0.0035x$	0.97	0	0.36
	365 days	$y = 3.8659 - 0.0048x + 0.0002x^2$	0.99	0	0.33

Table 4 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Oxisol B horizon, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270 and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 5.3456 + 0.0210x - 0.0003x^2$	0.97	<0.01	0.40
	30 days	$y = 5.6098 + 0.0175x - 0.0003x^2$	0.90	<0.01	0.8
	90 days	$y = 5.6931 - 0.0028x$	0.94	<0.01	0.34
	180 days	$y = 5.5506 + 0.0083x - 0.0002x^2$	0.99	<0.01	0.59
	270 days	$y = 5.5697 + 0.0087x - 0.0002x^2$	0.99	<0.01	0.39
	365 days	$y = 5.4793 - 0.0058x$	0.92	0	0.64
Maize	0.75 days	$y = 5.7183 + 0.0021x$	0.95	<0.01	0.33
	30 days	$y = 5.4283 + 0.0120x - 0.0002x^2$	0.96	<0.01	0.48
	90 days	$y = 5.3665 + 0.0169x - 0.0002x^2$	0.98	<0.01	0.52
	180 days	$y = 5.6608 + 0.0143x - 0.0002x^2$	0.86	<0.01	0.26
	270 days	$y = 5.7022 + 0.0178x - 0.0003x^2$	0.96	<0.01	0.76
	365 days	$y = 5.5528 + 0.01x - 0.0002x^2$	0.88	<0.01	0.55
Soybean	0.75 days	$y = 5.2764 + 0.0252x - 0.0002x^2$	0.99	<0.01	0.89
	30 days	$y = 5.6712 + 0.0146x$	0.98	<0.01	0.80
	90 days	$y = 5.7488 + 0.0042x$	0.77	<0.01	0.88
	180 days	$y = 5.8135 - 0.0036x + 0.0001x^2$	0.24	0.03	0.53
	270 days	-	-	0.18	0.68
	365 days	-	-	0.59	0.66

Table 5 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Inceptisol A with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.43	1.23
	30 days	-	-	0.57	0.39
	90 days	$y = 4.0512 - 0.0008x$	0.85	0.01	0.31
	180 days	$y = 3.7800 + 0.0026x$	0.98	<0.01	0.40
	270 days	$y = 3.8328 + 0.0113x - 0.001x^2$	0.97	<0.01	0.49
	365 days	-	-	0.18	0.36
Maize	0.75 days	$y = 3.6610 - 0.0031x + 0.0001x^2$	0.99	<0.01	0.41
	30 days	-	-	0.47	0.34
	90 days	$y = 4.0373 + 0.0012x$	0.94	<0.01	0.23
	180 days	$y = 3.8103 + 0.0013x$	0.97	<0.05	0.41
	270 days	$y = 4.0355 + 0.0026x$	0.94	<0.01	0.5
	365 days	$y = 3.8785 + 0.008x$	0.82	<0.01	0.37
Soybean	0.75 days	$y = 3.9040 + 0.0051x$	0.99	<0.01	0.37
	30 days	$y = 3.9654 + 0.0084x$	0.99	<0.01	0.27
	90 days	$y = 4.1694 + 0.0027x$	0.84	<0.01	0.40
	180 days	$y = 3.7738 + 0.015x$	0.75	<0.01	0.43
	270 days	$y = 3.8722 + 0.0019x$	0.93	<0.01	0.52
	365 days	$y = 3.7582 + 0.0026x$	0.95	0	0.36

Table 6 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Inceptisol A, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 5.0818 - 0.0022x$	0.77	<0.01	0.66
	30 days	$y = 5.2265 - 0.0032x$	0.98	<0.01	0.34
	90 days	$y = 4.8112 + 0.005x - 0.0001x^2$	0.94	<0.01	0.46
	180 days	$y = 4.8439 + 0.0073x - 0.0001x^2$	0.83	<0.01	0.36
	270 days	$y = 4.8789 + 0.0011x$	0.80	<0.01	0.26
	365 days	-	-	0.15	0.48
Maize	0.75 days	$y = 5.2246 - 0.0109x + 0.0002x^2$	0.94	<0.01	0.30
	30 days	-	-	0.07	0.28
	90 days	$y = 4.8689 + 0.0017x$	0.97	<0.01	0.24
	180 days	$y = 4.8435 + 0.0055x - 0.0001x^2$	0.99	<0.01	0.32
	270 days	$y = 4.9588 + 0.0018x$	0.75	<0.01	0.51
	365 days	$y = 4.9553 + 0.0009x$	0.68	<0.01	0.3
Soybean	0.75 days	$y = 4.9137 + 0.0041x$	0.98	<0.01	0.37
	30 days	$y = 4.9743 + 0.0086x$	0.99	<0.01	0.59
	90 days	-	-	0.23	0.47
	180 days	$y = 4.6428 - 0.0015x$	0.92	<0.01	0.29
	270 days	$y = 4.5710 - 0.0023x$	0.88	<0.01	0.62
	365 days	$y = 4.5693 - 0.002x$	0.98	<0.01	0.38

Table 7 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Inceptisol B with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.95	0.37
	30 days	-	-	0.73	0.58
	90 days	$y = 3.7625 + 0.0006x$	0.89	<0.05	0.31
	180 days	-	-	0.08	0.44
	270 days	-	-	0.98	0.53
	365 days	$y = 4.0237 + 0.0076x - 0.0001x^2$	0.98	<0.01	0.38
Maize	0.75 days	-	-	0.35	0.50
	30 days	-	-	0.06	0.59
	90 days	$y = 3.7382 + 0.0009x$	0.85	<0.01	0.25
	180 days	$y = 3.9168 + 0.0007x$	0.79	<0.01	0.26
	270 days	$y = 4.2695 + 0.0041x - 0.0001x^2$	0.63	<0.01	0.32
	365 days	$y = 4.5348 + 0.0047x - 0.0001x^2$	0.90	<0.01	0.24
Soybean	0.75 days	$y = 3.7506 + 0.0027x$	0.97	<0.01	0.25
	30 days	$y = 3.8052 + 0.0081x$	0.99	<0.01	0.40
	90 days	$y = 3.9773 + 0.005x + 0.0001x^2$	0.99	<0.01	0.33
	180 days	$y = 4.0054 + 0.0092x$	0.99	0	0.34
	270 days	$y = 4.2429 + 0.0071x$	0.97	<0.01	0.42
	365 days	$y = 3.9209 + 0.007x$	0.99	0	1.03

Table 8 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on pH after incubation of Inceptisol B, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha⁻¹ at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.07	2.19
	30 days	$y = 4.4801 + 0.0165x - 0.0003x^2$	0.91	<0.01	1.1
	90 days	$y = 5.0028 - 0.0141x + 0.0002x^2$	0.89	<0.01	0.63
	180 days	$y = 4.7822 + 0.0045x - 0.0001x^2$	0.32	<0.01	0.51
	270 days	-	-	0.12	0.82
	365 days	-	-	0.19	1.5
Maize	0.75 days	-	-	0.11	0.53
	30 days	-	-	0.09	0.74
	90 days	$y = 4.8206 + 0.0097x - 0.0001x^2$	0.95	<0.01	0.45
	180 days	$y = 4.8244 + 0.0133x - 0.0002x^2$	0.92	<0.01	0.85
	270 days	$y = 5.1215 + 0.0027x$	0.89	<0.01	0.39
	365 days	$y = 5.1787 + 0.0038x$	0.92	<0.01	0.73
Soybean	0.75 days	$y = 4.7225 + 0.0002x^2$	0.99	<0.01	0.86
	30 days	$y = 4.7572 + 0.035x - 0.0003x^2$	0.99	<0.01	1.24
	90 days	$y = 4.8743 + 0.033x - 0.0001x^2$	0.99	<0.01	0.66
	180 days	$y = 4.8978 + 0.0373x - 0.0006x^2$	0.97	0	1.07
	270 days	$y = 4.9308 + 0.0208x - 0.0004x^2$	0.81	<0.01	0.91
	365 days	-	-	0.31	1.1

Table 9 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on AI concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Oxisol A horizon with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.36	6.91
	30 days	$y = 1.2866 + 0.0131x - 0.0003x^2$	0.89	<0.01	2.55
	90 days	$y = 1.6298 - 0.0002x$	0.99	<0.01	3.28
	180 days	$y = 1.7386 - 0.0002x^2$	0.99	<0.01	2.71
	270 days	$y = 1.9028 - 0.0079x$	0.91	<0.01	3.45
	365 days	$y = 1.6047 + 0.0018x - 0.0002x^2$	0.95	0.01	2.93
Maize	0.75 days	$y = 1.2532 - 0.0066x$	0.98	<0.01	5.27
	30 days	$y = 1.4197 - 0.0101x$	0.93	<0.01	1.16
	90 days	$y = 1.6012 - 0.0137x$	0.99	<0.01	3.33
	180 days	$y = 1.787 - 0.0135x$	0.99	<0.01	2.37
	270 days	$y = 1.7412 - 0.012x$	0.98	0	2.74
	365 days	$y = 1.5153 - 0.0077x$	0.99	0	2.64
Soybean	0.75 days	$y = 1.3545 - 0.0327x + 0.0003x^2$	0.99	<0.01	5.36
	30 days	$y = 1.5841 - 0.0264x$	0.99	<0.01	4.9
	90 days	$y = 1.7232 - 0.0148x$	0.94	<0.01	1.08
	180 days	$y = 1.9160 - 0.0236x$	0.99	0	2.87
	270 days	$y = 1.9950 - 0.0248x$	0.98	0	2.81
	365 days	$y = 1.4623 - 0.0193x$	0.98	0	3.66

Table 10 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on Al concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Oxisol B horizon with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	$y = 0.652 + 0.0014x$	0.21	<0.01	5.95
	30 days	-	-	0.24	7.61
	90 days	$y = 0.7425 - 0.0035x + 0.0001x^2$	0.61	<0.01	2.54
	180 days	$y = 0.8428 - 0.0041x + 0.0001x^2$	0.93	<0.01	1.56
	270 days	$y = 0.8667 - 0.0034x + 0.0001x^2$	0.94	0.01	3.17
	365 days	$y = 0.7178 - 0.0046x + 0.0001x^2$	0.72	<0.01	4.42
Maize	0.75 days	$y = 0.7302 - 0.0048x$	0.95	0.01	10.72
	30 days	$y = 0.7583 - 0.0085x + 0.0001x^2$	0.98	<0.01	3.61
	90 days	$y = 0.7708 - 0.0067x$	0.97	<0.01	4.15
	180 days	$y = 0.8565 - 0.0116x + 0.0001x^2$	0.99	<0.01	3.06
	270 days	$y = 0.8398 - 0.007x$	0.95	0	5.04
	365 days	$y = 0.7117 - 0.0046x$	0.89	0	4.42
Soybean	0.75 days	$y = 0.7434 - 0.0242x + 0.0003x^2$	0.99	<0.01	11.91
	30 days	$y = 0.8893 - 0.0480x + 0.0006x^2$	0.98	<0.01	1.93
	90 days	$y = 0.8692 - 0.01x$	0.99	<0.01	5.85
	180 days	$y = 0.9783 - 0.0094x$	0.99	0	2.67
	270 days	$y = 0.8278 - 0.0059x$	0.92	0	4.74
	365 days	$y = 0.6470 - 0.0061x$	0.88	<0.01	8.85

