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SOIL FERTILITY EVALUATION OF ACID COARSE-TEXTURED ULTISOLS FOLLOWING CO-APPLICATION OF NATURAL AND SYNTHETIC LIME-PHOSPHORUS AMENDMENTS

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Abstract

Soil acidity and associated phosphorus (P) fixation in highly leached humid tropical soils are major constraints to their agronomic productivity. They thus require effective acidity-alleviating cum P-supplying fertility management. This study assessed the potential of co-application of wood ash (WA) and calcium oxide (CaO) as natural and synthetic limes with rock phosphate (RP) and single superphosphate (SSP) as natural and synthetic P-fertilizers, respectively for acid coarse-textured Ultisols. The WA and CaO were added at 157 and 5 kg ha^{-1} equivalents, and RP and SSP at 50 and 333 kg ha^{-1} equivalents, respectively to 5-kg potted soils. Over 9 weeks, treatment effects in the soil evaluated on soybean growth showed enhancements. Relative to the control, soil pH increased in WA/WA+RP by 107%-121%; the highest relative increases in total N were in WA+RP (2,350%), available P in WA+SSP (520%), and $K^+/Ca^{2+}/Mg^{2+}$ and base saturation in WA (50%-391%), with highest N-P-K uptake from WA+RP (450%-600%). The highest relative increases in above-soil plant growth and dry matter were in WA+RP/WA+SSP/CaO+SSP (63%-102% and 86%, respectively). Treatment residual effects over also 9 weeks showed similar nutrient-uptake/growth trends. Agronomic responses to treatment largely reflected soil pH-regulated differences in soybean uptake of P found to be linearly related to soil available P. Unlike WA, CaO needs P-fertilizer to improve soil productivity. Overall, however, WA+RP/WA+SSP/CaO+SSP is suggested for the soils.

***Key words**: soil acidity, soil amendments, wood ash, rock phosphate, soybean growth.*

INTRODUCTION

Soil nutrient depletion and degradation have been the major cause of decline in crop yields and per capita food production in sub-Saharan Africa (Henao & Baanante, 2006; Obalum et al., 2012). These problems are aggravated by unsustainable use of mineral fertilizers (Ayuke et al., 2007). There is even a greater challenge in acid soils, which according to Chude et al. (2005), are soils with a pH < 5.5. Acid soils are characterized by complex interactions among soil physical, physicochemical and biological properties which limit nutrient availability, plant growth and crop yields (Fageria & Baligar, 2008). Low yields in acid soils are mainly attributed to aluminum (Al) toxicity and high phosphorus (P)-fixing potential (Fink et al., 2014; Ugwu et al., 2024a).

Soybean (*Glycine max* L.) which belongs to the Fabaceae family is highly valued in the world for its oil (21%) and protein (39-40%) content (Hou et al., 2009). In Nigeria, soybean is in high demand due to its competitive uses especially as a raw material for the food and feed industries (Obalum et al., 2011). The major challenge in increasing its current production to meet this continuously growing demand is the acidic nature and low nutrient status of the soils (Adeyeye et al., 2014). Nutrient elements such as potassium (K), calcium (Ca) and magnesium (Mg) are deficient in acid soils (Keino et al., 2015). High concentrations of Fe^{3+} and Al^{3+} in acid soils form less soluble phosphates thus reducing the concentration of available P (Penn & Camerato, 2019). Phosphorus plays an essential role in many physiological processes (Onasanya et al., 2009). Its deficiency affects the growth and proliferation of N-fixing bacteria (Míguez-Montero et al., 2020), nodule formation and functioning (Bakari et al., 2020), as well as crop maturation and disease resistance (Ezawa et al., 2002). Under acidic conditions, Fe^{3+} and Al^{3+} toxicity retard microbial activities and nutrient cycling, leading to reduced nutrient uptake and root growth (Fageria et al., 2013).

Among other options, liming with (hydr)oxides, carbonates, and silicates of Ca or Mg as well as application of mineral P-fertilizers are often used to enhance P availability and the productivity of highly weathered acid soils (Haling et al., 2010). Apart from increasing soil pH, liming reduces Al toxicity, improves the physical and biological conditions of soils (Holland et al., 2018), thereby increasing availability of nutrients, especially the exchangeable Ca and Mg and the easily fixed P (Bello & Udofia, 2013). For acid tropical soils, synthetic limes with fast-mineralizing manures have been reported to enhance exchangeable Ca, overall cation exchange (Ogumba et al., 2024a), P availability, and hence crop yields (Nnadi et al., 2020; Ugwu et al., 2024a; Ameh et al., 2025).

By contrast, prolonged and unsustainable uses of synthetic limes and mineral P-fertilizers often lead to soil acidification and nutrient imbalances (Karmakar et al., 2020), while posing a threat to environmental and human health. These adverse effects, coupled with the scarcity and high cost of conventional liming materials and mineral fertilizers (Haynes & Mokolobate, 2001), have made research interest to tilt towards alternative, cheaper, available and environment-friendly options of organic liming and P sources such as wood ash (Mbah et al., 2010) and rock phosphate (Hallal et al., 2019), respectively.

Wood ash (WA) contains oxides and hydroxides of Ca, Mg and potassium (K), and to a lesser extent, sodium (Na), making it similar to the conventional liming materials (Brady & Weil, 2006). It also contains many of the nutrients originally absorbed from the soil by plants, which may add to the nutrient content of the soil and improve crop growth and yield (Nwite et al., 2011a). Several research works have portrayed the effectiveness of WA as a liming material (Nwite et al., 2011a, 2011b; Nottidge & Nottidge, 2012; Osundare, 2014), and of ash generally in improving crop productivity (Onah et al., 2023).

Among the rock phosphate (RP) deposits in Nigeria, those of Sokoto and Ogun have potential for exploitation and commercialization, existing in pellet, nodule, vesicular and granular forms (Adediran & Sobulo, 1998). Since the discovery of these deposits, there have been studies on their suitability use as P sources for different soils and crops across Nigeria (Obigbesan & Udosen, 1995; Akande et al., 1998; Akinrinde & Obigbesan, 2006; Obaje et al., 2013; Fayiga & Obigbesan, 2017). The Sokoto RP has been shown to be more suitable for direct application to the soil as natural lime due to its low content of Fe and Al oxides which are responsible for P-fixation (Akinrinde et al., 2003). This quality makes it similar to the Togo RP used by Nigerian fertilizer companies in producing single superphosphate (SSP) fertilizer (Fayiga & Obigbesan, 2017). Additionally, Sokoto RP is highly reactive with high content of carbonates that could lime acid soils (Akinrinde & Obigbesan, 2006).

Given that tropical soils have inherently low P-fertility status and that soil acidity, Al^{3+} toxicity and P deficiency often co-exist; strategies aimed at improving the productivity of acidic soils must involve measures to increase soil pH and P content. Combined application of natural lime and P fertilizer could be a potential substitute or complement to conventional liming materials and mineral P fertilizers. There is, however, paucity of information on the effects of lime and P sources on soil properties and soybean growth. The aim of this study was therefore to assess the potentials of wood ash and rock phosphate as alternatives to calcium oxide (CaO) and SSP as lime and P sources, respectively for soybean production in an acidic P-deficient soil.

