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Lime and manure application to low-fertility tropical soils enhances phosphorus bioavailability for increased agronomic productivity

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ABSTRACT

Liming and manuring to ameliorate soil acidity and enhance mineralization in acid tropical soils could promote their agronomic productivity. Synthetic lime and poultry-droppings manure's effects in sandy-loam Ultisols were evaluated on soybean growth, exploring its relationships with soil pH, soil available P and plant P content. Lime was applied at 0, 2.5 and 5 t ha^{-1} equivalents and manure at 0, 25 and 50 t ha^{-1} equivalents to 2.5-kg potted soils. Crop growth was monitored and soil-plant analysis done during and after six weeks of growth, respectively. Treatment had more pronounced effects on plant height than leafiness of the soybean plants, being generally highest in the combination of lime at 2.5 t ha^{-1} and manure at 50 t ha^{-1} where the plants were about three times taller compared to unamended control. Soybean plants grew better due to 2.5 than 0 and 5 t ha^{-1} lime and to 50 than 0 and 25 t ha^{-1} manure. Plant height and leaf area depended on soil pH-influenced soil available P ($R^2 = 0.69^{**}$) and plant P content ($R^2 = 0.85^{**}$), respectively, while above-soil biomass depended on soil pH or plant height ($R^2 = 0.74^{**}$). Moderate synthetic liming (2.5 t ha^{-1}) with ample poultry-droppings manuring (50 t ha^{-1}) could enhance crop early-stage vegetative growth in low-fertility tropical soils, due largely to amelioration of soil acidity to enhance plant uptake of bioavailable P.

Keywords: acid tropical soils; synthetic lime; nutrient-rich manure; soil available P; plant nutrition.

1. Introduction

Highly weathered tropical soils are known to be naturally acidic and hence of low fertility status (Caires et al., 2008; Fageria et al., 2011; Ubi et al., 2017). These acidic soils that receive high amounts of rainfall over years are leached of basic ions (Ubi et al., 2017). Heavy rainfall is thus one major cause of basic cations removal through leaching over a long period of time. Leaching increases acidity as leached soils are left with toxic and insoluble compounds of iron (Fe) and aluminium (Al) in soil (Zhang et al., 2016). Acidic soils, therefore, have high amount of Fe and Al oxides with high specific surface area (Achat et al., 2010). These oxides have high appetite for phosphate which can sometimes become almost insatiable (Bueis et al., 2019). Oxides of Fe and Al are the main sorbents of phosphate responsible for phosphorus (P) sorption in acidic soils and thus its unavailability to plants in these soils (Turrión et al., 2008; Achat et al., 2010; Bueis et al., 2019). Poor availability of P is a major limiting constraint for crop production in acidic soils (Wang et al., 2010). Tropical soils are also of low fertility status with low soil organic matter (SOM) content due to high mineralization rate. The SOM influences the physical, chemical, and biological characteristics of the soil (Adiaha, 2017; Sandirakirana and Arifin, 2021). Depletion of SOM adversely affects P bioavailability and thus limits crop productivity in

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these acid low-fertility soils. By contrast, increases in SOM imply greater ability of soil to resist the natural tendency of becoming acidic (Ejersa, 2021). Soil content of SOM influences the activities of soil microbes which transform organic P into inorganic P (Allison & Vitousek, 2005; Bueis et al., 2019), just as microbial decomposition of SOM releases inorganic P, a form accessible by plants (Gichangi, 2019). Organic acids originating from SOM decomposition enhance the solubility of calcium (Ca) phosphates, and these organics are adsorbed by Fe and Al oxides, blocking P sorption sites (Bueis et al., 2019). Also, SOM is a major constituent of soil sorption complex which is responsible for the binding of ions in the soil and thus plays a critical role in P sorption (Debicka et al., 2016; Chukwuma et al., 2024).