Table 11 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on Al concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Inceptisol A with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.24	3.56
	30 days	-	-	0.82	3.76
	90 days	-	-	0.19	3.4
	180 days	$y = 4.8221 - 0.0125x$	0.92	<0.01	3.12
	270 days	$y = 5.3449 - 0.0098x$	0.90	<0.01	2.43
	365 days	-	-	0.63	3.86
Maize	0.75 days	$y = 3.073 + 0.0092x - 0.0004x^2$	0.89	<0.01	2.32
	30 days	$y = 3.1138 + 0.0104x - 0.0003x^2$	0.65	<0.01	2.09
	90 days	$y = 3.0788 - 0.008x$	0.98	<0.01	3.11
	180 days	$y = 4.4351 - 0.0104x$	0.74	0.01	4.00
	270 days	$y = 5.2778 - 0.0111x$	0.93	<0.01	2.85
	365 days	$y = 4.0758 - 0.0072x$	0.82	<0.01	2.71
Soybean	0.75 days	$y = 3.2835 - 0.0290x$	0.98	<0.01	3.95
	30 days	$y = 3.1077 - 0.0397x$	0.91	<0.01	4.58
	90 days	$y = 3.2863 - 0.0223x$	0.97	<0.01	0.76
	180 days	$y = 5.1482 - 0.0004x$	0.86	0	0.65
	270 days	$y = 5.4218 - 0.0239x$	0.95	<0.01	3.76
	365 days	$y = 3.8311 - 0.0232x$	0.99	0	3.21

Table 12 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on Al concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Inceptisol A, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	-	-
	30 days	-	-	-	-
	90 days	$y = 0.1915 - 0.0015x$	0.70	<0.01	12.79
	180 days	-	-	0.43	14.19
	270 days	$y = 0.2638 - 0.0017x$	0.80	<0.01	0.26
	365 days	-	-	0.11	11
Maize	0.75 days	-	-	-	-
	30 days	-	-	-	-
	90 days	$y = 0.1643 - 0.0011x$	0.87	0.02	12.44
	180 days	$y = 0.2146 - 0.001x$	0.79	<0.01	6.00
	270 days	-	-	-	-
	365 days	$y = 0.1736 - 0.0041x$	0.74	0	12.73
Soybean	0.75 days	-	-	-	-
	30 days	-	-	-	-
	90 days	$y = 0.539 - 0.0022x$	0.63	<0.01	6.95
	180 days	-	-	0.24	5.8
	270 days	-	-	0.34	7.36
	365 days	$y = 0.5396 - 0.0012x$	0.52	0.01	5.23

Table 13 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on Al concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Inceptisol B with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.41	3.25
	30 days	$y = 2.8411 + 0.0067x$	0.55	0.02	4.49
	90 days	-	-	0.35	8.34
	180 days	$y = 4.0559 - 0.0264x$	0.91	<0.01	1.36
	270 days	$y = 4.1144 + 0.0171x - 0.0002x^2$	0.94	0.01	1.61
	365 days	-	-	0.90	1.5
Maize	0.75 days	$y = 3.3024 - 0.0073x$	0.87	0.03	3.98
	30 days	$y = 3.1767 - 0.0003x^2$	0.85	<0.01	2.87
	90 days	-	-	0.06	3.19
	180 days	-	-	0.15	2.51
	270 days	$y = 3.9408 - 0.0046x$	0.72	<0.01	2.45
	365 days	$y = 3.2950 - 0.0067x$	0.92	<0.01	2.2
Soybean	0.75 days	$y = 3.3075 - 0.0241x$	0.91	<0.01	5.79
	30 days	$y = 4.0497 - 0.0552x$	0.99	<0.01	1.70
	90 days	$y = 3.7918 - 0.0548x$	0.99	<0.01	5.44
	180 days	$y = 4.1251 - 0.0607x$	0.99	0	3.71
	270 days	$y = 3.5295 - 0.0522x$	0.99	0	2.87
	365 days	$y = 3.0048 - 0.0398x$	0.98	0	5.15

Table 14 - Equations from the analysis of variance of the regressions, correlation coefficient (R^2), P -value and coefficient of variation (CV) for effects on Al concentration ($\text{cmol}_c \text{kg}^{-1}$) after incubation of Inceptisol B, amended with liming, with each residue (Loblolly pine, Maize, and Soybean) at rates of 0, 6, 12, 24, and 48 t ha^{-1} at times of 0.75, 30, 90, 180, 270, and 365 days after the start of incubation.

Residue	Time	Regression equations	R^2	P -value	CV(%)
Loblolly pine	0.75 days	-	-	0.051	64.54
	30 days	-	-	-	-
	90 days	-	-	-	-
	180 days	$y = 0.1261 + 0.0001x^2$	0.96	<0.01	11.92
	270 days	$y = 0.1573 - 0.0133x + 0.0003x^2$	0.81	<0.01	33.68
	365 days	$y = 0.1243 + 0.0008x$	0.87	<0.01	10.81
Maize	0.75 days	-	-	0.51	27.72
	30 days	-	-	0.59	20.03
	90 days	$y = 0.0815 - 0.0026x + 0.0002x^2$	0.66	<0.01	11.56
	180 days	$y = 0.1085 - 0.0077x + 0.0001x^2$	0.87	<0.01	15.81
	270 days	-	-	-	-
	365 days	-	-	-	-
Soybean	0.75 days	-	-	-	-
	30 days	-	-	-	-
	90 days	-	-	-	-
	180 days	-	-	-	-
	270 days	-	-	-	-
	365 days	$y = 0.0788 + 0.0078x - 0.0005x^2 + 0.0001x^3$	0.97	<0.01	14.38

Table 15 - Means and standard deviation of triplicates of pH for Oxisol A horizon incubated with 0, 6, 12, 24 or 48 t ha⁻¹ of Loblolly pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
0.75 days	0	3.55	0.01		3.49	0.02		3.72	0.02		5.23	0.08		5.56	0.01		5.35	0.09	
	6	3.53	0.01		3.49	0.006		3.75	0.006		5.39	0.06		5.58	0.03		5.52	0.04	
	12	3.50	0.01		3.50	0.006		3.85	0.03		5.45	0.02		5.60	0.02		5.63	0.02	
	24	3.49	0.01		3.54	0.02		3.99	0.01		5.47	0.01		5.61	0.02		5.74	0.02	
	48	3.50	0.01		3.62	0.006		4.20	0.04		5.44	0.02		5.68	0.006		5.92	0.01	
30 days	0	3.61	0.01		3.60	0.006		3.50	0.04		5.00	0.07		5.34	0.01		5.16	0.03	
	6	3.60	0.01		3.62	0.006		3.52	0.01		5.11	0.03		5.24	0.02		5.20	0.02	
	12	3.62	0.01		3.65	0.01		3.62	0.01		5.17	0.02		5.29	0.01		5.23	0.04	
	24	3.67	0.01		3.75	0.006		3.77	0.01		5.20	0.01		5.34	0.01		5.43	0.04	
	48	3.75	0.01		3.85	0.006		4.32	0.02		5.25	0.01		5.43	0.006		6.00	0.06	

		Without liming						With liming					
Residue		Loblolly pine			Maize			Soybean			Loblolly pine		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
90 days	0	3.53	0.02	3.52	0.01	3.61	0.01	5.04	0.01	5.13	0.01	5.32	0.02
	6	3.52	0.01	3.53	0.01	3.64	0.01	5.15	0.03	5.18	0.01	5.40	0.02
	12	3.53	0.01	3.55	0.01	3.71	0.01	5.18	0.01	5.25	0.03	5.37	0.03
	24	3.57	0.01	3.66	0.02	3.82	0.03	5.21	0.01	5.34	0.01	5.51	0.01
	48	3.70	0.01	3.85	0.006	4.04	0.02	5.28	0.02	5.42	0.01	5.74	0.08
180 days	0	3.63	0.01	3.59	0.01	3.55	0.02	5.26	0.02	5.20	0.04	5.15	0.05
	6	3.62	0.01	3.58	0.006	3.57	0.01	5.30	0.03	5.27	0.03	5.22	0.02
	12	3.64	0.01	3.61	0.006	3.64	0.01	5.29	0.02	5.34	0.01	5.21	0.04
	24	3.69	0.01	3.70	0.006	3.75	0.01	5.30	0.01	5.41	0.04	5.35	0.07
	48	3.87	0.01	3.85	0.01	3.96	0.02	5.32	0.03	5.48	0.02	5.42	0.08

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	3.71	0.01		3.72	0.02		3.90	0.03		5.16	0.03		5.17	0.03		5.32	0.006	
	6	3.71	0.01		3.79	0.02		3.98	0.01		5.26	0.02		5.30	0.05		5.32	0.02	
	12	3.73	0.01		3.85	0.01		4.03	0.01		5.25	0.02		5.34	0.02		5.30	0.03	
	24	3.76	0.01		3.93	0.01		4.10	0.02		5.27	0.02		5.41	0.02		5.45	0.05	
	48	3.93	0.01		4.02	0.01		4.25	0.01		5.30	0.02		5.48	0.03		5.48	0.09	
365 days	0	3.83	0.04		3.82	0.04		3.61	0.01		5.17	0.03		5.05	0.02		5.29	0.03	
	6	3.90	0.01		3.87	0.02		3.69	0.02		5.19	0.04		5.05	0.04		5.30	0.05	
	12	3.94	0.01		3.88	0.006		3.74	0.00		5.13	0.02		5.09	0.02		5.26	0.03	
	24	3.97	0.05		3.91	0.01		3.88	0.01		5.10	0.03		5.15	0.01		5.41	0.06	
	48	4.09	0.02		3.94	0.02		4.08	0.01		5.12	0.04		5.17	0.03		5.42	0.09	

Table 16 - Means and standard deviation of the triplicates of pH for Oxisol B horizon incubated with 0, 6, 12, 24, or 48 t ha⁻¹ of Loblolly pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
0.75 days	0	3.81	0.04		3.82	0.11		3.86	0.03		5.33	0.006		5.71	0.006		5.27	0.06	
	6	3.74	0.01		3.73	0.006		3.91	0.01		5.48	0.03		5.74	0.006		5.42	0.06	
	12	3.74	0.02		3.73	0.006		3.97	0.02		5.57	0.03		5.75	0.02		5.56	0.03	
	24	3.72	0.006		3.78	0.01		4.29	0.03		5.64	0.006		5.76	0.03		5.73	0.04	
	48	3.71	0.02		3.84	0.01		4.50	0.01		5.63	0.01		5.82	0.01		5.93	0.05	
30 days	0	3.92	0.02		3.89	0.01		3.94	0.06		5.57	0.08		5.41	0.03		5.69	0.02	
	6	3.93	0.01		3.93	0.006		3.98	0.01		5.75	0.03		5.51	0.03		5.77	0.04	
	12	3.98	0.01		3.95	0.006		4.21	0.05		5.79	0.01		5.57	0.03		5.84	0.02	
	24	4.00	0.01		4.01	0.02		4.60	0.05		5.84	0.05		5.60	0.01		5.96	0.05	
	48	4.00	0.01		4.06	0.006		5.30	0.13		5.83	0.01		5.63	0.02		6.40	0.08	

Without liming										With liming															
Residue		Loblolly pine				Maize				Soybean				Loblolly pine				Maize				Soybean			
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
90 days	0	3.84	0.01	3.85	0.03	4.00	0.01	5.69	0.01	5.36	0.02	5.68	0.08	5.69	0.01	5.36	0.02	5.68	0.08	5.69	0.01	5.36	0.02	5.68	0.08
	6	3.85	0.006	3.86	0.01	4.01	0.01	5.67	0.02	5.46	0.04	5.83	0.01	5.67	0.02	5.46	0.04	5.83	0.01	5.67	0.02	5.46	0.04	5.83	0.01
	12	3.88	0.02	3.91	0.01	4.03	0.01	5.66	0.01	5.57	0.03	5.82	0.05	5.66	0.01	5.57	0.03	5.82	0.05	5.66	0.01	5.57	0.03	5.82	0.05
	24	3.91	0.006	3.95	0.006	4.07	0.02	5.65	0.01	5.63	0.02	5.86	0.03	5.65	0.01	5.63	0.02	5.86	0.03	5.65	0.02	5.63	0.02	5.86	0.03
	48	3.92	0.01	4.04	0.01	4.31	0.05	5.55	0.03	5.71	0.02	5.94	0.05	5.55	0.03	5.71	0.02	5.94	0.05	5.55	0.03	5.71	0.02	5.94	0.05
180 days	0	3.96	0.006	4.00	0.01	4.02	0.01	5.55	0.05	5.62	0.01	5.84	0.04	5.55	0.05	5.62	0.01	5.84	0.04	5.55	0.05	5.62	0.01	5.84	0.04
	6	3.96	0.01	4.05	0.006	4.01	0.01	5.60	0.02	5.79	0.02	5.78	0.006	5.60	0.02	5.79	0.02	5.78	0.006	5.60	0.02	5.79	0.02	5.78	0.006
	12	3.98	0.02	4.09	0.006	4.00	0.006	5.62	0.03	5.82	0.02	5.74	0.01	5.62	0.03	5.82	0.02	5.74	0.01	5.62	0.03	5.82	0.02	5.74	0.01
	24	4.00	0.01	4.14	0.006	3.99	0.01	5.64	0.01	5.85	0.01	5.80	0.03	5.64	0.01	5.85	0.01	5.80	0.03	5.64	0.01	5.85	0.01	5.80	0.03
	48	4.01	0.01	4.19	0.01	4.09	0.03	5.49	0.02	5.89	0.01	5.79	0.04	5.49	0.02	5.89	0.01	5.79	0.04	5.49	0.02	5.89	0.01	5.79	0.04