MATERIALS AND METHODS

Experimental Setup and Treatments

A glasshouse pot experiment was carried out at the University of Nigeria Teaching and Research Farm, Nsukka, southeastern Nigeria, located at 06º52' N, 07º24' E. The soil is deeply weathered, of coarse sandy-loam texture, and well-drained; with very low values of total exchangeable bases, cation exchange capacity (CEC), base saturation and organic matter contents. The soil is classified as Ultisols. The risk of leaching also exists, not only due to the prevailing high-intensity rainfall, but also to the porous granular surface structure of the soil (Obalum & Obi, 2014).

Wood ash (WA) used in the experiment was collected randomly from Owerre-Eze Orba, neighbouring to the site of the experiment. It was homogenized and sieved to remove debris. The CaO with 88% calcium carbonate equivalent (neutralizing value) was obtained from the stock owned by the Soil Physics & Water Management Research Team in the Department of Soil Science of the University of Nigeria, Nsukka, Nigeria. The RP obtained from the Sokoto deposit was used as the natural source of P, while SSP purchased from the local market in Nsukka served as the synthetic source of P.

Topsoil (0-20 cm) samples were randomly collected from spots in the University of Nigeria Teaching & Research Farm. The soil samples were bulked to obtain a composite sample which was then passed through a 2-mm mesh sieve. Then, 5 kg of the soil was thoroughly mixed with the amendments according to treatments and put in labeled -L plastic pots. In this experiment, natural lime (WA), synthetic lime (CaO) and non-addition of lime were studied concurrently with natural P source (RP), synthetic P source (SSP) and non-addition of P-fertilizer. The WA and CaO were added to the potted soils at rates equivalent to 157 and 5 kg ha^{-1}, respectively, whereas RP and SSP were added at rates equivalent to 50 and 333 kg ha^{-1}, respectively. These amendments were mixed with the potted soils two weeks prior to sowing of soybean seeds, except SSP that was applied two weeks after sowing (WAS).

Each of the three lime amendments was combined with each of the three P-fertilizer amendments, giving nine treatments. All treatments were replicated three times in a completely randomized design (CRD). Three seeds of soybean (*Glycine max* L.) were sown at a depth of about 2-3 cm. At 1 WAS, seed replacement was done for those that failed to germinate. Seedlings were later, at 2 WAS, thinned down to one rigorous seedling per potted soil. Water was supplied to each potted soil at 75 cl every other day, while weeds were regularly removed by hand-picking.

Agronomic Data Collection

Agronomic data on plant height, number of leaves, and leaf area were collected at weekly intervals beginning from 2 WAS till the 8th week. At the end of the nine-week period of the experiment, the shoots were harvest and oven-dried at 70°C to constant weight to obtain the dry matter termed shoot biomass. To assess the residual effects of the different treatments, the potted soils were, without re-application of the amendments, immediately replanted to soybean.

Soil Laboratory Analyses

Pre-planting and postharvest soil samples, as well as organic amendments used in the study, were air-dried, crushed and sieved through a 2-mm-mesh sieve. Soil pH was determined using a glass electrode pH meter in water and KCl in a soil-liquid ratio of 1:2.5 (McLean, 1982). Soil organic carbon was determined using the Walkley and Black wet dichromate oxidation method (Nelson and Sommers, 1982); this was multiplied by van Bemmelen constant of 1.724 to convert to soil organic matter. Total nitrogen (N) was determined using Micro-Kjeldahl wet digestion method (Bremmer & Mulvaney, 1982). Soil available P (AvP) was determined, after extraction using Bray II, by the Olsen and Sommers' (1982) method. Exchangeable bases were extracted using neutral 1N NH_4OAc, after which Ca^{2+} and Mg^{2+} were determined by atomic absorption, and K^+ by flame photometer. Soil exchangeable acidity was determined by KCl displacement method, while apparent cation exchange capacity (CEC) of the soil was determined by the pH-7 NH_4OAc method.

Assessment of Soybean Nutrients Uptake

The oven-dried shoots were ground and passed through 2 mm-mesh sieve and 0.5 g of it used to analyze their N, P, and K contents. For each of these nutrient elements, uptake by the soybean plants was calculated as follows:

Shoot uptake of nutrient from 5-kg potted soil

$$\text{(g per 5-kg soil)} = \frac{\%\ \text{nutrient} \times \text{shoot dry matter (g)}}{100}.$$

Properties of the Soil Prior to Amendment and of the Amendments Used in the Study

The physicochemical properties of the soil before planting are presented in Table 1, while Table 2 shows the composition of the WA and RP.

Statistical Analysis

By concept, the study focused on synergistic and sole effects of the lime/P-fertilizer amendments. One-way analysis of variance was thus performed on the data, separating means using the Duncan's multiple range test at the probability level $p \leq 0.05$. Shoot biomass was also regressed on plant N-P-K uptake and soil properties. For both analyses, SPSS software version 21 was used.

Table 1. Physical and physicochemical properties of the soil before planting

Parameter	Content	Parameter	Content
Clay (g kg^{-1})	120	Available P (mg kg^{-1})	10.6
Silt (g kg^{-1})	50	K^+ (cmol kg^{-1})	0.11
Fine sand (g kg^{-1})	390	Ca^{2+} (cmol kg^{-1})	0.50
Coarse sand (g kg^{-1})	440	Mg^{2+} (cmol kg^{-1})	0.60
Textural class	Sandy loam	Na^+ (cmol kg^{-1})	0.12
pH-H_2O	4.9	EA (cmol kg^{-1})	0.13
(g kg^{-1})	22.9	Apparent CEC (cmol kg^{-1})	6.30
Total N (g kg^{-1})	2.25		

SOM - soil organic matter, EA - exchangeable acidity, CEC - cation exchange capacity.

Table 2. Chemical composition of wood ash and rock phosphate used in the study

Amendments	WA	RP
pH-H_2O	12.4	9.5
% SOM	2.35	1.47
% Total N	3.28	0.10
Phosphorus (g kg^{-1})	85.7	32.5
K (g kg^{-1})	87.2	12.6
Ca (g kg^{-1})	543.6	10.4
Mg (g kg^{-1})	29.0	8.9
Na (g kg^{-1})	6.4	0.1

RP - rock phosphate, WA – wood ash, SOM - soil organic matter, AvP - available P

RESULTS

Effects of treatments on selected soil physicochemical properties

All the amendments, except SSP, significantly increased the soil pH relative to the control (Table 3); however, WA (54.83%) and WA+RP (51.72%) had the highest relative improvements. Sole application of WA significantly improved K^+, Ca^{2+}, Mg^{2+} and base saturation in the soil by approximately 50%, 376%, 186% and 391%, respectively. Though the highest increase in AvP was obtained from potted soils amended with WA+SSP (520%), it was not significantly different from WA+RP and sole WA. Apart from WA+RP and WA+SSP which were not significantly different from the control, all the treatments enhanced soil K^+ content. Treatment WA+RP had the highest relative increases in total N (2,350%), while CaO+RP had the highest relative increases in apparent CEC (325%). Soil organic matter and Na^+ were not affected by treatment in this first crop growth phase.

In the test of treatment residual effects (Table 4), a similar trend was observed in which WA and WA+RP significantly enhanced the soil pH by 102% and 95%, respectively. Relative increases in soil organic matter were highest in potted soils treated with CaO+RP (39%), while those amended with WA+RP had the highest relative increases in soil total N (2,400%). In contrast, sole application of WA resulted in the highest relative increases in soil AvP (236%), Ca^{2+} (689%), and base saturation (556%). Treatments WA, CaO+RP and RP showed the same values of K^+, values of which represented a 100% increase in K^+ relative to the control. However, the highest relative increase in Mg^{2+} (190%) was obtained from treatment WA+RP, which did not differ significantly from WA. The corresponding treatments for the apparent CEC of the soil were WA+RP (108%) and CaO+RP (116%). The residual effect of treatment on Na^+ showed higher values in potted soils without WA than those with WA (WA+RP, WA+SSP and WA), which in turn showed higher values than the control.