Liming is a common management practice in most agricultural systems used to mitigate soil acidification toward enhancing crop productivity in such soils (Mkhonza et al., 2020). The application of lime brings about desirable soil pH, decreases toxicity of Fe and Al, increases Ca and magnesium supplies as well as enhances the availability of P (Mkhonza et al., 2020). Increased soil pH, resulting from lime application, increases microbial activity (Rousk et al., 2020; Paradelo et al., 2015). This in turn enhances decomposition of SOM (Garbuio et al., 2011; Grover et al., 2017). Lime application increases the availability of nutrients, which would otherwise be strongly limited by low soil pH (Rastija et al., 2014), improving nutrient uptake (Takala, 2019; Mkhonza et al., 2020). Lime application increases P availability by decreasing the amount of Fe and Al ions and P fixation on their oxides (Mkhonza et al., 2020). Liming creates a favourable root environment for plants as a result of these different effects it has on soils.

Manures can be a valuable, relatively cheap source of P and other essential plant nutrients (Hanč et al., 2008; Saleem et al., 2017; Obalum et al., 2020). Mineralization following manure addition to soils enhances nutrient availability by transforming nutrient elements from organic to inorganic forms (Saleem et al., 2017). Application of manures to acid soils can boost SOM which being negatively charged complexes Fe and Al ions, inhibiting their crystallization and role in P sorption and/or precipitation as insoluble phosphates in soils (Haynes & Mokolobate, 2001; Brady & Weil, 2008). Through adsorption site competition, organic acids in manures also inhibit phosphate adsorption (Borggaard et al., 2005). Soil application of manures thus promote arable crops production via increased P bioavailability (Haynes & Mokolobate, 2001; Adiaha, 2017).

Synthetic limes can be combined with P fertilizers for increased crop productivity in tropical Africa (Desalegn et al., 2016; Amsalu & Beyene, 2020; Tshiabukole et al., 2022). However, combining lime and organic P source in the coarse-textured soils of the region might, by alleviating the toxic effects of Fe-Al oxides (Islam et al., 2021), ensure non-sorption of the released P. Poultry droppings can have more liming and P-supplying effects in acid tropical soils than other manures of organic origin (Adubasim et al, 2018; Ugwu et al., 2020; Chukwuma et al., 2024). In such soils, a compatibility question mark is hanging on co-application of ash as organic lime and poultry-droppings manure (Nwite et al., 2013), but impressive agronomic responses had been found for co-application of synthetic lime and this manure (Nnadi et al., 2020). Lime-manure mix not only aligns with the global principle of organic-inorganic complementation in soil and water management but is also more practicable than co-application of ash and rock phosphate that is among the P-fertility management options proposed for the soils (Ndzeshala et al., 2021).

In the present study, we opted to combine lime and poultry-droppings manure, justified by the greater ability of lime to raise soil pH compared to ash (Materechera & Mkhabela, 2002) and the high cost of ash equivalent of lime for the variable-charge and pH-buffered soil investigated (Ndzeshala et al., 2021), vis-a-vis this manure’s prized effectiveness. Research on the synergy of these soil amendments in the tropics has, however, used rather low application rates of especially the manure component (Islam et al., 2022; Kabango et al., 2022; Akpan et al., 2023). Therefore, objectives of this study were to evaluate the agronomic responses to the effects of co-application of synthetic lime and poultry-droppings manure at standardized rates of the former in coarse-textured tropical soils, determine their effects on P availability in the soils, and examine the relationships between crop growth and soil available P and plant uptake of it.

2. Methodology

2.1 Soil of the study

The research was conducted using soil from the University of Nigeria Teaching & Research Farm, which was collected some 5 m away from the glasshouse of the Department of Soil Science (06°51'47''N, 07°25'22''E; 443 m asl) at Nsukka campus of the University. The climate is humid tropical, with mean annual rainfall of 1600 mm, mean minimum/maximum temperatures of 21/31 °C, and relative humidity in the range of 55-90%. Soils of the area are mostly underlain by false-bedded sandstone or upper-coal measure. At the surface horizons, they can be excessively 'porous' and hence well-drained and often prone to drought (Obalum & Obi, 2014). The occurrence of the soils in a high-rainfall zone, coupled with their 'porous' attribute, makes them highly leached of basic cations and hence strongly acid (Obalum et al., 2011a). By the prevailing climate/soil-supported cum anthropogenic vegetation, the area typifies a Derived Savannah in southeastern Nigeria.