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	3.93	0.02		4.19	0.02		4.03	0.01		5.57	0.02		5.68	0.08		5.75	0.04	
	6	3.99	0.006		4.26	0.006		4.06	0.02		5.62	0.03		5.82	0.04		5.76	0.01	
	12	4.04	0.01		4.30	0.01		4.10	0.01		5.63	0.02		5.90	0.03		5.73	0.03	
	24	4.06	0.006		4.36	0.006		4.11	0.01		5.66	0.02		5.95	0.03		5.79	0.03	
	48	4.05	0.02		4.42	0.03		4.21	0.02		5.50	0.01		5.95	0.01		5.81	0.06	
365 days	0	3.96	0.04		4.17	0.006		3.87	0.006		5.51	0.04		5.53	0.06		5.68	0.05	
	6	4.02	0.00		4.19	0.006		3.84	0.01		5.45	0.01		5.63	0.006		5.72	0.04	
	12	4.05	0.01		4.22	0.006		3.84	0.006		5.35	0.04		5.67	0.01		5.70	0.04	
	24	4.08	0.02		4.26	0.006		3.85	0.01		5.36	0.01		5.68	0.01		5.73	0.02	
	48	4.10	0.01		4.27	0.03		4.02	0.02		5.20	0.04		5.69	0.03		5.72	0.03	

Table 17 - Means and standard deviation of triplicates of pH for Inceptisol A incubated with 0, 6, 12, 24, or 48 t ha⁻¹ of Loblolly pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
0.75 days	0	3.69	0.01		3.66	0.01		3.90	0.01		5.10	0.06		5.24	0.03		4.91	0.02	
	6	3.62	0.04		3.64	0.01		3.93	0.01		5.09	0.01		5.15	0.01		4.93	0.02	
	12	3.68	0.02		3.64	0.02		3.98	0.01		5.02	0.03		5.10	0.01		4.98	0.03	
	24	3.65	0.01		3.64	0.01		4.03	0.01		5.02	0.01		5.08	0.01		5.02	0.02	
	48	3.66	0.00		3.71	0.01		4.15	0.02		4.98	0.03		5.07	0.01		5.10	0.02	
30 days	0	3.96	0.02		3.95	0.03		3.97	0.01		5.23	0.02		5.17	0.01		4.95	0.03	
	6	3.97	0.01		3.94	0.01		4.02	0.01		5.21	0.01		5.18	0.03		5.04	0.04	
	12	3.97	0.01		3.94	0.01		4.06	0.01		5.18	0.01		5.16	0.00		5.09	0.02	
	24	3.97	0.01		3.95	0.01		4.16	0.02		5.14	0.01		5.15	0.01		5.19	0.03	
	48	3.95	0.01		3.96	0.01		4.37	0.01		5.08	0.02		5.15	0.01		5.38	0.03	

Without liming										With liming									
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
90 days	0	4.05	0.01	4.04	0.01	4.15	0.02	4.80	0.02	4.87	0.01	4.73	0.02						
	6	4.04	0.006	4.04	0.01	4.20	0.01	4.85	0.01	4.87	0.02	4.74	0.02						
	12	4.05	0.01	4.05	0.01	4.23	0.01	4.87	0.01	4.89	0.01	4.74	0.01						
	24	4.03	0.01	4.07	0.01	4.21	0.01	4.88	0.02	4.91	0.01	4.70	0.02						
	48	4.01	0.02	4.09	0.01	4.31	0.02	4.88	0.04	4.95	0.01	4.71	0.04						
180 days	0	3.78	0.01	3.81	0.01	3.79	0.01	4.83	0.02	4.84	0.03	4.65	0.02						
	6	3.80	0.01	3.82	0.01	3.78	0.01	4.88	0.01	4.88	0.01	4.62	0.01						
	12	3.82	0.01	3.82	0.02	3.79	0.01	4.94	0.01	4.90	0.01	4.62	0.01						
	24	3.83	0.01	3.85	0.01	3.78	0.01	4.93	0.01	4.94	0.01	4.62	0.01						
	48	3.91	0.02	3.87	0.03	3.86	0.03	4.93	0.02	4.96	0.01	4.57	0.02						

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	3.82	0.03		4.02	0.01		3.86	0.03		4.86	0.01		4.93	0.04		4.59	0.02	
	6	3.90	0.02		4.06	0.02		3.89	0.01		4.90	0.01		4.98	0.01		4.56	0.05	
	12	3.97	0.006		4.07	0.02		3.90	0.01		4.90	0.01		4.98	0.01		4.53	0.01	
	24	4.00	0.01		4.11	0.01		3.92	0.02		4.91	0.01		5.03	0.04		4.50	0.01	
	48	4.04	0.02		4.15	0.03		3.96	0.02		4.93	0.01		5.03	0.01		4.47	0.04	
365 days	0	3.82	0.01		3.88	0.01		3.77	0.01		4.90	0.04		4.95	0.01		4.56	0.02	
	6	3.84	0.01		3.89	0.01		3.77	0.01		4.94	0.01		4.96	0.01		4.56	0.02	
	12	3.84	0.02		3.88	0.02		3.78	0.00		4.94	0.01		4.96	0.02		4.55	0.01	
	24	3.84	0.006		3.89	0.01		3.81	0.02		4.93	0.01		5.00	0.01		4.52	0.03	
	48	3.85	0.006		3.92	0.01		3.89	0.02		4.95	0.02		4.99	0.02		4.47	0.01	

Table 18 - Means and standard deviation of triplicates of pH for Inceptisol B incubated with 0, 6, 12, 24, or 48 t ha⁻¹ of pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
0.75 days	0	3.58	0.02		3.57	0.01		3.76	0.01		4.77	0.05		4.77	0.02		4.73	0.03	
	6	3.58	0.01		3.55	0.02		3.77	0.01		4.93	0.10		4.81	0.02		4.73	0.03	
	12	3.57	0.01		3.54	0.01		3.77	0.01		5.07	0.02		4.81	0.04		4.74	0.02	
	24	3.58	0.02		3.55	0.02		3.81	0.01		5.00	0.06		4.79	0.01		4.85	0.07	
	48	3.58	0.01		3.56	0.01		3.89	0.01		4.92	0.08		4.83	0.02		5.12	0.04	
30 days	0	3.47	0.03		3.77	0.03		3.82	0.02		4.46	0.08		4.93	0.04		4.75	0.06	
	6	3.45	0.02		3.78	0.01		3.85	0.01		4.58	0.06		4.93	0.05		4.97	0.04	
	12	3.46	0.01		3.78	0.03		3.90	0.01		4.69	0.03		4.87	0.02		5.13	0.01	
	24	3.46	0.02		3.82	0.01		3.99	0.01		4.69	0.02		4.91	0.04		5.45	0.07	
	48	3.45	0.01		3.82	0.00		4.20	0.02		4.70	0.02		4.86	0.006		5.85	0.09	

Without liming										With liming									
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean
90 days	0	3.76	0.01	3.74	0.01	3.98	0.01	5.04	0.04	4.83	4.83	0.03	4.89	0.01	4.89	0.01	4.89	0.01	4.89
	6	3.77	0.01	3.73	0.01	4.00	0.01	4.88	0.04	4.87	4.87	0.01	5.05	0.02	5.05	0.02	5.05	0.02	5.05
	12	3.76	0.01	3.75	0.01	4.05	0.01	4.85	0.01	4.89	4.89	0.02	5.25	0.03	5.25	0.03	5.25	0.03	5.25
	24	3.78	0.02	3.77	0.01	4.14	0.01	4.81	0.02	5.01	5.01	0.02	5.60	0.03	5.60	0.03	5.60	0.03	5.60
	48	3.79	0.01	3.78	0.01	4.36	0.02	4.76	0.01	5.01	5.01	0.01	6.15	0.06	6.15	0.06	6.15	0.06	6.15
180 days	0	3.73	0.01	3.91	0.01	4.01	0.01	4.80	0.03	4.80	4.80	0.04	4.94	0.05	4.94	0.05	4.94	0.05	4.94
	6	3.74	0.03	3.92	0.01	4.06	0.01	4.76	0.04	4.95	4.95	0.07	5.05	0.02	5.05	0.02	5.05	0.02	5.05
	12	3.75	0.01	3.94	0.01	4.12	0.02	4.87	0.01	4.95	4.95	0.01	5.24	0.01	5.24	0.01	5.24	0.01	5.24
	24	3.76	0.01	3.93	0.01	4.22	0.01	4.83	0.03	5.03	5.03	0.04	5.49	0.06	5.49	0.06	5.49	0.06	5.49
	48	3.77	0.01	3.95	0.01	4.45	0.02	4.80	0.01	5.06	5.06	0.02	5.33	0.09	5.33	0.09	5.33	0.09	5.33

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	4.05	0.05		4.25	0.01		4.21	0.03		4.95	0.04		5.10	0.006		4.96	0.01	
	6	4.06	0.01		4.31	0.02		4.30	0.01		4.95	0.07		5.14	0.03		5.04	0.02	
	12	4.06	0.01		4.33	0.00		4.35	0.01		5.03	0.02		5.15	0.006		5.03	0.01	
	24	4.05	0.01		4.31	0.02		4.42	0.00		5.01	0.02		5.21	0.02		5.24	0.08	
	48	4.06	0.01		4.33	0.01		4.57	0.03		4.97	0.01		5.24	0.02		4.91	0.06	
365 days	0	4.02	0.02		4.53	0.02		3.90	0.01		4.92	0.08		5.15	0.04		4.82	0.01	
	6	4.07	0.02		4.56	0.00		3.98	0.01		4.82	0.10		5.21	0.02		4.81	0.02	
	12	4.11	0.01		4.59	0.01		4.00	0.01		4.95	0.07		5.23	0.04		4.81	0.01	
	24	4.14	0.01		4.59	0.01		4.09	0.03		4.94	0.09		5.30	0.06		4.85	0.11	
	48	4.17	0.01		4.58	0.01		4.25	0.08		4.84	0.01		5.35	0.006		4.75	0.03	

Table 19 - Means and standard deviation of triplicates of Al^{3+} ($\text{cmol}_c \text{ kg}^{-1}$) for Oxisol A and B horizon, without liming, incubated with 0, 6, 12, 24, or 48 t ha^{-1} of Loblolly pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Soil		Oxisol A horizon						Oxisol B horizon											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
0.75 days	0	1.18	0.10	1.26	0.02	1.37	0.03	0.71	0.01	0.72	0.04	0.74	0.09						
	6	1.19	0.09	1.21	0.03	1.17	0.02	0.66	0.07	0.68	0.03	0.60	0.01						
	12	1.31	0.04	1.21	0.05	0.98	0.07	0.58	0.04	0.70	0.02	0.53	0.01						
	24	1.20	0.09	1.07	0.09	0.79	0.02	0.71	0.03	0.63	0.04	0.29	0.05						
	48	1.18	0.06	0.95	0.07	0.57	0.08	0.73	0.03	0.49	0.14	0.17	0.03						
30 days	0	1.29	0.03	1.35	0.02	1.64	0.04	0.85	0.1	0.76	0.03	0.88	0.01						
	6	1.31	0.02	1.39	0.01	1.39	0.08	0.79	0.04	0.72	0.03	0.67	0.01						
	12	1.45	0.01	1.37	0.01	1.22	0.06	0.77	0.03	0.65	0.01	0.33	0.01						
	24	1.38	0.06	1.16	0.01	0.97	0.05	0.73	0.01	0.61	0.03	0.12	0.01						
	48	1.14	0.02	0.93	0.01	0.32	0.02	0.81	0.07	0.54	0.01	0.00	0.00						