Effects of treatments on nutrient uptake

In the first soybean growth phase of the experiment, WA+RP, WA+SSP and WA had the highest overall significant effect on N and K uptake (Figure 1a and 1c, respectively). Apart from CaO and SSP, all treatments enhanced P uptake with no significant differences between treatments (Figure 1b). In the test of treatment residual effects, the highest relative increases in N (500%) and K (600%) uptake were recorded in WA+RP (Figure 2a and 2c, respectively). Similar relative increases in soybean uptake of P were recorded for WA+RP (567%), WA+SSP (550%) and CaO+RP (500%), as well as for the sole application of WA (550%) (Figure 2b).

Table 3. Immediate effect of lime and phosphorus sources on selected soil physicochemical properties

Amendment	pH-H_2O	SOM	Total N	AvP (mg kg^{-1})	K^+	Ca^{2+}	Mg^{2+}	Na^+	% Base saturation†	CEC (cmol kg^{-1})
		(g kg^{-1})			(cmol kg^{-1})					
WA+RP	8.7 ± 0.30^{a}	14.0 ± 0.12^{a}	9.8 ± 0.01^{a}	11.18 ± 0.00^{b}	0.04 ± 0.00^{b}	5.20 ± 0.00^{b}	1.93 ± 0.02^{b}	0.02 ± 0.00^{a}	60.4 ± 1.71^{a}	17.7 ± 1.18^{bc}
WA+SSP	7.4 ± 0.11^{b}	14.0 ± 0.10^{a}	0.7 ± 0.01^{d}	15.38 ± 0.04^{a}	0.03 ± 0.00^{b}	2.67 ± 0.06^{c}	1.47 ± 0.05^{cd}	0.02 ± 0.00^{a}	25.3 ± 0.80^{bc}	17.5 ± 1.26^{bc}
WA	9.3 ± 0.65^{a}	14.6 ± 0.05^{a}	0.7 ± 0.02^{d}	13.02 ± 0.00^{ab}	0.06 ± 0.00^{a}	7.00 ± 0.01^{a}	2.86 ± 0.01^{a}	0.02 ± 0.00^{a}	61.4 ± 0.93^{a}	21.0 ± 0.54^{b}
CaO+RP	7.0 ± 0.34^{b}	15.1 ± 0.01^{a}	0.7 ± 0.01^{d}	8.30 ± 0.01^{c}	0.06 ± 0.00^{a}	2.33 ± 0.06^{d}	1.30 ± 0.02^{cd}	0.03 ± 0.00^{a}	13.8 ± 1.94^{de}	41.2 ± 0.08^{a}
CaO+SSP	5.9 ± 0.34^{c}	14.4 ± 0.01^{a}	1.1 ± 0.05^{b}	8.66 ± 0.11^{c}	0.06 ± 0.00^{a}	1.23 ± 0.02^{e}	1.47 ± 0.02^{cd}	0.03 ± 0.00^{a}	30.1 ± 1.82^{b}	18.8 ± 1.96^{bc}
CaO	5.2 ± 0.40^{cd}	14.8 ± 0.02^{a}	0.6 ± 0.01^{e}	4.23 ± 0.18^{e}	0.05 ± 0.01^{a}	1.40 ± 0.12^{e}	1.77 ± 0.07^{bc}	0.03 ± 0.00^{a}	15.6 ± 1.72^{de}	21.0 ± 1.22^{b}
RP	5.1 ± 0.60^{d}	14.8 ± 0.02^{a}	0.9 ± 0.01^{c}	4.66 ± 0.01^{d}	0.06 ± 0.01^{a}	1.33 ± 0.10^{e}	1.90 ± 0.07^{b}	0.03 ± 0.00^{a}	19.7 ± 1.57^{cd}	19.5 ± 1.80^{b}
SSP	4.6 ± 0.12^{e}	14.3 ± 0.09^{a}	0.7 ± 0.02^{d}	9.50 ± 0.10^{c}	0.06 ± 0.01^{a}	1.33 ± 0.12^{e}	1.63 ± 0.05^{c}	0.03 ± 0.00^{a}	23.5 ± 1.64^{bc}	14.4 ± 1.51^{c}
Control	4.2 ± 0.05^{e}	13.3 ± 0.05^{a}	0.4 ± 0.01^{f}	2.48 ± 0.15^{e}	0.04 ± 0.01^{b}	1.47 ± 0.06^{f}	1.00 ± 0.00^{e}	0.03 ± 0.00^{a}	12.5 ± 1.58^{e}	9.7 ± 0.81^{d}

WA - wood ash, CaO - calcium oxide, RP - rock phosphate, SSP - single superphosphate,
SOM - soil organic matter, AvP - available phosphorus, CEC - apparent cation exchange capacity
†Computed as the percentage ratio of total exchangeable bases ($K^+ + Ca^{2+} + Mg^{2+} + Na^+$) to the effective CEC of the soil
Values are means ± standard deviations, and those followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$.

Table 4. Residual effect of lime and phosphorus sources on selected soil physicochemical properties