The soil used for the study, derived from false-bedded sandstone, is deeply weathered and of oxide-rich mineralogy. It is hence characterized by coarse texture and reddish-brown moist colour, belonging to the order Ultisols of the USDA's Soil Taxonomy. The particle size distribution of the surface horizon (sand, silt and clay contents of 750, 70 and 180 g kg^{-1}, respectively) places the soil in the texture class of Sandy Loam and qualifies it as a coarse-textured one.

2.2 Procurement of study materials

Topsoil (0 - 20 cm) was collected from a part of the Teaching & Research Farm that had been under fallow for over threes. The heap of soil was spread and left to air-dry in the glasshouse for about two weeks. Thereafter, it was crushed and sieved using 2-mm sieve to remove any gravels and dry plant parts before potting. Before the pot trials, the air-dry topsoil showed acidic soil pH of 5.2, soil organic carbon and total nitrogen contents of 13.78 and 0.53 g kg^{-1}, respectively, available P content of 5.20 mg kg^{-1}, and apparent cation exchange capacity of 13.60 cmol kg^{-1}.

Quicklime (CaO) with calcium carbonate equivalent of 88% (CaO-88%) and treated seeds of a soybean variety with an indeterminate growth habit used as the test crop were bought from the local market at Nsukka, southeastern Nigeria. Poultry droppings was sourced from the Battery Cage System of the Animal Science Section of the Farm. Curing of the fresh poultry-droppings manure was done sun-drying for one week. Then, it was crushed and sieved to allow for proper mixing with the soil. A proximate analysis on the dry manure showed that it had a pH of 8.8 and C, N, P, K, Ca, Mg and Na contents of 283, 24.50, 5.20, 6.50, 11.00, 4.90 and 2.40 g kg^{-1}, respectively.

2.3 Experimental design and procedure

The research was executed as a glasshouse study, using ceramic pots of approximate capacity 2.25 L with drainage hole at the bottom. Treatments consisted of factorial combination of three rates (0, 2.5 and 5.0 t ha^{-1}) of quicklime and three rates (0, 25 and 50 t ha^{-1}) of poultry-droppings manure. Lime rates were adopted after 2.5 t ha^{-1} for similar sandy-loam Ultisols (Agba et al., 2017), while manure rates were adopted after the optimum 'agronomic' rate for the sandy-loam Ultisols investigated, found to be 20-25 t ha^{-1} (Ogunezi et al., 2019; Onah et al., 2023). The factorial combination gave nine treatments replicated three times in a completely randomized design (CRD). These treatments were thoroughly mixed with 2.5 kg air-dry topsoil and, thereafter, placed into the pots. Assuming a soil bulk density of 1,500 kg m^{-3}, the application rates translated into 0, 2.5 and 5.0 g per potted soil for quicklime and 0, 25 and 50 g per potted soil for poultry-droppings manure. These soil application rates are represented as L_0, $L_{2.5}$ and $L_{5.0}$ for lime rates and PD_0, PD_{25} and PD_{50} for manure rates. The three replications of the nine lime-manure treatments gave a total of 27 potted soils for the study.

The potted soils were watered to field capacity and left overnight before sowing soybean. Two seeds were sown per potted soil. One week later, the young seedlings were thinned to one stand per potted soil. From soybean sowing till six weeks after sowing (WAS) when the pot experiment was terminated, the potted soils/seedlings were watered to pre-determined field capacity at two-day intervals, while manually removing weeds as they emerged. The glasshouse had its side louvers wide open such that the environmental conditions including lighting duration, temperature, relative humidity, etc. in and outside the glasshouse were the same throughout the study.

2.4 Agronomic data collection

Plant morphological growth data were collected weekly during 2-6 WAS. Growth parameters considered were plant height (from soil level to the tip of plant); leaf area, estimated as 0.31LW (with L and W as average lengths and widths of two broadest leaves of the seedling, respectively); and number of leaves per plant. At 6 WAS, the plants were cut off from their soil base and allowed to undergo curing at the prevailing ambient temperature at the glasshouse for 48 h before weighing to obtain the above-soil biomass. Plant leaf samples were collected from the cured biomass for P content analysis. This aligned with the proposition of 6 WAS of soybean as its vegetative growth stage for plant nutrient analysis on the mature leaves (Stammer & Mallarino, 2018). The leaf samples were air-dried further for three weeks before the analysis.