Soil		Oxisol A horizon						Oxisol B horizon											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
90 days	0	1.62	0.03		1.62	0.06		1.80	0.02		0.76	0.03		0.79	0.04		0.85	0.01	
	6	1.62	0.02		1.53	0.03		1.65	0.01		0.70	0.01		0.73	0.01		0.81	0.04	
	12	1.60	0.07		1.45	0.02		1.43	0.01		0.70	0.02		0.68	0.02		0.77	0.02	
	24	1.48	0.05		1.27	0.06		1.36	0.03		0.71	0.01		0.58	0.03		0.63	0.04	
	48	1.14	0.05		0.95	0.03		1.04	0.01		0.69	0.01		0.47	0.02		0.39	0.07	
180 days	0	1.75	0.04		1.78	0.04		1.94	0.08		0.84	0.01		0.86	0.02		0.99	0.02	
	6	1.73	0.03		1.70	0.04		1.79	0.03		0.83	0.01		0.78	0.01		0.90	0.01	
	12	1.68	0.05		1.67	0.01		1.63	0.01		0.80	0.01		0.75	0.02		0.88	0.04	
	24	1.64	0.04		1.45	0.05		1.29	0.02		0.78	0.01		0.64	0.02		0.75	0.01	
	48	1.27	0.06		1.14	0.03		0.82	0.03		0.81	0.01		0.57	0.02		0.53	0.02	

Soil	Oxisol A horizon						Oxisol B horizon											
Residue	Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	
270 days	0	1.84	0.04	1.77	0.03	2.07	0.02	0.87	0.01	0.88	0.03	0.82	0.04					
	6	1.87	0.07	1.64	0.04	1.83	0.02	0.86	0.02	0.79	0.01	0.77	0.05					
	12	1.85	0.10	1.58	0.06	1.65	0.03	0.83	0.01	0.74	0.03	0.75	0.02					
	24	1.75	0.03	1.49	0.04	1.35	0.08	0.84	0.03	0.63	0.02	0.74	0.03					
	48	1.49	0.03	1.16	0.01	0.84	0.02	0.91	0.05	0.53	0.06	0.52	0.01					
365 days	0	1.58	0.07	1.54	0.02	1.52	0.07	0.74	0.04	0.75	0.03	0.63	0.04					
	6	1.64	0.04	1.45	0.03	1.32	0.06	0.67	0.03	0.68	0.02	0.58	0.01					
	12	1.62	0.01	1.42	0.03	1.23	0.01	0.66	0.04	0.63	0.01	0.59	0.06					
	24	1.53	0.03	1.32	0.03	0.92	0.01	0.70	0.02	0.57	0.01	0.57	0.07					
	48	1.35	0.05	1.16	0.05	0.57	0.01	0.77	0.02	0.51	0.05	0.32	0.04					

Table 20 - Means and standard deviation of triplicates of Al^{3+} ($cmol_c\ kg^{-1}$) for Inceptisol A incubated with 0, 6, 12, 24, or 48 $t\ ha^{-1}$ of Loblolly pine, maize or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		With liming											
Residue		Without liming				Loblolly pine				Maize			
Time	Dose ($t\ ha^{-1}$)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
0.75 days	0	3.01	0.08	3.05	0.06	3.38	0.08	0.00	0.00	0.00	0.00	0.09	0.00
	6	3.10	0.11	3.09	0.03	3.08	0.08	0.00	0.00	0.00	0.00	0.08	0.00
	12	2.88	0.15	3.23	0.12	2.81	0.11	0.00	0.00	0.00	0.00	0.00	0.00
	24	2.99	0.12	3.03	0.07	2.64	0.16	0.00	0.00	0.00	0.00	0.00	0.00
	48	3.02	0.05	2.72	0.01	1.90	0.08	0.00	0.00	0.00	0.00	0.00	0.00
30 days	0	2.79	0.14	3.05	0.07	3.32	0.13	0.00	0.00	0.00	0.00	0.00	0.00
	6	2.79	0.06	3.21	0.07	2.98	0.10	0.00	0.00	0.00	0.00	0.00	0.00
	12	2.85	0.14	3.28	0.05	2.23	0.13	0.00	0.00	0.00	0.00	0.00	0.00
	24	2.84	0.12	3.12	0.08	2.14	0.09	0.00	0.00	0.00	0.00	0.00	0.00
	48	2.87	0.04	2.98	0.04	1.30	0.08	0.00	0.00	0.00	0.00	0.00	0.00

Without liming										With liming									
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
90 days	0	2.96	0.12		3.05	0.09		3.26	0.03		0.21	0.04		0.17	0.01		0.54	0.01	
	6	3.08	0.09		3.03	0.03		3.17	0.02		0.18	0.02		0.15	0.02		0.51	0.02	
	12	3.00	0.10		3.02	0.07		2.96	0.01		0.14	0.01		0.15	0.02		0.49	0.06	
	24	3.10	0.07		2.90	0.13		2.88	0.01		0.16	0.01		0.14	0.01		0.54	0.02	
	48	3.16	0.12		2.68	0.11		2.17	0.03		0.12	0.01		0.11	0.01		0.42	0.04	
180 days	0	4.77	0.21		4.61	0.26		5.13	0.01		0.21	0.03		0.22	0.01		0.76	0.03	
	6	4.73	0.12		4.23	0.17		5.29	0.04		0.20	0.03		0.21	0.01		0.72	0.04	
	12	4.69	0.12		4.25	0.19		4.93	0.04		0.19	0.02		0.20	0.01		0.72	0.04	
	24	4.64	0.09		4.16	0.10		5.08	0.03		0.23	0.03		0.18	0.01		0.72	0.04	
	48	4.16	0.14		3.98	0.05		4.38	0.01		0.19	0.03		0.18	0.01		0.67	0.06	

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	5.41	0.03		5.23	0.07		5.33	0.04		0.27	0.02		0.27	0.01		0.68	0.04	
	6	5.27	0.09		5.29	0.19		5.38	0.38		0.24	0.03		0.25	0.03		0.65	0.08	
	12	5.13	0.18		5.16	0.02		5.05	0.09		0.24	0.03		0.24	0.03		0.64	0.01	
	24	5.14	0.12		4.94	0.22		4.97	0.11		0.23	0.03		0.00	0.00		0.69	0.05	
	48	4.89	0.14		4.77	0.11		4.22	0.09		0.18	0.03		0.00	0.00		0.61	0.03	
365 days	0	4.22	0.13		4.09	0.04		3.82	0.01		0.19	0.03		0.16	0.01		0.57	0.01	
	6	4.05	0.08		3.94	0.04		3.70	0.16		0.16	0.01		0.17	0.01		0.51	0.03	
	12	4.10	0.21		4.08	0.11		3.57	0.11		0.17	0.02		0.17	0.02		0.52	0.01	
	24	4.15	0.13		3.91	0.16		3.26	0.11		0.18	0.01		0.00	0.00		0.49	0.03	
	48	4.05	0.20		3.71	0.12		2.72	0.09		0.15	0.01		0.00	0.00		0.49	0.03	

Table 21 - Means and standard deviation of triplicates of Al^{3+} ($cmol_c\ kg^{-1}$) for Inceptisol B incubated with 0, 6, 12, 24, or 48 $t\ ha^{-1}$ of Loblolly pine, maize, or soybean at 0 (0.75), 30, 90, 180, 270, and 360 days.

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
0.75 days	0	2.87	0.14		3.35	0.12		3.09	0.07		0.04	0.01		0.06	0.00		0.08	0.02	
	6	2.86	0.14		3.25	0.03		3.27	0.09		0.03	0.02		0.05	0.01		0.06	0.01	
	12	2.99	0.01		3.22	0.18		3.12	0.26		0.00	0.00		0.05	0.00		0.08	0.01	
	24	2.97	0.03		3.04	0.07		2.81	0.12		0.04	0.04		0.05	0.00		0.05	0.00	
	48	2.93	0.07		2.99	0.16		2.07	0.21		0.07	0.02		0.07	0.03		0.00	0.00	
30 days	0	2.68	0.06		3.24	0.01		4.05	0.01		0.05	0.01		0.03	0.01		0.15	0.01	
	6	2.93	0.15		3.11	0.11		3.70	0.07		0.07	0.01		0.04	0.01		0.00	0.00	
	12	3.05	0.10		3.24	0.09		3.39	0.03		0.06	0.00		0.04	0.01		0.00	0.00	
	24	3.05	0.15		3.24	0.13		2.77	0.06		0.06	0.00		0.04	0.01		0.00	0.00	
	48	3.10	0.16		2.85	0.06		1.38	0.06		0.07	0.01		0.04	0.01		0.00	0.00	

Without liming										With liming									
Residue	Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean			
Time	Dose (t ha ⁻¹)	Mean	Standard deviation	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		
90 days	0	2.67	0.49	3.50	0.09		3.88	0.07		0.00	0.00		0.06	0.01		0.15	0.015		
	6	2.99	0.10	3.55	0.10		3.47	0.09		0.06	0.00		0.08	0.006		0.00	0.00		
	12	3.01	0.09	3.55	0.06		3.06	0.26		0.07	0.06		0.08	0.00		0.00	0.00		
	24	2.93	0.17	3.53	0.09		2.41	0.19		0.07	0.003		0.00	0.00		0.00	0.00		
	48	3.08	0.05	3.28	0.17		1.21	0.03		0.06	0.00		0.00	0.00		0.00	0.00		
180 days	0	3.86	0.05	3.71	0.03		4.10	0.06		0.11	0.01		0.13	0.01		0.11	0.03		
	6	3.90	0.05	3.71	0.06		3.78	0.17		0.14	0.02		0.04	0.006		0.00	0.00		
	12	3.96	0.05	3.74	0.01		3.44	0.12		0.12	0.01		0.04	0.006		0.00	0.00		
	24	3.48	0.06	3.61	0.15		2.62	0.12		0.13	0.01		0.00	0.00		0.00	0.00		
	48	2.70	0.04	3.56	0.13		1.22	0.03		0.27	0.03		0.00	0.00		0.00	0.00		

Treatment		Without liming						With liming											
Residue		Loblolly pine			Maize			Soybean			Loblolly pine			Maize			Soybean		
Time	Dose (t ha ⁻¹)	Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation		Mean	Standard deviation	
270 days	0	4.12	0.05		3.92	0.07		3.64	0.04		0.14	0.03		0.00	0.00		0.11	0.01	
	6	4.22	0.06		3.97	0.03		3.21	0.10		0.14	0.05		0.00	0.00		0.00	0.00	
	12	4.24	0.11		3.90	0.02		2.85	0.06		0.00	0.00		0.00	0.00		0.00	0.00	
	24	4.42	0.03		3.74	0.09		2.15	0.02		0.00	0.00		0.00	0.00		0.00	0.00	
	48	4.39	0.08		3.75	0.17		1.10	0.11		0.15	0.01		0.00	0.00		0.12	0.03	
365 days	0	3.94	0.07		3.29	0.02		3.03	0.07		0.12	0.02		0.00	0.00		0.08	0.01	
	6	3.92	0.11		3.26	0.05		2.70	0.04		0.14	0.01		0.00	0.00		0.11	0.01	
	12	3.92	0.02		3.26	0.06		2.65	0.09		0.14	0.01		0.00	0.00		0.12	0.01	
	24	3.95	0.02		3.08	0.09		1.92	0.04		0.14	0.01		0.00	0.00		0.09	0.02	
	48	3.95	0.02		2.99	0.10		1.13	0.23		0.17	0.02		0.00	0.00		0.09	0.02	

CHAPTER 2: *CHEMICAL CHARACTERIZATION OF BRAZILIAN SOYBEAN STRAW TO MITIGATE SOIL ACIDITY

Carla Gomes de Albuquerque, Antônio Carlos Vargas Motta, Fabiana Gavelaki, Stephen A. Prior,
Jefferson Dieckow

ABSTRACT

Background Soybean is the main legume cultivated in the world, but knowledge of the straw chemical composition is scarce. **Aims** The objectives of this study were to characterize soybean straw from two producing regions in Brazil and evaluate its potential in mitigating the acidity of an oxisol. **Methods** Samples of soybean straw were collected in Paraná and Rio Grande do Sul states, in southern Brazil, and in the state of Bahia, in northeastern Brazil. C and N were quantified in an elemental analyzer, Ca, Mg, K, Na, S, P, Cu, Mn, Zn, V, Ni and Ba by ICP-OES, pH and available alkalinity (OH^-) by titration. An oxisol was incubated with the straw and pH CaCl_2 and Al^{3+} were analyzed after one month. **Results** The straw from the Bahia state presented a higher content of Mg, K and P while C, N, S, OH^- , Cu, Mn, V, Ni and Ba were higher in the residue from the south. The pH increased and Al^{3+} decreased in the oxisol after incubation with the straw, with no difference between the two regions and soil pH correlated with the OH^- ($r = -0.68$) of the southern straw and with the sum of cations ($r = -0.74$) from the Bahia straw. **Conclusion** The chemical quality of the soybean straw depends on the region, varying mainly in terms of fertilization and liming, and the addition of plant material to the soil, regardless of the composition, is beneficial as it reduces acidity.