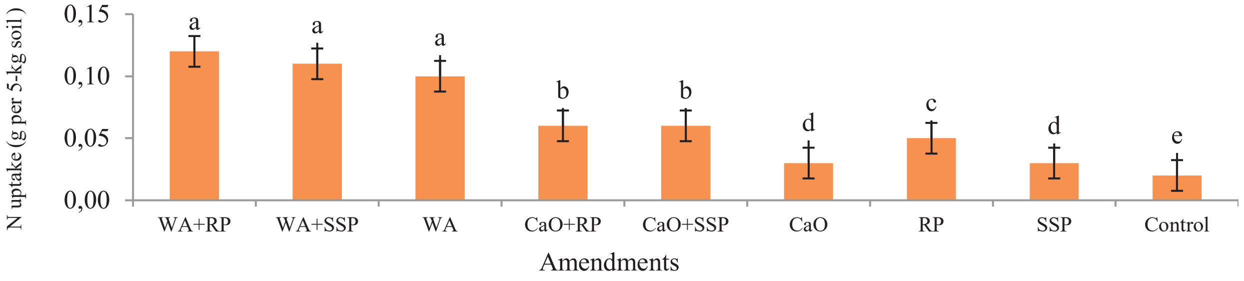
Amendment	pH-H_2O	SOM	Total N	AvP (mg kg^{-1})	K^+	Ca^{2+}	Mg^{2+}	Na^+	% Base saturation†	CEC (cmol kg^{-1})
		(g kg^{-1})			(cmol kg^{-1})					
WA+RP	8.2 ± 0.10^{a}	13.8 ± 0.17^{bc}	10.0 ± 0.01^{a}	11.20 ± 0.00^{b}	0.05 ± 0.00^{abcd}	5.43 ± 0.01^{b}	2.90 ± 0.01^{a}	0.02 ± 0.01^{b}	55.1 ± 1.30^{b}	20.2 ± 0.63^{a}
WA+SSP	5.7 ± 0.43^{b}	13.7 ± 0.10^{bc}	7.3 ± 0.05^{ab}	7.56 ± 0.00^{bcd}	0.04 ± 0.01^{abc}	3.47 ± 0.06^{cd}	1.90 ± 0.01^{b}	0.02 ± 0.01^{b}	26.8 ± 1.90^{cd}	11.3 ± 1.15^{b}
WA	8.50 ± 0.20^{a}	14.1 ± 0.05^{bc}	5.9 ± 0.44^{b}	12.53 ± 0.06^{a}	0.06 ± 0.01^{a}	7.10 ± 0.00^{a}	2.86 ± 0.01^{a}	0.02 ± 0.00^{b}	68.9 ± 1.45^{a}	12.1 ± 0.57^{ab}
CaO+RP	5.2 ± 0.68^{bc}	16.3 ± 0.11^{a}	0.7 ± 0.01^{c}	8.38 ± 0.00^{abcd}	0.06 ± 0.01^{a}	4.63 ± 0.15^{bc}	1.50 ± 0.01^{bc}	0.03 ± 0.00^{a}	13.7 ± 1.65^{e}	21.0 ± 1.53^{a}
CaO+SSP	4.9 ± 0.60^{cd}	14.3 ± 0.05^{bc}	1.1 ± 0.05^{c}	8.25 ± 0.00^{abcd}	0.05 ± 0.00^{abcd}	3.07 ± 0.01^{cd}	1.47 ± 0.01^{bc}	0.03 ± 0.00^{a}	31.5 ± 1.81^{c}	18.8 ± 0.60^{ab}
CaO	4.8 ± 0.68^{cd}	14.5 ± 0.08^{ac}	0.5 ± 0.01^{c}	6.03 ± 0.00^{cd}	0.05 ± 0.01^{abcd}	2.07 ± 0.01^{ef}	1.97 ± 0.01^{b}	0.03 ± 0.00^{a}	15.5 ± 0.94^{de}	17.0 ± 0.50^{ab}
RP	4.9 ± 0.32^{cd}	15.1 ± 0.03^{ab}	0.8 ± 0.05^{c}	8.25 ± 0.00^{abcd}	0.06 ± 0.01^{a}	2.83 ± 0.01^{de}	1.90 ± 0.01^{b}	0.03 ± 0.00^{a}	22.0 ± 1.24^{cde}	11.8 ± 0.20^{b}
SSP	4.3 ± 0.01^{d}	13.1 ± 0.11^{cd}	0.7 ± 0.01^{c}	9.50 ± 0.00^{abc}	0.04 ± 0.01^{cd}	2.33 ± 0.06^{de}	1.23 ± 0.01^{c}	0.03 ± 0.00^{a}	17.5 ± 1.43^{ce}	14.4 ± 1.00^{ab}
Control	4.2 ± 0.05^{d}	11.7 ± 0.05^{d}	0.4 ± 0.01^{c}	3.73 ± 0.00^{d}	0.03 ± 0.00^{d}	0.90 ± 0.01^{f}	1.00 ± 0.00^{e}	0.01 ± 0.01^{c}	10.5 ± 0.06^{e}	9.7 ± 0.05^{c}

WA - wood ash, CaO - calcium oxide, RP - rock phosphate, SSP - single superphosphate,
SOM - soil organic matter, AvP - available phosphorus, CEC - apparent cation exchange capacity
†Computed as the percentage ratio of total exchangeable bases ($K^+ + Ca^{2+} + Mg^{2+} + Na^+$) to the effective CEC of the soil
Values are means ± standard deviations, and those followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$.

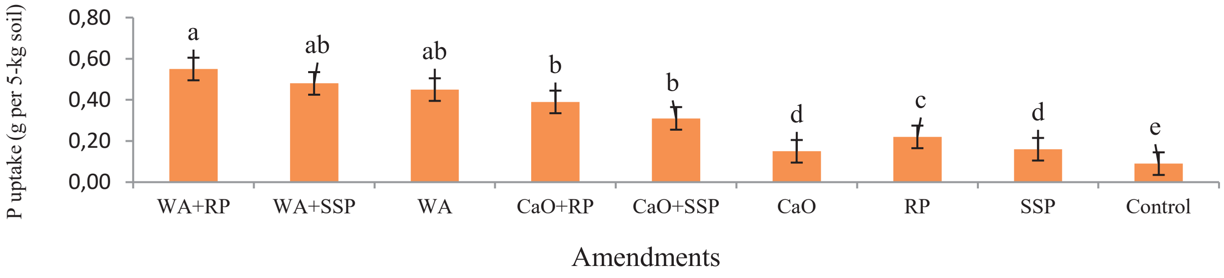
Effects of treatments on soybean growth parameters and shoot biomass yield

All the amendments significantly increased soybean plant height, except CaO and SSP which were not significantly different from the control at 2 and 4 WAS (Table 5). The highest number of leaves was consistently obtained from treatments WA+SSP and CaO+SSP. All the treatments significantly increased the leaf area at 6 WAS, except CaO and RP which also were not significantly different from the control at 2 and 4 WAS, respectively. However, only treatments WA+RP, WA+SSP and WA had significant effects on leaf area. In the second growth phase of testing treatment residual effects, treatment WA+SSP consistently showed the tallest plants and was similar to WA+RP and CaO+SSP (Table 6). This WA+SSP surpassed the control by 64%, 102% and 96% at 2, 4 and 6 WAS, respectively. Treatment had no significant effect on number of leaves of the soybean plants at 2 WAS but at 4 and 6 WAS, when WA+RP and WA+SSP produced similar effects. A similar trend was observed for leaf area, with the duo of WA+RP and WA+SSP consistently showing the highest significant effect.

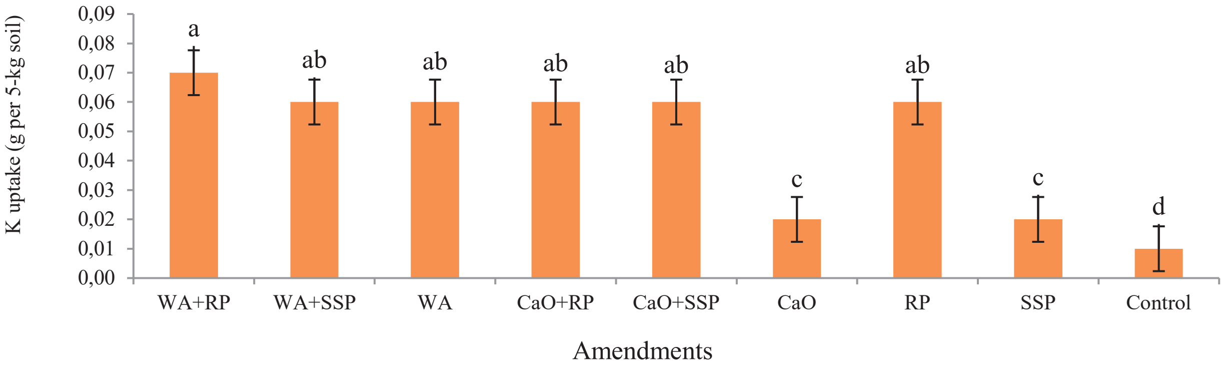
The data for the immediate and residual effects of treatment on soybean shoot biomass are presented in Figures 3a and 3b, respectively. In the first growth phase when treatment immediate effects were evaluated on soybean growth, WA+RP, WA+SSP and CaO+SSP and sole application of WA produced highest amounts of shoot biomass. For the residual effects of treatment, these treatments except WA, still recorded highest amount of shoot biomass.