2.5 Laboratory analyses

Soil samples were air-dried to constant weight, crushed and passed through a 2-mm mesh sieve before analyses. Soil pH was determined in suspensions of soil in deionized water in a solid-liquid ratio of 1:2.5 (McLean, 1982), and the values measured potentiometrically using a Beckman's zeromatic glass electrode pH metre. Available P was extracted with Bray 2 solution; thereafter, the values were measured colorimetrically using the method described by Olsen & Sommers (1982). Plant P content was analyzed by digesting 0.5 g of plant samples with 20 ml each of nitric acid and perchloric acid, after which the digest was washed with distilled water and later extraction was done using Bray 2 solution (Olsen & Sommers, 1982).

2.6 Data analyses

Data were analysed using GenStat and SPSS software. First, two-way analysis of variance appropriate for CRD experiments was used to test for differences in treatment effects using GenStat. Where significant differences existed, the means were separated by the Fisher's least significant difference procedure at $p \leq 0.05$ (F-LSD$_{0.05}$).

Also, Pearson's bivariate correlations and step-wise multiple linear regressions were carried out using SPSS. This was to examine the relationships among the vegetative growth indices of soybean, soil pH, soil content of available P, and soybean plant P content.

3. Results and discussion

3.1 Effects of lime and manure rates on soybean growth parameters

The effects of lime and manure rates on plant height, leaf area and number of leaves per soybean plant are shown (Figures 1, 2 and 3, respectively). Generally, plant height differed among treatments. The data show a trend of highest values in treatment L$_{2.5}$+PD$_{50}$. Leaf area, however, differed among treatments only at 3 and 4 WAS. The trend observed in leaf area was same as for plant height; highest values were consistently observed in treatment L$_{2.5}$+PD$_{50}$. Number of leaves differed among treatments at 4, 5 and 6 WAS. The highest values for this growth parameter were observed in treatment L$_{2.5}$+PD$_{50}$ at 2 and 3 WAS, while treatment L$_{2.5}$+PD$_{25}$ showed highest values at the later growth stages being 4, 5 and 6 WAS. For all growth parameters measured in this study, lowest values were generally observed in treatment L$_0$+PD$_0$ (control).

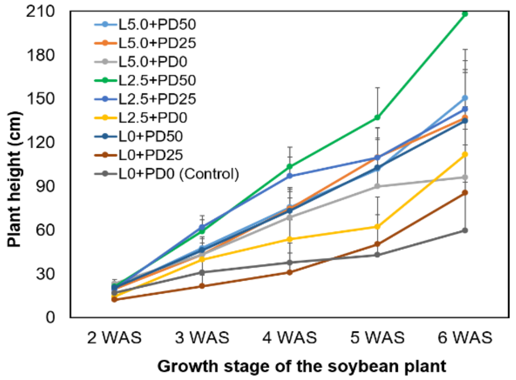

Figure 1. Effects of synthetic lime and poultry-droppings manure application to the coarse-textured acid soil on plant height (cm) of the soybean variety with an indeterminate growth habit used as test crop (*n* = 27). L$_0$, L$_{2.5}$ and L$_{5.0}$ – lime at 0, 2.5 and 5 t ha^{-1}, respectively; PD$_0$, PD$_{25}$ and PD$_{50}$ – poultry-droppings manure at 0, 25 and 50 t ha^{-1}, respectively; WAS – weeks after sowing. Error bars represent Fisher's least significant difference at $p \leq 0.05$ (F-LSD$_{0.05}$).