Keywords: Plant residue. *Glycine max.* acidic soils. Brazilian Cerrado. Oxisol

*Prepared in accordance with standards of Journal of Plant Nutrition and Soil Science

1 INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is a crop of great economic importance worldwide, as it is a source of protein and vegetable oil (OECD/FAO, 2023). Brazil is the world's main producer of the crop, representing 39% of production, with expected production in the 2023/2024 harvest of 316.7 million tons (CONAB, 2023; USDA, 2024). Since 2013/2014, the cultivated area in Brazil has grown from 30,100 ha to 45,600 ha in 2023/2024, with an expected growth of 0.8% per year over the next decade (OECD/FAO, 2023; USDA, 2024). At a national level, the states of Mato Grosso (26%), Paraná (15%), Rio Grande do Sul (14%), Goiás (10%), Mato Grosso do Sul (8%), Minas Gerais (5%) and Bahia (5%) are the main producers (USDA, 2024).

Soybeans were cultivated for the first time in Brazil in 1931 in Rio Grande do Sul, as the characteristics of the region were very similar to the largest producing regions of the crop in the United States, a country that dominated world production at the time (Sousa and Busch, 1998). The states that traditionally dominated soybean cultivation in the country were Rio Grande do Sul, Santa Catarina, Paraná and São Paulo, however, with the increasing expansion of cultivation from the 1960s and 1970s onwards, the states of Mato Grosso, Mato Grosso do South, Goiás, Tocantins, Maranhão, Minas Gerais and Bahia began to be explored in order to expand the growth of culture (Sousa and Busch, 1998). In the last decade, the MATOPIBA (Maranhão, Tocantins, Piauí and Bahia) region has been the greatest expansion in soybean cultivation (Rausch et al. 2019). This area, located in the central region of Brazil, is characterized by the Cerrado-type vegetation, and have soils with contrasting properties with those of states that traditionally dominated soybean production.

The expansion of soybeans in the Cerrado was due to the development of cultivars with characteristics for good development in the region, the improvement of techniques to increase soil fertility, as it has soils responsive to agricultural practices, as well as the flat to gently undulating relief (Fontana and Oliveira, 2015; Sousa and Busch, 1998). Cerrado soils are highly weathered, acidic, with high aluminum (Al^{3+}) contents and saturation m% and low natural availability of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) (Lopes and Guilherme, 2016). In addition to low soil fertility, agricultural production in the Cerrado region has other limitations such as a dry period lasting 5 to 6 months (from April/May to September), low water retention capacity and limited root development due to Ca deficiency and high saturation of toxic Al in the surface layers (Lopes and Guilherme, 2016). In the state of Bahia, where the main area of agricultural production is concentrated in the extreme west of the state, these limitations are added to the predominantly sandy composition, low levels of organic matter, resulting in low soil aggregation (Fontana and Oliveira, 2015).

Oxisols constitute the main group of acidic soils that have been exploited in agriculture in tropical regions, such as the Cerrado, and subtropical regions, such as Paraná and Rio Grande do Sul due to liming and fertilization practices (Fageria and Baligar, 2008). However, the acidification process can be accelerated through the extraction of basic cations such as Ca^{2+} , Mg^{2+} and K^{+} by crops, without adequate replacement, with a consequent increase in the activity of H^{+} and Al^{3+} in the

exchange complex, as well as with fertilizers based on ammonium (Fageria and Baligar, 2008). In Brazil, no-till has been widely practiced in soybean-based cultivation areas, consisting of the adoption of conservation practices of soil preparation, crop rotation and permanent soil cover (Fuentes-Llanilo et al. 2021). Maintaining crop residues promotes soil protection, as well as helping in the process of supplying nutrients to underlying crops through cycling (Maluf et al. 2015). In this sense, the knowledge of the nutritional content and quality of residues from large crops, such as soybeans, is very important.

It is known that covering the soil with crop residue is beneficial because facilitate to maintain a good temperature on the surface and a good stock and infiltration of water, as well as its evaporation, and increases the organic matter (Heckler et al 1998; Maria et al. 2019; Possamai et al. 2022). In this sense, organic materials with a high C/N ratio are more effective, as they have a slower decomposition rate, maintaining soil cover for a long period (Canalli et al. 2019; Heckler et al. 1998). Soybean contributes around 4 Mg ha⁻¹ of dry matter, while the appropriate value would be at least 10 Mg ha⁻¹. However, considering the evolution of the area occupied by soybean cultivation in recent years and the fact that legumes constitute an important source of nutrients for the soil (Fuentes-Llanilo et al. 2021; Possamai et al. 2022), our study contributes to the understanding of the chemical constitution of soybean straw in different environments as there is no literature, to our knowledge, about characterization of the chemical composition of the nutrients, trace elements and available alkalinity (OH⁻) of soybean straw from large crops in order to investigate its potential in nutrient cycling and its benefits in relation to soil acidity.

The decomposition of organic residues by microorganisms results in the production of organic acids, which, if the pK_a of the carboxylic groups (-RCOOH) is greater than the pH of the soil, there is an association of H⁺ in the soil with these functional groups, resulting in an increase in the pH (Berg and McClaugherty, 2003; Brady and Weil, 2013). If the pK_a of these groups is lower than the soil pH, deprotonation occurs with the formation of organic anions (-RCOO⁻) and acidification (Rukshana et al. 2012). There are several other reactions resulting from the decomposition of organic materials that can alleviate soil acidity, such as decarboxylation of organic anions and ammonification (Sakala et al. 2004; Souza; Miranda; Oliveira, 2007; Tang; Yu, 1999). The alkalinity of plant residue could mitigate soil acidity through its decomposition and this characteristic is defined by the difference between the base content (Ca²⁺, Mg²⁺, K⁺ and Na⁺) and the content of inorganic anions (H₂PO₄⁻, SO₄²⁻ and Cl⁻) being directly linked to the amount of organic anions in the residue, with which the bases are associated (Vanzolini et al. 2017).

The objectives of this study were to characterize the soybean straw in two important producing areas in Brazil, with contrasting climatic and soil conditions and to determine whether there are differences in the chemical composition depending on the region. Furthermore, we evaluate the potential for mitigating the acidity of these soybean straws on acidic soil (Oxisol).

2 MATERIAL AND METHODS

2.1 COLLECTION AND CHARACTERIZATION OF SOYBEAN STRAW

Soybean straw was collected manually, minimizing both the collection of residues from previous crops and soil, in delimited areas of 0.25 m² in commercial farms located in five municipalities in the state of Paraná and one municipality in the state of Rio Grande do Sul, in southern Brazil (n = 51), as well as in four municipalities in the western of the state of Bahia, in northeastern Brazil (n = 47) (Table 1). In Paraná, the cultivars collected were NS 6906 IPRO, HO PIRAPÓ IPRO, NEO 610 IPRO, BMX ZEUS, Nidera NA5909, DONMARIO DM57i52, DONMARIO DM53I54 IPRO, Nidera NS5505i2X; in Rio Grande do Sul the cultivar was DONMARIO DM59I58. In western Bahia, the following cultivars were collected: Domínio IPRO, M8349 IPRO, GH1687 IPRO, 58B28 IPRO, HO Juruena IPRO and Extrema IPRO (characteristics of each cultivar are in Supplementary material – Table 1). The collected material consisted of the aerial part of the soybean plant (mostly leaves, branches and stems, and some pod remains) that were deposited under the ground after the grain harvest, in the 2022/2023 crop season, in the months of February to April 2023. The straws were stored in paper bags and dried in an oven at 65°C for 4 h and weighed to determine the dry matter. They were then homogenized, grounded, and sieved for characterization (< 1 mm).

TABLE 1 – Location of soybean straw collections, climate according to Koppen, number of samples collected in each location and average dry matter (g) collected in the field (in 0.25 m²).

Municipality	Parent material	¹ Climate	Number of samples	² Dry matter (g)	Dry matter (kg ha ⁻¹)
Lidianópolis-PR	Basalt	Cfa	9	147.8	5911.5
Turvo-PR	Basalt	Cfb	3	251.6	10065.3
Luiziana-PR	Basalt	Cfb	3	249.1	9962.7
Lapa-PR	Sedimentary rocks	Cfb	9	129.4	5177.8
Fernandes Pinheiro-PR	Sedimentary rocks	Cfb	21	182.9	7316.6
Erechim-RS	Basalt	Cfa	6	116.4	4655.8
Luís Eduardo Magalhães-BA	Sedimentary rocks	Aw	2	76.0	3040.8
Formosa do Rio Preto-BA	Sedimentary rocks	Aw	3	162.8	6513.3
Barreiras-BA	Sedimentary rocks	Aw	18	106.3	4251.7
Riachão das Neves-BA	Sedimentary rocks	Aw	24	169.2	6987.4

¹Cfa – temperate, humid, hot summer; Cfb – temperate, humid, cool summer; Aw – rainy tropical, dry winter.

²Average of the dry matter of all samples of soybean straw collected in each municipality.

The Ca, Mg, P, S, Cu, Mn, Zn, Ni, Ba and V contents were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian 720-ES) and K and Na using a

flame photometer. Extractions were made by digesting 200 mg of plant residue grounded with 4 mL of HNO_3 65% P.A, 1 mL de H_2O_2 and 3 mL of Milli-Q water in a microwave (Mars Xpress 6, CEM) with heating at 1300 W for 20 min at a maximum temperature of 180°C for 15 min. The extracts were filtered through slow filter paper in a 25 mL flask and the volume was completed with ultrapure Milli-Q water. Total C and N were determined in an elemental analyzer (ELEMENTAR -Vario EL III) and pH was determined in Reverse osmosis H_2O in a ratio of 1:10 (m/v) (Teixeira, 2017).

The straws available alkalinity was determined through titration using 0.5 g of each plant residue and addition of 25 mL of 0.015 mol L^{-1} CaCl_2 solution, followed by shaking for 15 min. The pH of each residue was determined and titrated with H_2SO_4 5 mmol L^{-1} until pH 4 was reached (Sakala et al. 2004).