1a) N uptake

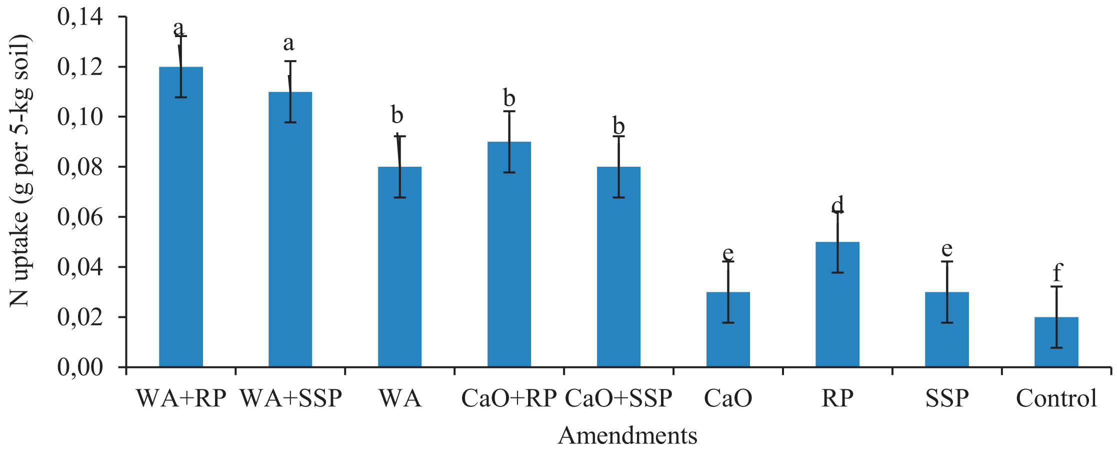


1b) P uptake

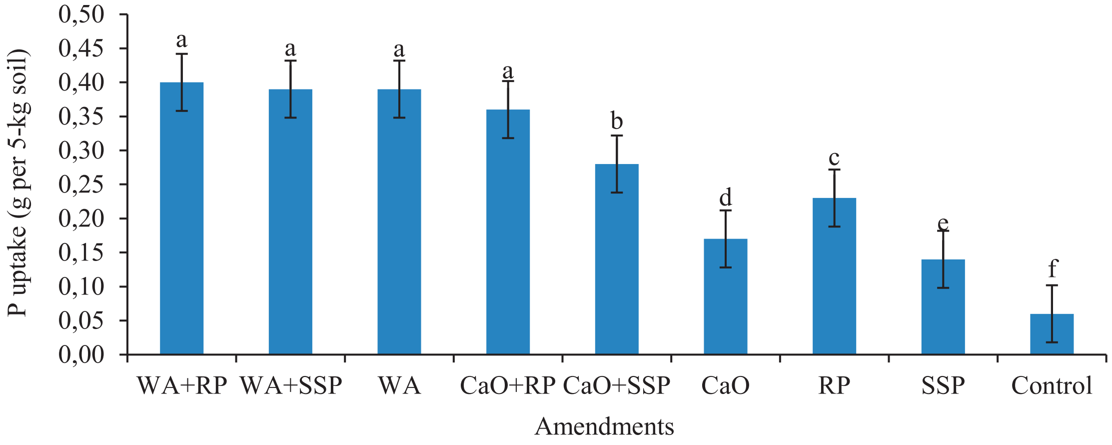


1c) K uptake

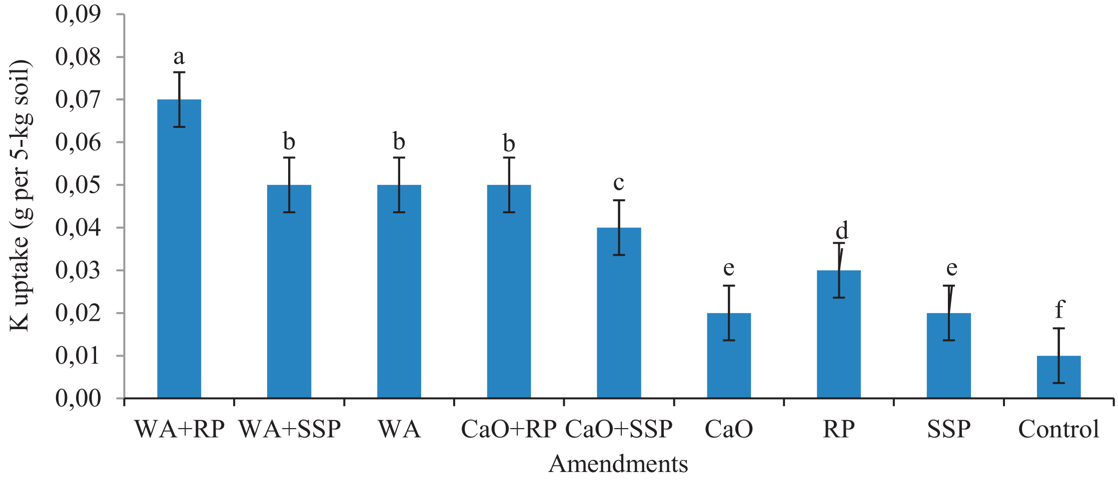
Figure 1. Immediate effects of treatment on N (1a), P (1b) and K (1c) uptake
WA - wood ash, RP - rock phosphate, SSP - single superphosphate, CaO - calcium oxide
Means followed by the same letter(s) are not significantly different at $p \leq 0.05$



2a) N uptake



2b) P uptake



2c) K uptake

Figure 2. Residual effects of treatment on N (2a), P (2b) and K (2c) uptake
WA - wood ash, RP - rock phosphate, SSP - single superphosphate, CaO - calcium oxide
Means followed by the same letter(s) are not significantly different at $p \leq 0.05$

Table 5. Immediate effects of lime and phosphorus sources on plant height, number of leaves, and leaf area at 2, 4 and 6 weeks after sowing (WAS)