2.2 SOYBEAN STRAW INCUBATION EXPERIMENT IN SOIL

In plastic bags, 150 g of air-dried soil were weighed and mixed with amounts of soybean straw equivalent to 48 t ha^{-1} , considering a soil layer of 0-0.2m. A high dose was tested to simulate a possible cumulative effect over several years. The mixture of soil and straw was homogenized and then the water content in the mixture was adjusted to 80% of field capacity adding reverse osmosis water. All bags were closed using an elastic band and maintaining aeration through a plastic tube, to maintain the aerobic conditions of the experiment, at approximately 25°C in a greenhouse for 30 days.

2.2.1 Incubated soil

An Oxisol (Soil Taxonomy; Latossolo - SiBCS), horizon A, was selected and collected in the Campos Gerais region, in Paraná state. The soil was air-dried, sieved ($< 2\text{ mm}$) and analyzed for: pH CaCl_2 0.01 mol L^{-1} (1:2.5 m/v); Ca, Mg and Al, extracted with KCl 1 mol L^{-1} and determined by flame atomic absorption spectroscopy and titration with 0.025 mol L^{-1} NaOH and bromothymol blue indicator, respectively; P and K, extracted with Mehlich-I and determined by colorimetry and flame photometry, respectively. Particle size analyzes to determine the sand, silt and clay fractions were carried out using the pipette method and total C and N were determined using an elemental analyzer (ELEMENTAR -Vario EL III) (Teixeira, 2017). The results of the chemical analyzes were: pH CaCl_2 = 3.76; Al^{3+} = $1.37\text{ cmol}_c\text{ kg}^{-1}$; $\text{H}+\text{Al}$ = $9.0\text{ cmol}_c\text{ kg}^{-1}$; Ca^{2+} = $0.66\text{ cmol}_c\text{ kg}^{-1}$; Mg^{2+} = $0.28\text{ cmol}_c\text{ kg}^{-1}$; K^+ = $0.08\text{ cmol}_c\text{ kg}^{-1}$; P = mg kg^{-1} ; C = 19.82 g kg^{-1} e N = 1.2 g kg^{-1} . The particle size analyzes were: sand = 600 g kg^{-1} ; silt = 50 g kg^{-1} and clay = 350 g kg^{-1} .

2.2.2 Chemical analysis of incubated soils

After 30 days of incubation with straw, the soil was dried in an oven at 40°C and sieved ($<2\text{mm}$), and pH (1:2.5 m/v, CaCl_2 0.01 mol L^{-1}) and Al^{3+} (KCl 1 mol L^{-1}) were analyzed. The pH was determined using a table pH meter equipped with a glass electrode and the available Al^{3+} was

analyzed by titration using a digital burette with 0.025 mol L NaOH⁻¹ and bromothymol blue indicator (Teixeira, 2017).

2.3 EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

The results of the chemical composition (macro and micronutrients and trace elements), pH, C, N and alkalinity of soybean straw were evaluated by separating them in the southern (Paraná and Rio Grande do Sul straws) and northeastern regions (western Bahia region) of Brazil using the Mann-Whitney test at 5% significance, with boxplots to represent the medians and data distribution through graphs made in the OriginLab software. Correlations (Spearman) were evaluated between pH, available alkalinity and nutrients of soybean straw among themselves, for both regions.

The soil incubation experiment with soybean straw was carried out following a completely randomized experimental design, resulting in 98 experimental units, considering each straw sample one repetition, and then separating in two groups: Southern (n = 51) and Northeastern (n = 47). pH CaCl₂ and Al³⁺ results were subjected to the Shapiro-Wilk normality test at 5% significance. Obtaining normality, analysis of variance (ANOVA) and the Tukey test were performed to evaluate the difference between the control treatment (without straw addition) and the straw from the south and northeast. Correlations (Pearson) were evaluated between the main chemical attributes of alkalinity of soybean straw (pH, available alkalinity and sum of cations) and pH CaCl₂ e Al³⁺ of the soil incubated with straw. All statistics were done using RStudio software.

3 RESULTS

3.1 CHEMICAL CHARACTERIZATION OF SOYBEAN STRAW

There was a significant difference ($P < 0.05$) between Mg, K, Na, P, S, OH⁻, Cu, Mn, Ba, V, Ni, C and N (Figures 1 and 2) in soybean straw from the southern and northeastern regions of Brazil. Soybean straw from the Northeast presented significantly higher medians ($P < 0.05$) of Mg, K, Na and P than straw from the southern region. In the south, the straw presented higher S contents (Figure 1a and b). Available alkalinity was higher in straw collected in Paraná and Rio Grande do Sul, as well as the C content and N (Figure 2b, c and d). Soybean straw from the south also showed higher levels of Cu, Mn, Ba, V and Ni (Figure 1c).

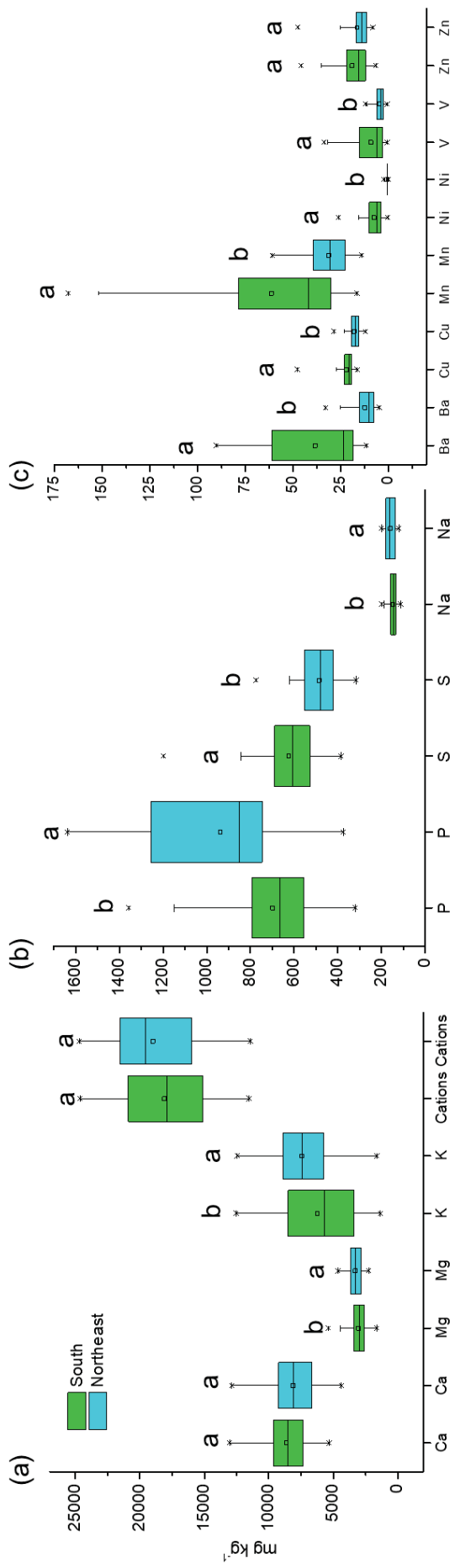


FIGURE 1 – Boxplots of Ca, Mg, K, Cations (Ca+Mg+K+Na contents) (a), P, S, Na (b) and Ba, Cu, Mn, Ni, V and Zn contents in soybean straw collected in the south (green) and northeast regions (blue) from Brazil. Contents representations with same letters do not differ from each other according to the Mann-Whitney test, at 5% significance ($P > 0.05$).

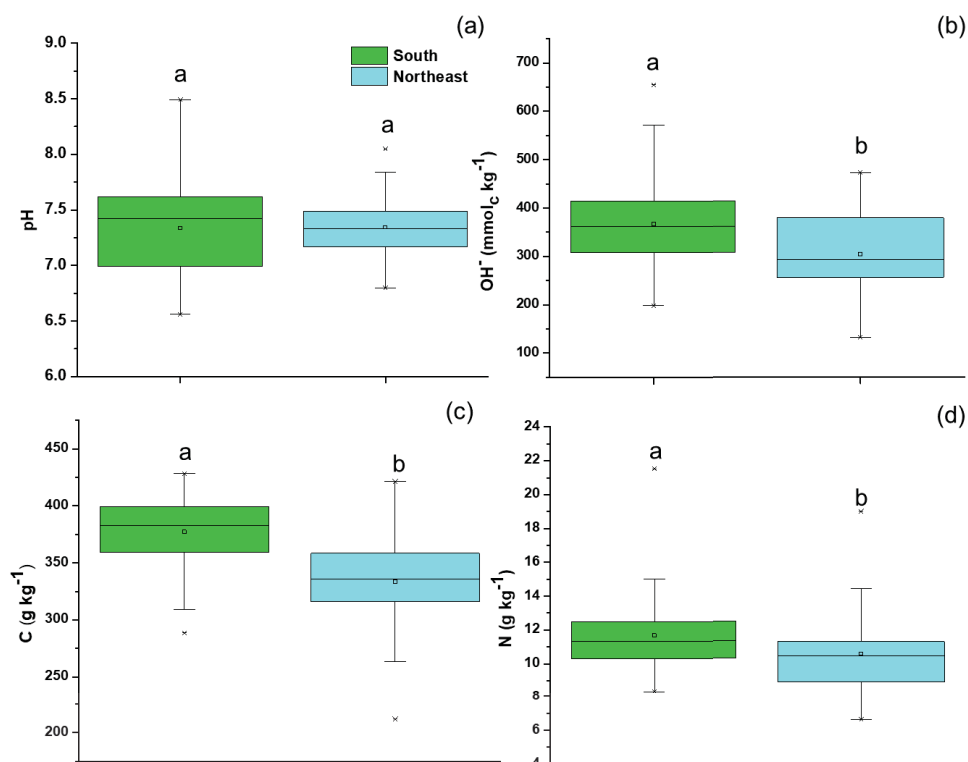


FIGURE 2 - Boxplots of pH (a), OH^- (b), C (c) and N (d) in soybean straw collected in the southern regions (green) and northeast (blue) of Brazil. Contents representations with same letters do not differ from each other according to the Mann-Whitney test, at 5% significance ($P > 0.05$).

The pH of soybean straw in the southern region (Figure 3a) had a moderate correlation ($\rho = 0.57$, $P < 0.01$) with their Mg content, as well as available alkalinity (OH^-) ($\rho = 0.66$, $P < 0.01$). The available alkalinity of straw in the southern region also had a moderate correlation with the sum of cations ($\rho = 0.67$, $P < 0.01$) (Figure 3a). Soybean straw from the northeast (Figure 3b) region presented Ca levels with a moderate correlation with its pH ($\rho = 0.59$, $P < 0.01$) and with its S content ($\rho = 0.59$, $P < 0.01$). The available alkalinity of soybean straw from the northeast region correlated with its pH ($\rho = 0.51$, $P < 0.01$), with its K content ($\rho = 0.57$, $P < 0.01$) and showed a strong correlation ($\rho = 0.73$, $P < 0.01$) with the sum of cations. The pH of straw from the northeast also correlated with the sum of cations ($\rho = 0.50$, $P < 0.01$).