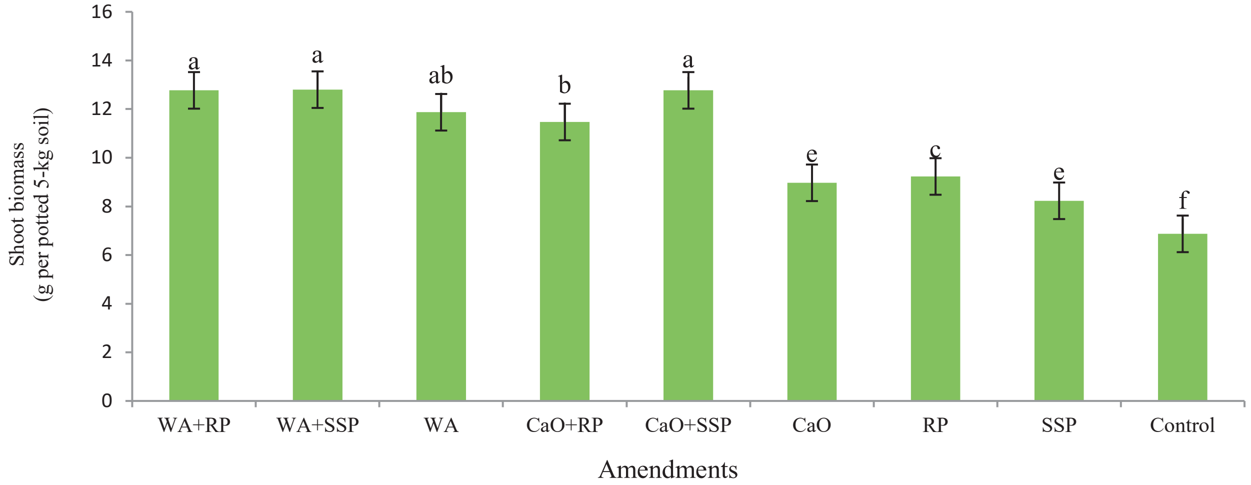
Treatments	Plant Height (cm)			Number of Leaves (cm)			Leaf Area (cm^{2})		
	2 WAS	4 WAS	6 WAS	2 WAS	4 WAS	6 WAS	2 WAS	4 WAS	6 WAS
WA+RP	28.1±0.76^{a}	56.5±1.21^{a}	80.3±0.59^{a}	13.3±1.15^{b}	12.6±1.51^{abcd}	13.3±1.15^{b}	34.0±0.52^{abc}	43.1±1.10^{ab}	86.4±1.48^{a}
WA+SSP	28.1±0.86^{a}	57.5±1.04^{a}	81.0±0.46^{a}	15.3±0.01^{a}	15.3±0.57^{a}	16.3±0.57^{a}	36.3±0.01^{ab}	46.8±1.40^{a}	81.0±1.76^{ab}
WA	26.0±0.40^{ab}	52.1±1.11^{a}	75.6±0.01^{a}	12.3±0.01^{bc}	13.6±0.57^{abc}	12.3±0.57^{bc}	34.4±0.18^{ab}	40.4±1.05^{b}	81.3±0.88^{ab}
CaO+RP	28.0±1.08^{a}	54.0±1.16^{a}	81.0±0.57^{a}	13.0±1.73^{b}	13.3±1.30^{abcd}	13.0±0.01^{b}	35.9±0.98^{ab}	44.5±1.8^{ab}	71.5±1.08^{cd}
CaO+SSP	24.2±1.25^{bc}	50.8±1.46^{ab}	82.3±0.48^{a}	15.6±1.73^{a}	14.6±1.16^{ab}	15.6±1.15^{a}	40.4±0.66^{a}	45.5±1.59^{ab}	74.2±1.56^{bc}
CaO	22.5±1.25^{cd}	39.0±1.15^{cd}	58.3±1.64^{b}	11.6±1.15^{bc}	10.0±1.00^{cd}	11.6±0.57^{bc}	27.9±0.32^{d}	34.5±1.04^{b}	65.4±0.92^{d}
RP	26.4±1.88^{ab}	49.3±1.73^{abc}	66.3±1.52^{b}	13.0±1.51^{b}	13.3±0.57^{bcd}	13.0±1.00^{b}	31.2±0.86^{bcd}	32.8±1.52^{cd}	66.7±1.20^{cd}
SSP	22.6±1.00^{cd}	39.6±1.21^{bcd}	59.6±1.60^{b}	12.3±1.00^{bc}	14.0±1.20^{ab}	12.3±1.52^{bc}	34.5±0.88^{ab}	35.5±1.04^{c}	67.2±1.33^{cd}
Control	11.3±0.57^{d}	17.6±1.30^{d}	28.6±1.07^{c}	9.6±0.01^{c}	5.6±1.15^{d}	9.3±0.57^{c}	19.6±0.69^{d}	29.0±1.62^{d}	33.4±1.01^{d}

WA - wood ash, CaO - calcium oxide, RP - rock phosphate, SSP - single superphosphate.
Values are means ± standard deviations, and those followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$.

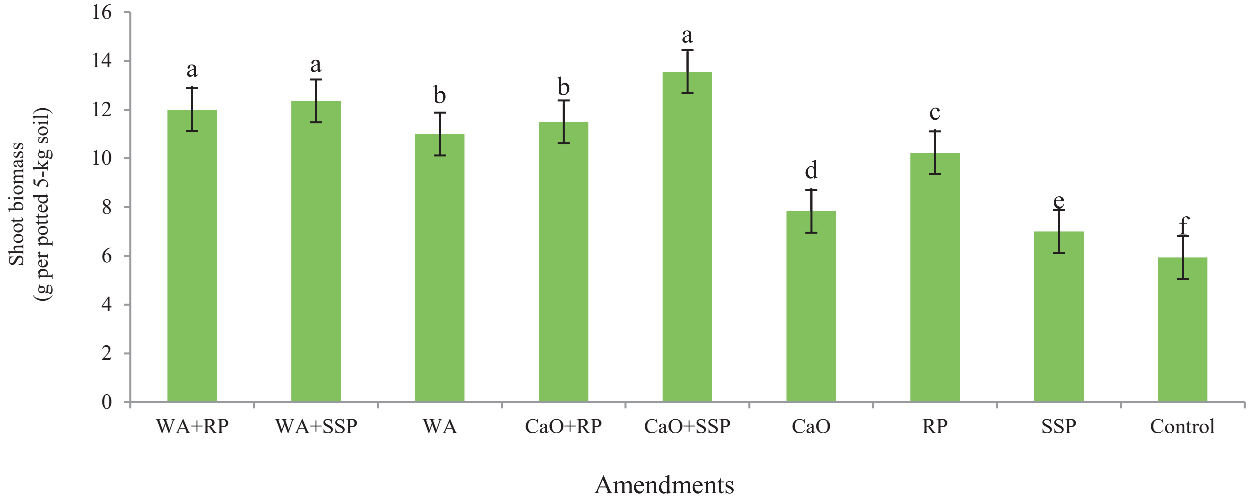
Table 6. Residual effects of lime and phosphorus sources on plant height, number of leaves, and leaf area at 2, 4 and 6 weeks after sowing (WAS)

Treatments	Plant Height (cm)			Number of Leaves (cm)			Leaf Area (cm^{2})		
	2 WAS	4 WAS	6 WAS	2 WAS	4 WAS	6 WAS	2 WAS	4 WAS	6 WAS
WA+RP	17.3±1.05^{ab}	33.3±0.80^{a}	74.3±1.13^{a}	4.6±0.57^{a}	8.3±0.57^{a}	11.6±0.57^{a}	31.2±1.25^{ab}	52.3±0.52^{a}	98.7±0.66^{a}
WA+SSP	18.5±1.08^{a}	34.6±1.13^{a}	75.3±1.00^{a}	4.6±0.57^{a}	8.3±0.57^{a}	11.6±0.57^{a}	32.5±1.22^{a}	51.9±0.89^{a}	99.0±0.13^{a}
WA	15.5±1.00^{bc}	31.0±1.15^{ab}	67.3±0.88^{ab}	4.6±0.57^{a}	7.6±1.10^{b}	10.6±0.57^{abc}	26.0±1.53^{bc}	53.3±0.69^{a}	90.3±1.09^{ab}
CaO+RP	15.3±0.86^{bc}	31.3±1.13^{ab}	67.0±0.64^{ab}	4.6±0.57^{a}	7.0±0.01^{b}	11.6±0.57^{a}	25.5±0.91^{bc}	51.4±0.90^{a}	88.3±1.26^{b}
CaO+SSP	17.1±1.30^{ab}	30.0±1.05^{ab}	74.3±1.08^{a}	4.6±0.57^{a}	6.6±0.57^{bcd}	10.6±0.57^{abc}	25.1±0.69^{cd}	57.0±0.83^{a}	86.5±0.71^{b}
CaO	13.1±0.80^{de}	25.6±1.03^{b}	51.6±0.83^{c}	4.3±0.57^{a}	6.3±0.57^{cd}	10.0±1.00^{bcd}	23.5±0.62^{cd}	51.8±0.80^{a}	66.2±0.64^{c}
RP	14.3±1.45^{cd}	27.0±1.03^{b}	54.6±1.21^{bc}	4.6±0.57^{a}	7.0±1.00^{b}	11.0±0.01^{ab}	25.2±1.13^{cd}	51.8±0.89^{a}	85.2±0.60^{b}
SSP	15.0±.060^{cd}	26.3±0.76^{b}	55.3±0.50^{bc}	4.6±0.57^{a}	6.3±0.57^{cd}	9.6±0.57^{cd}	22.4±1.23^{c}	55.5±0.80^{a}	79.8±1.22^{b}
Control	11.3±0.79^{e}	17.1±0.74^{d}	38.3±0.60^{d}	3.6±0.57^{a}	5.6±0.57^{d}	9.5±0.57^{d}	19.0±1.33^{d}	20.0±0.75^{b}	44.8±0.88^{d}

WA - wood ash, CaO - calcium oxide, RP - rock phosphate, SSP - single superphosphate
Values are means ± standard deviations, and those followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$.



3a) Immediate effect



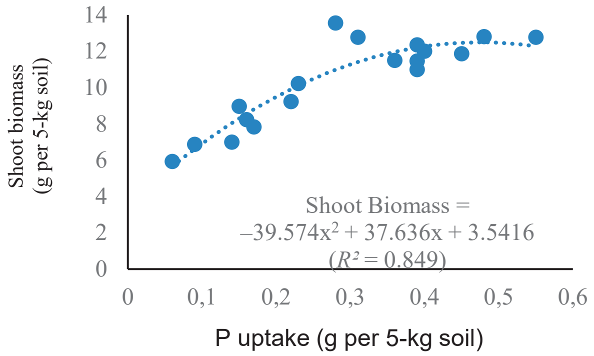
3b) Residual effect

Figure 3. Immediate (3a) and residual (3b) effects of treatment on shoot biomass
WA - wood ash, RP - rock phosphate, SSP - single superphosphate, CaO - calcium oxide
Means followed by the same letter(s) are not significantly different at $p \leq 0.05$

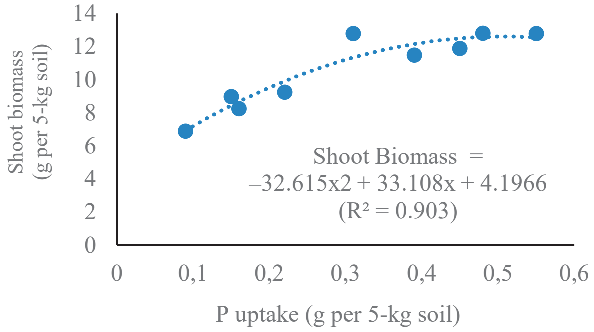
Treatment effects on soybean shoot biomass versus corresponding plant N-P-K uptake and soil physicochemical properties

The relating of shoot biomass of the soybean plants to their uptake/accumulation of the three primary nutrients (N, P and K) and soil physico-chemical properties of the various treatments involved multiple linear regression by stepwise procedure. The regression for both the immediate and residual effects combined showed that shoot biomass depended on plant P uptake as its sole predictor, for which it is now shown graphically to be of quadratic form (Figure 4a). When done separately for the immediate and residual effects, shoot biomass still depended on one variable in each case - plant P and N uptake, respectively (Figure 4b and 4c). Indeed, plant P and N uptake showed a very close association (Figure 5), the strength being similar for both the immediate and residual effects ($R^2 = 0.986$-0.977).

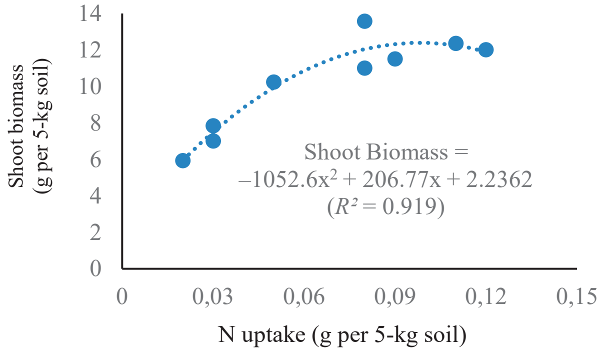
Notably, for the three primary nutrient elements, there were linear positive plant uptake-soil content relationships. Whether the immediate and residual effects were considered together or separately, the best of this relationship with a high level of consistency was for P ($R^2 = 0.917$-0.934); those for N and K showed R^2 values in the ranges of 0.477-0.737 and 0.797-0.855, respectively.



4a) Immediate and residual effects combined ($n = 18$)



4b) Immediate effects only ($n = 9$)



4c) Residual effects only ($n = 9$)

Figure 4. Regression of shoot biomass of soybean on plant uptake of P for immediate and residual effects of treatment combined (4a), immediate effects of treatment only (4b), and residual effects of treatment only (4c)

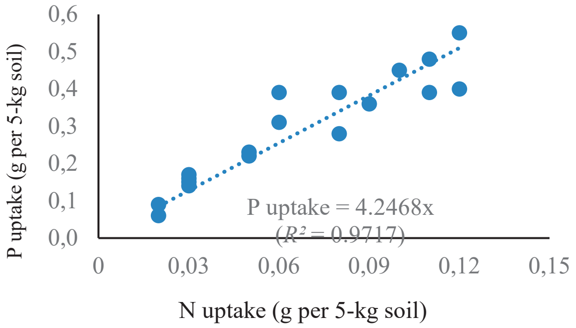


Figure 5. Relationship between plant uptake of P and N for immediate and residual effects of treatment combined ($n = 18$)

DISCUSSIONS

The sandy-loam soil of this study was slightly acidic and of low fertility status. Such soils are not suitable for crop production without external inputs (Akinrinde & Obigbesan, 2000). Increases in soil pH after liming improve the physical, physicochemical and biological properties of the soil (Holland et al., 2018), thereby increasing the availability of nutrients, especially P, Ca and Mg (Bello & Udofia, 2013). The increases in soil microbial activities imply greater decomposition and mineralization of N and P (Mkhonza et al., 2020). The outstanding performance of WA in this study could be attributed to its initial high pH (Table 2). Apart from its liming effect, WA also contains many of the nutrients originally absorbed from the soil by plants such as P, K, Ca, Mg, and Na (Nwite, 2016). This could account for its significantly increasing Ca^{2+} and Mg^{2+}. Nwite et al. (2011a) recorded a 100% increase in soil pH following the application of rice husk ash, wood ash and leaf ash. Increases in soil pH following application of rice husk ash, wood ash and/or leaf ash to similar soils have been reported from some studies (Nwite et al., 2011b; 2012a; 2012b; 2017; Nnadi et al., 2021). Similar to our data for WA here, Nottidge & Nottidge (2012) reported increases in soil pH, nutrient content, nodulation, N uptake/accumulation and soybean grain yield in a WA-amended acid soil.

The increases in soil AvP of WA+SSP could be due to the synergistic effects of liming from WA and P supply from SSP. The Ca^{2+} and Mg^{2+} in liming materials displace Al^{3+}, Fe^{2+} and H^+ from the exchange sites, resulting in P-desorption and availability. Lime-induced increases in soil pH also implies dissolution of Al and Fe phosphate (Anderson et al., 2021). The inability of CaO to increase AvP in the soil points to the high level of sorption due to low pH. The SSP had positive effects on soil AvP. Application of SSP at 60 kg ha^{-1} to a similar soil did not increase its pH and AvP (Umeugokwe et al., 2021). Therefore, SSP increasing AvP here could be due to its relatively high application rate of 333 kg ha^{-1}. The relatively non-significant effect of sole RP may be attributed to its low solubility compared to SSP, which is further compromised under conditions of low pH, high P-sorption, low organic matter content and low microbial activity (Arenberg & Arai, 2019).