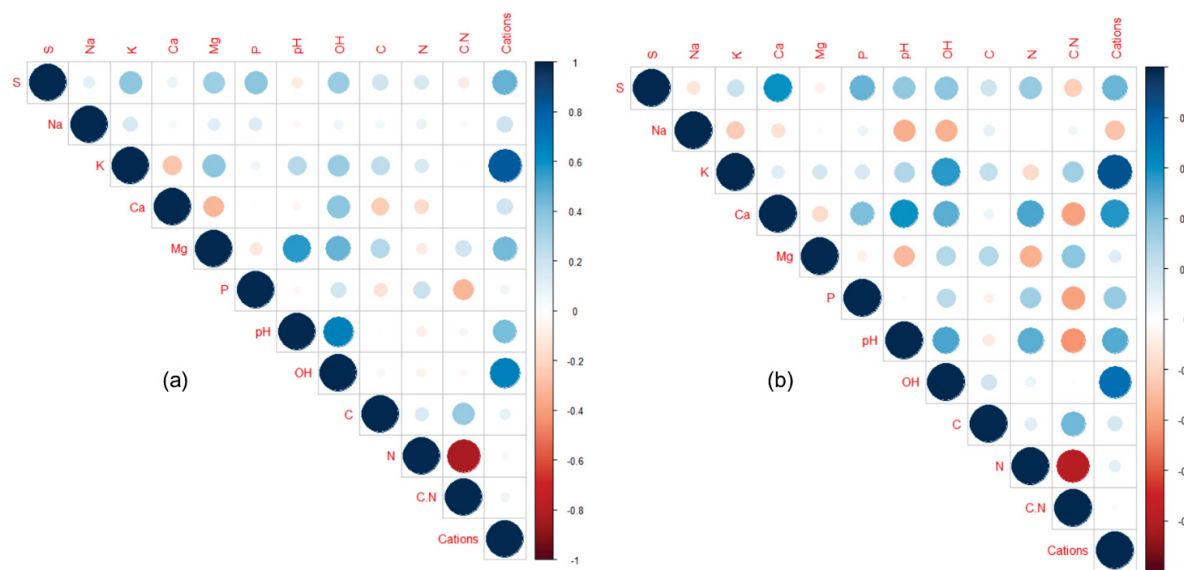


FIGURE 3 – Representation of Spearman correlation coefficients (ρ) among the nutrients, pH, C/N and OH^- of soybean straw from the southern (a) and northeastern (b) regions of Brazil. Cations = Σ Ca, Mg, K and Na.

3.2 pH CaCl_2 AND Al^{3+} OF SOIL INCUBATED WITH SOYBEAN STRAW

Incubation with soybean straw increased the pH CaCl_2 of the natural soil ($\text{pH}_{\text{control}} = 3.74$) by approximately 0.30 units (Figure 4a). Soil exchangeable Al ($\text{Al}^{3+}_{\text{control}} = 1.19 \text{ cmol}_c \text{ kg}^{-1}$) decreases by approximately $0.40 \text{ cmol}_c \text{ kg}^{-1}$ when incubated with soybean straw for 30 days (Figure 4b). There was no significant effect on soil pH and exchangeable Al after incubation with straw from different regions of the country ($P > 0.05$) (Figure 4).

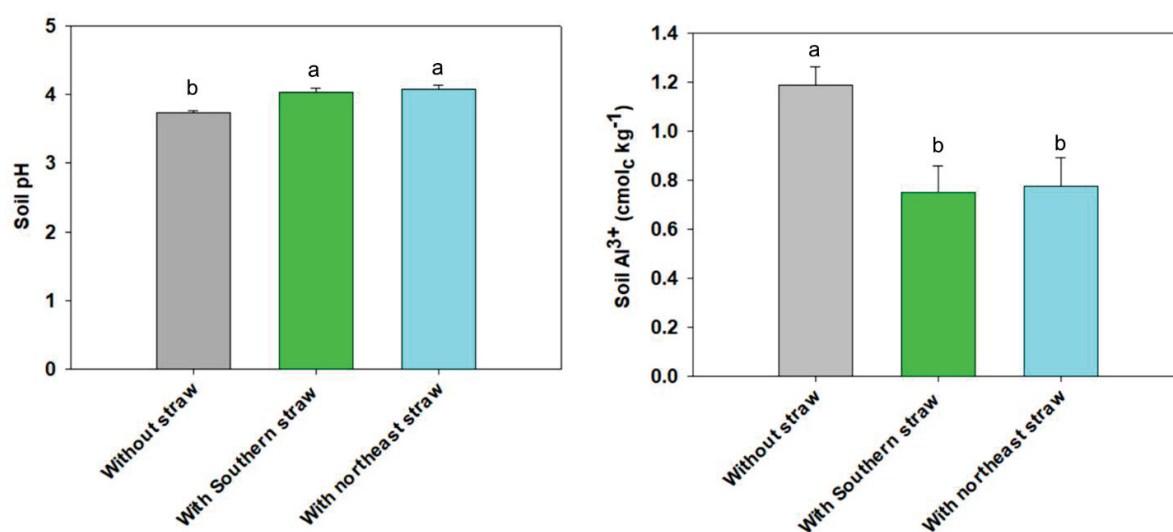


FIGURE 4 – Average pH CaCl_2 (a) and Al^{3+} (b) of the soil in the control treatment (without straw – gray), with soybean straw from the south region (green) and with straw from the northeast region (blue) of Brazil, after incubation for 30 days. Treatments with the same letters do not differ from each other according to the Tukey Test, at 5% significance.

The attributes of soybean straw from the southern region (Figure 5a) that correlated with the pH CaCl₂ of the incubated soil were available alkalinity ($r = 0.68$, $P = 0$) and the sum of cations ($r = 0.51$, $P < 0.01$). The Al³⁺ of the incubated soil correlated with the available alkalinity of the straw ($r = -0.59$, $P = 0$), as well as with the pH CaCl₂ resulting from incubation ($r = -0.80$, $P = 0$) (Figure 5a). The available alkalinity of the straw in the northeast region (Figure 5b) also correlated with the result of the pH CaCl₂ of the incubated soil ($r = 0.62$, $P = 0$). The sum of cations in the straw influenced the final pH of the soil ($r = 0.74$, $P = 0$). The exchangeable Al of the soil resulting from incubation with straw was influenced by the available alkalinity ($r = -0.52$, $P < 0.01$), by the pH CaCl₂ of the soil ($r = -0.69$, $P = 0$) and with the sum of cations from soybean straw ($r = -0.62$, $P = 0$) (Figure 5b).

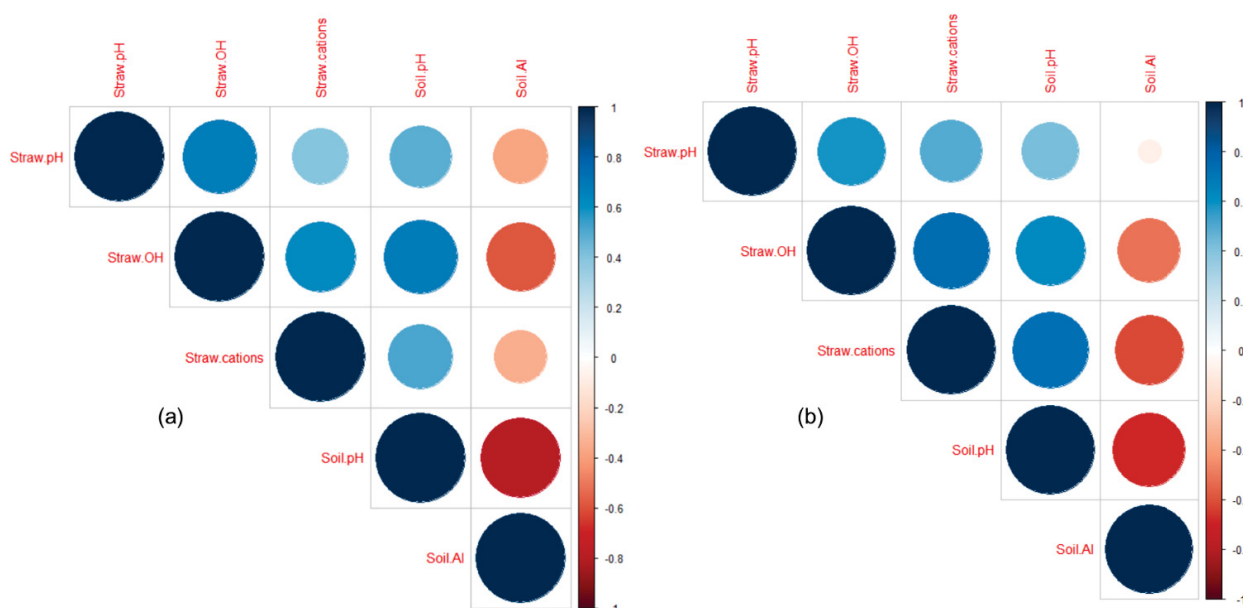


FIGURE 5 – Representation of Pearson correlation coefficients (r) between pH (Straw pH), available alkalinity (Straw OH⁻) and cations (Straw cations - Σ = Ca, Mg, K and Na) from soybean straws from the southern (a) and northeastern (b) regions of Brazil with the pH CaCl₂ (Soil pH) and Al³⁺ (Soil Al) of the soil incubated for 30 days with the respective straws.

4 DISCUSSION

The differences in the chemical composition of soybean straw from the Paraná and Rio Grande do Sul states (south) and western Bahia state (northeast) in Brazil can be attributed to several factors such as the characteristics of the soil, especially parent material, texture and fertility. Yet, climate, which affects temperature, light and rainfall distribution, capacity exploration of the root system, the characteristics of the cultivars, which must present different physiological behaviors to guarantee good productivity according to the environment in which they are used and even the use of herbicides that have the capacity to complex with cations (Tagliapietra et al. 2022; Zobiole et al. 2012) can affect soybean straw composition.

Regarding the soils where the soybean straws were obtained, the western Bahia has sedimentary parent material (sandstones from the Urucuia Formation) and predominance of sand fraction in the granulometry (Supplementary material - Table 2) (Fontana et al. 2016). This Cerrado region has natural highly weathered soils with low values of pH, Ca^{2+} , Mg^{2+} , K^+ , P, low CEC and high Al^{3+} saturation, but with good constructed fertility with liming and the use of fertilizer, as observed in the soil analyzes in Supplementary material, Table 2 (Fontana et al. 2016; de Freitas et al. 2014). In cultivation areas, soil pH values are normally close to neutrality, with good Ca^{2+} and Mg^{2+} and Al^{3+} contents very close to zero (de Freitas et al. 2014). The soils of Paraná and Rio Grande do Sul are characteristic of subtropical regions, clayey with high organic matter, which contributed to the increase in the predominance of negative charges and CEC (Costa et al. 2004). The differences of the soils in the two regions impact the chemical composition of the plant as they affect the availability and absorption of nutrients.

The macronutrient levels in soybean straw followed the order: $\text{C} > \text{N} > \text{Ca} > \text{K} > \text{Mg} > \text{P} > \text{S}$ (Figures 1 and 2). For micronutrients, the levels were higher in $\text{Mn} > \text{Cu} > \text{Zn} > \text{Ni}$. Ba was the trace element most found in soybean straw in both regions, followed by V. The levels of N, P, K and S found in soybean straw were lower than the levels obtained by Kurihara et al. (2013) in the aerial part of soybeans, while the Ca, Mg, Mn and Zn contents were equivalent and the Cu content was higher. Compared to the study of Zobiolo et al. (2012), the levels of N, P, K, S, Zn and Mn in our study were lower, Ca and Mg were equivalent and Cu had a higher content. The differences between the levels found in our study and the literature are probably due to the decomposition of part of the plant and the release of nutrients since the soybean residue was collected after the grain harvest. Mainly, N and K contents have a short half-life of release, but there is a strong climatic influence, such as rainfall distribution, which can accelerate this process (Padovan et al. 2006).

In the plant, Ca has low mobility and low translocation to the grains (low harvest rate), resulting in high concentration in the stem, leaves and petioles (Marschner, 2012; Tagliapietra et al. 2022). In the case of legumes such as soybeans, Ca is a very important element in biological N fixation, especially in the initial phases of interaction between plant and rhizobia in nodule formation. Because of this, N_2 -fixing plants demand more Ca (Sousa et al. 2007). Ca is located in the plant's cell wall and is the macronutrient with the lowest rate of mineralization through decomposition, which probably partially explains the equivalent levels in both locations (Figure 1a) (Maluf et al. 2015; Padovan et al. 2006).

Mg, K and P, which were observed in higher concentrations in soybean straw from western Bahia (Figure 1a and b), have high mobility within the plant (Marschner, 2012; Tagliapietra et al. 2022). Mg (together with Ca^{2+}) is highly replenished in the soil through liming, in both locations, reaching levels considered adequate in cultivation areas in Cerrado soils (Fontana et al. 2016). The use of potassium fertilizers in cultivated soils in western Bahia maintains good K^+ levels for plants, even with leaching potential from the soils in the region (Donagemma et al. 2016). The P is the nutrient most limiting to the productivity of soils in the Cerrado, however, in cultivated soils for several years with phosphate fertilization, these areas currently have average or adequate levels of P (Fundação MT, 2023). Cerrado soils formed from sandstone are advantageous in terms of P

availability compared to other tropical soils as the low clay content reduced their retention in the colloids which was showed by Barbosa et al. (2022) and can increase its absorption by crops (de Freitas et al. 2014).