Soil acidity and P-deficiency limit the growth of rhizobia (N-fixing bacteria) and thus retard nodulation and N-fixation in soybean (Hussain, 2017; Míguez-Montero et al., 2020). Therefore, the maximum increases in total N content of the soil amended with WA+RP and CaO+SSP could be due to the liming effects of WA and CaO, as well as the supply of P from RP and SSP. High carbonate content has been reported in the RP from the Sokoto deposit which accords it a liming effect (Akinrinde & Obigbesan, 2006). According to a review by Hallal et al. (2019), RPs of sedimentary origin are variable and have complex chemical composition, making them a source of other plant nutrients apart from P. It is, therefore, not surprising that WA+RP enhanced most soil properties including total N.

The significant effects of lime/P-fertilizer co-application and WA on soybean growth could be attributed partly to the increases in soil pH and Ca^{2+} and Mg^{2+} levels in the soil. This reduces Al toxicity in the root region and encourages root growth and proliferation (Sanjay et al., 2018), nodulation (Bakari et al., 2020), and enhances nutrient uptake efficiency (Onwuka et al., 2009). Increases in total N due to WA+RP and CaO+SSP may be responsible for their effects on soybean vegetative growth. Increases in plant height, number of leaves and leaf area imply greater surface area, better light interception by leaves of the photosynthetically active radiation as well as the plants' ability to transform the intercepted radiation into biomass (Mohammadi et al., 2015). Similar increases in soybean dry matter with co-application of farmyard manure and mineral P-fertilizers were reported by Chiezey (2013).

The combination of either WA or CaO with RP in this experiment increasing the solubility of RP leading to increases in soil AvP is attributed to the effect of such a combination on soil pH (Akande et al., 2004). For this soil investigated, however, AvP values in especially WA+RP and WA are rather low for their soil pH values (Chukwuma et al., 2024; Obalum et al., 2024). This suggests that non-manure amendments with liming effect act to raise soil pH which may not reflect in AvP (Ugwu et al., 2024a; Ebido et al., 2025), while pointing to the complementary role of organic substrates onto such soil amendments. Non-manure amendments raise soil pH to levels that favour the thriving and optimal functioning of P-solubilizing microbes supplied by organic amendments to the soil supply which too serve as substrates onto them. Thus, co-application of CaO and poultry manure was found to enable the manifestation of the linear pH-AvP relationship in the soil investigated (Ugwu et al., 2024a).

Increases in soil pH, organic matter, total N, AvP and cation exchange due to organic amendments in sandy-loam Ultisols often lead to increased shoot biomass (Ogumba et al., 2024b). Organic amendments mineralize slowly but steadily compared to inorganic ones, hence the residual effects of WA, RP and, to larger extents, their co-application with other amendments. The residual effects of CaO and SSP in sole but mostly co-application (CaO+SSP) could be attributed to the short duration of the study.

The ability of soybean to biologically fix N and the role of lime/P in nodulation and N-fixation (Bakari et al., 2020; Míguez-Montero et al., 2020), would explain the increases in N uptake. The increases in P uptake from WA+RP were due to soil pH-induced enhancement of P-availability (Nottidge & Nottidge, 2012). Phytohormones in limed soils solubilize P and unavailable nutrients, facilitating their uptake through enhanced root surface area (Nduwumuremyi, 2013).

Combined application of lime and P-fertilizer irrespective of source consistently enhanced soil fertility and improved soybean growth and shoot biomass compared to their sole applications, with treatment WA as an exception. This could be due to the inherent low pH and P content of the native soil and its high P-sorption potential (Chukwuma et al., 2024). The synergistic effect of lime and P-fertilizer could explain the better results from their combinations. Similar results with lime/P-fertilizer treatments have severally been reported (Akande et al., 2005; Inagaki et al., 2016; Alemu et al., 2017; Yadesa et al., 2019). In this study, lime/P-fertilizer combinations with WA were generally more effective than those with CaO, probably because of the non-manure nature of the P-fertilizers (Nwite et al., 2013).

Soybean shoot biomass reflected plant uptake of P or its closely associated N, more than their soil available forms or any of the other soil physico-chemical properties serving as indicators of soil fertility. On examining the data for plant uptake of P in relation to these soil properties further, we found it to show a linear positive relationship with soil pH (R^2 = 0.937). Similar to these results, Ugwu et al. (2024a) reported, following lime-manure application to these sandy-loam Ultisols, that soybean dry matter correlated more with soil pH-regulated P uptake than soil AvP. Notably, treatment SSP improved soil AvP but not shoot biomass. Thus, agronomic responses to acidity-ameliorating amendments in these soils being driven by soil pH-regulated bioavailable P rather than soil AvP could be linked to their supply of liming elements (Ca and Mg). This is followed by attraction of the ensuing base-forming cations (Ca^{2+} and Mg^{2+}) to organic matter in soil solution which implies their retention against leaching and hence increases in soil pH.

Plant dry matter (shoot biomass) accumulation was defined almost entirely by P uptake alone which in turn was very closely related with soil AvP, as also found by Ugwu et al. (2024a). These results underline the need for increased soil P availability through P-fertility management in tropical agriculture. Indeed, for the acid soil of the present study, above-soil dry matter yield has been reported to depend on soil pH-regulated contents of plant macro-nutrients mostly AvP (Obalum et al., 2020), or in conjunction with Ca^{2+} or Mg^{2+} (Ndzeshala et al., 2023). Also, there have been other soil fertility trials with similar soils in Nigeria reporting the dependence of crop growth and dry matter accumulation on soil total N and Ca^{2+} (Ebido et al., 2024) or soil pH, AvP, Ca^{2+} and/or Mg^{2+} (Ugwu et al., 2024b; Ameh et al., 2025). These observations fused with our data lend credence to our proposition of elevated soil pH after Ca-Mg dissociation in the presence of organic matter as the mechanism by which bioavailable P defines the productivity of arable crops in low-fertility tropical soils.

CONCLUSIONS

All the amendments significantly improved the selected soil fertility indices and soybean height, number of leaves, leaf area and shoot biomass compared to the control. The natural lime (WA) and P-fertilizer (RP) compared favourably with and sometimes proved superior to their synthetic counterparts (CaO and SSP, respectively). Also, co-application treatments natural and synthetic limes with natural and synthetic P-fertilizers were generally superior to their sole applications. Thus, WA+RP, WA+SSP, CaO+SSP and sometimes CaO+RP were not always superior to WA but to CaO, RP and SSP, which were in turn generally superior to the control. Overall, natural limes are better complements than synthetic ones to both natural and synthetic P-fertilizers The WA should be used alongside natural/synthetic P-fertilizers. Where WA is not readily available, CaO should be used alongside synthetic P-fertilizers. Where material costs inhibit co-application of lime and P-fertilizer, WA could be used as an alternative to CaO that is also superior to RP and SSP, but which may have smaller residual effects.

The effectiveness of any chosen amendment option stems its ability to raise the soil pH which regulates P bioavailability to crops in acid, coarse-textured soils of low P-fertility in the humid tropics. The findings of this study have implications for sustainable enhanced agronomic production in the region. Considering the harm to the environment and the fiscal cost of synthetic amendments, the findings also have ecological and economic implications.

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