The higher S values in soybean straw from the southern region (Figure 1b) compared to straw from the Cerrado may be related to the respective N value (Figure 2d), since these two nutrients have coordinated assimilation in the plant (Tagliapietra et al. 2022). Biological N fixation is responsible for 60% of the nitrogen that is assimilated in soybeans (Fundação MT, 2023). In acidic, sandy tropical soils poor in organic matter, such as the soils of western Bahia, there are low concentrations of S in the soil because organic matter is one of the main sources of S and due to the sandy texture of the soil, organic matter is susceptible to decomposition (Fundação MT, 2023; Tagliapietra et al. 2022).

The Zn, Mn and Cu are naturally deficient micronutrients in the Brazilian Cerrado (Lopes and Cox, 1977). This can be a combination of poor concentration of parent material and high degree of weathering. Of the 51 straws collected in the south, 42% (n=21, 15 in the state of Paraná and 6 in Rio Grande do Sul) were cultivated in areas with soils derived from basalt and 48% (n=30) in soils originating from sedimentary rocks (Brazil, 1973; Mineropar, 2001). Western Bahia constitutes a homogeneous area in terms of parent material, with the entire region being derived from sediments (Fontana et al. 2016). In general, the highest level of Fe, V, Mn, Cu, Co, Zn and Ni can be found in soil formed under igneous basic rock such as basalt with clayey texture in opposite to formed under sandstone with sandy texture (Magri et al. 2022; Motta et al. 2020; Suppi et al. 2022), which explains the higher levels in soybean straw sampled in the south (Marques et al. 2004). The weathering can also play a role to metal concentration since some elements can be decreased because of loss such as Mn (Silva et al. 2022; Suppi et al. 2018) and concentrated such as Fe (Silva et al. 2022). Holmgren et al. (1993) did a large soil survey and found inverse relationship with Zn, Cu and Ni with weathering and CEC. These could explain the higher concentration of Ba, Cu, Mn, Ni and V in the straws from south than Bahia. However, it could not explain the similarity of Zn values between the regions and low difference for Cu. This fact could be related to addition of Cu and Zn to build up soil fertility as corrective fertilization (high rate) in the initial preparation of soil as well as later by supplementation application during sowing, especially for Zn, following research center indication of Cerrado region (Sousa and Lobato, 2004).

The characterization of nutrients and alkalinity of straw (Figure 3) showed a high correlation ($r > 0.6$) between available alkalinity (OH^-) and plant cations, regardless of the region where they were grown. When the plant absorbs cations, H^+ is extruded into the rhizosphere to maintain chemical balance (Sousa et al. 2007). Depending on the legume, 37 to 49 mg H^+ are released per gram of N fixed, increasing its alkalinity in relation to other crops (Cooper and Scherer, 2012).

The available alkalinity (OH^-) of soybeans in this study (362.8 $\text{mmol}_e \text{ kg}^{-1}$ in the south and 293.4 $\text{mmol}_e \text{ kg}^{-1}$ in northeast) were lower than the value found for characterization of soybean by Albuquerque et al. (2024, personal communication) (541.3 $\text{mmol}_e \text{ kg}^{-1}$) and Sakala et al. (2004) (577 $\text{mmol}_e \text{ kg}^{-1}$). However, in our study, the straw was collected after the grain harvest (after the final of a cycle of the plant), meaning that there was more time to absorption of P and S occur, which reduces the alkalinity through extrusion of OH^- to the rhizosphere. The OH^- value was significantly higher in

straw from the south (Figure 2b), possibly due the high P content in Cerrado straw (Figure 1b) may have caused high extrusion of OH^- from the plant, reducing the available alkalinity of soybean residue from this region.

Incubating soybean straw with acidic soil for one month increased the pH and decreased exchangeable Al (Figure 4a and b) regardless of which region the straw came from. Regardless of the chemical attributes of the plant residue, the straw decomposition is beneficial to alleviate soil acidity. The pH ($r = 0.68$) and exchangeable Al ($r = -0.59$) of the soil incubated with straw from the southern region (Figure 5a) had a higher correlation with the available alkalinity (OH^-) of the plant than the soil incubated with straw from the northeast region ($r = 0.62$ and $r = -0.52$, respectively) (Figure 5b). This can be attributed to the significantly higher ($P < 0.05$) OH^- value in southern soybean straw (Figure 2b). Release of available alkalinity (OH^-) directly affects soil pH as it decreases the activity of H^+ in the soil solution and attenuates the activity of Al^{3+} by hydrolysis, forming $\text{Al}(\text{OH})_3$, which is unavailable to plants (Abdulaha-Al Baquy et al. 2017).

The sum of cations in straw from the western Bahia (Figure 5b) had a more relevant impact on soil pH, with a much higher correlation ($r = 0.74$) than that of these two attributes in the incubation with straw from south ($r = 0.51$) (Figure 5a). The correlation of the soil Al ($r = -0.62$) with the sum of cations of western Bahia straw (Figure 5b) did not occur with the same attribute from the southern straw ($P > 0.05$) (Figure 5a). The release of cations from decomposed organic material alleviates the acidity of the soil, as it replaces H^+ and Al^{3+} in the exchange complexes and increases base saturation (Marschner and Noble, 2000).

These incubation results demonstrate that the available alkalinity of soybean straw from the south contributed more significantly to the increase in pH as well as the decrease in Al^{3+} in the soil, while with straw from western Bahia the sum of cations was more important in this sense. However, regardless of the chemical attribute of the straw (OH^- or sum of cations), the pH and final exchangeable Al of the incubated soil did not differ depending on the origin of the residue.

According to Barth et al. (2018), in a study of nutrient export by soybean crops in the state of Paraná, of a total of 15 g Ca kg^{-1} of crop biomass, only 2.9 g of Ca was removed from the system in the form of grains per kg of dry matter, which represents 19% of the Ca absorbed by the plant. The Ca that was not collected in the grains remained in the system, mitigating the acidification caused by Ca absorption. Most of the absorbed Mg was also returned to the system (64%). The replacement of exported nutrients is done by returning them to the system from the moment that the plant residue is decomposed through nutrient cycling (Pereira et al. 2017). The present study showed that, in addition to the replacement of cations such as Ca^{2+} , Mg^{2+} and K^+ , there is a great contribution from the crop residues that covers the soil such as soybean in providing alkalinity in the form of OH^- which can help to alleviate the effects of soil acidification.

5 CONCLUSIONS

The levels of inorganic components of soybean straw from Brazilian southern states (Paraná and Rio Grande do Sul) differed from the levels founded in straw from western region of Bahia state.

These differences are marked by higher contents of C, N, S, available alkalinity (OH^-), Cu, Mn, Zn, Ba, V and Ni for straw collected in Paraná and Rio Grande do Sul, while higher values of Mg, K and P are founded for soybean straw from western Bahia. The nutritional differences in straw from the two regions are due to a set of factors inherent to each location, such as soil characteristics, the amount of sand and organic matter, and the fertilization and liming management adopted.

The incubation of an Oxisol with straw from both regions increased the pH and decreased exchangeable Al in the soil, regardless of where the organic material came from, and the decrease in acidity was correlated with the available alkalinity (OH^-) of the southern straw and the sum of cations in the straw from western Bahia. It has been demonstrated that, regardless of the chemical quality of the residue, the effect of adding plant residue is positive and moderately reduces soil acidity.

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SUPPLEMENTARY MATERIAL

TABLE 1 – Characteristics of the varieties of soybean straw collected in commercial farms in Paraná, Rio Grande do Sul e Bahia states (Brazil).

Variety	Growth habit	Cycle	Transgenic
NS 6906 IPRO	Indetermined	Short maturity	IPRO
HO PIRAPÓ IPRO	Indetermined	Standard maturity	IPRO
NEO 610 IPRO	Indetermined	Short maturity	IPRO
BMX ZEUS IPRO	Indetermined	Short maturity	IPRO
Nidera NA5909	Indetermined	Short maturity	¹ RR
DONMARIO DM57152 IPRO	Indetermined	Standard maturity	² IPRO
DONMARIO DM53154 IPRO	Indetermined	Short maturity	IPRO
Nidera NS5505 i2X	Indetermined	Standard maturity	³ i2X
DONMARIO DM59158 IPRO	Indetermined	Short maturity	IPRO
Domínio IPRO	Indetermined	Standard maturity	IPRO
M8349 IPRO	Determined	Short maturity	IPRO
GH1687 IPRO	Indetermined	Standard maturity	IPRO
58B28 IPRO	Indetermined	Standard maturity	IPRO
HO Juruena IPRO	Determined	Late maturity	IPRO
Extrema IPRO	Indetermined	Standard maturity	IPRO

¹Roundup ready biotechnology = resistance to glyphosate; first generation of transgenic.

²Intacta RR2 PRO = RR biotechnology plus Cry1Ac and Cry 1F proteins that added resistance to caterpillars into; second generation of transgenic.

³IPRO plus Cry1A105 + Cry1Ab2 proteins that added more resistance to some other caterpillars; third generation of transgenic.

TABLE 2 – Chemical analysis of macro and micronutrients and soil particle size in the locations where the soybean straw samples were collected in western Bahia.

Municipality	N° of samples	pH	CaCl ₂	K ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	Base saturation (%)	P	C	Cu	Fe	Mn	Zn	Sand	Silt	Clay
						cmol _c dm ⁻³			mg dm ⁻³	g dm ⁻³		mg dm ⁻³					g kg ⁻¹
Riachão das Neves-BA	3		5.3	0.07	1.5	0.8	0	56	10.7	8	0.2	73	5	0.6	711	75	214
Riachão das Neves -BA	3		5.2	0.05	1.4	0.7	0	57	26.1	6	0.4	71	5	0.8	759	70	171
Barreiras-BA	3		5.2	0.05	1.7	0.9	0	61	25.7	6	0.3	61	4	1.8	770	89	141
Barreiras-BA	3		5.2	0.03	1.2	0.4	0	49	14.7	6	0.3	57	4	1.2	765	90	145
Barreiras -BA	3		5.0	0.04	1.6	0.6	0	46	10.4	7	0.4	53	4	0.8	708	115	177
Barreiras -BA	3		4.8	0.09	1.5	0.3	0.12	48	39.4	8.5	2.4	66	9.2	4.5	755	25	220
Barreiras -BA	3		4.9	0.07	1.7	0.3	0.15	43	19.6	9.3	1.0	58	7.9	4.7	730	25	245
Barreiras -BA	3		5.6	0.05	1.9	0.7	0	64	49	8	1.2	48	10.5	6	793	107	100
Formosa do Rio Preto-BA	3		5.5	0.06	2.2	1.1	0	63	10.5	9	0.4	130	4.5	0.9	673	73	254
Luís Eduardo Magalhães-BA	2		5.9	0.03	1.5	0.8	0	70	15.6	6	0.2	54	5	1.5	796	112	92
Riachão das Neves-BA	3		5.3	0.09	2.2	0.8	0	76	29.4	6.8	0.2	27	5.2	1.6	830	0	170
Riachão das Neves-BA	3		5.3	0.18	2.9	1.0	0	83	25.1	6.1	1.2	22.3	11.1	3.7	760	10	230
Riachão das Neves-BA	3		4.6	0.14	2.4	0.9	0.1	84	25.4	9.3	0.8	19.2	8.1	3.7	760	10	230
Riachão das Neves-BA	3		5.1	0.15	2.3	0.9	0	73	26.2	7.1	0.9	19.1	9.1	3.2	820	10	170
Riachão das Neves-BA	3		5.5	0.13	2.4	1.1	0	83	3.8	4.7	0.2	35.3	2.1	0.55	800	10	190

*Soil from one locality from Riachão das Neves (BA) where three samples were collected was not analyzed.

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