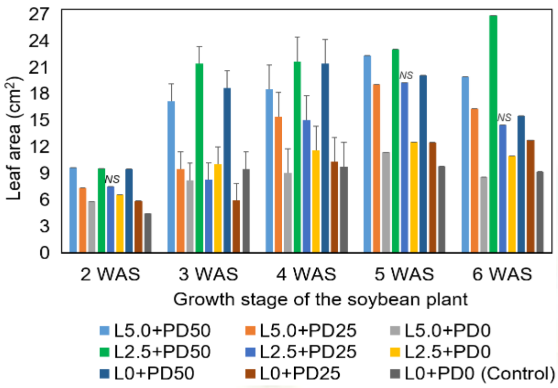

Figure 2. Effects of synthetic lime and poultry-droppings manure application to the coarse-textured acid soil on mean leaf area (cm^2) of the soybean plant (*n* = 27). L$_0$, L$_{2.5}$ and L$_{5.0}$ – lime at 0, 2.5 and 5 t ha^{-1}, respectively; PD$_0$, PD$_{25}$ and PD$_{50}$ – poultry-droppings manure at 0, 25 and 50 t ha^{-1}, respectively; WAS – weeks after sowing; NS – not significant at $p \leq 0.05$. Error bars represent Fisher's least significant difference at $p \leq 0.05$ (F-LSD$_{0.05}$).

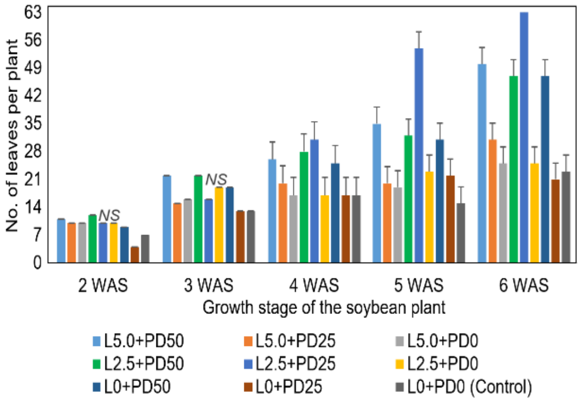

Figure 3. Effects of synthetic lime and poultry-droppings manure application to the coarse-textured acid soil on number of leaves per soybean plant (*n* = 27). L$_0$, L$_{2.5}$ and L$_{5.0}$ – lime at 0, 2.5 and 5 t ha^{-1}, respectively; PD$_0$, PD$_{25}$ and PD$_{50}$ – poultry-droppings manure at 0, 25 and 50 t ha^{-1}, respectively; WAS – weeks after sowing; NS – not significant at $p \leq 0.05$. Error bars represent Fisher's least significant difference at $p \leq 0.05$ (F-LSD$_{0.05}$).

The main effects of treatment showed that lime application rate affected soybean growth. Except for plant height trend of $L_5 > L_{2.5} > L_0$ during 2 WAS, plant height and leaf area generally differed thus $L_{2.5} = L_5 > L_0$ during 2 and 5 WAS, but $L_{2.5} > L_5 > L_0$ and $L_{2.5} > L_5 = L_0$, respectively during 3, 4 and 6 WAS. So, apart from 2 WAS, lime rate of 2.5 t ha^{-1} produced the tallest plants all through the growth phase of the soybean plants. For number of leaves per plant, the trend was $L_{2.5} = L_5 > L_0$ during 2 and 3 WAS, but $L_{2.5} > L_5 = L_0$ during 4, 5 and 6 WAS. The effects of poultry-droppings manure were rather more definite in that all three growth indices of soybean generally differed thus $PD_{50} > PD_{25} = PD_0$ during 2 and 3 WAS and $PD_{50} > PD_{25} > PD_0$ during 4, 5 and 6 WAS. Overall, liming at 2.5 t ha^{-1}, on one hand, and applying manure at 50 t ha^{-1}, on the other hand, enhanced the vegetative growth of soybean the most.

There was a general trend of treatments with lime and manure promoting soybean growth more than sole application of either. Thus, liming and manuring could have synergistic effects in plant growth in acid low-fertility soils. Liming creates a favourable root environment by ensuring desirable soil pH, decreasing Fe and Al toxicity, and enhancing the availability macronutrients. It also improves soil biological activity and mineralization of organic compounds, thereby improving nutrient uptake (Saleem et al., 2017; Takala, 2019). Also, the addition of manures increases microbial activity that ensures the biochemical transformations and mineralization of plant nutrients (Saleem et al., 2017). Liming ensured nutrient elements made available from the manure were accessible for plant uptake due to its effect of decreased acidity. Appropriate combination of synthetic lime and mineral fertilizers could improve the bioavailability of plant nutrients for enhanced crop growth and yields (Ameyu, 2019; Nnadi et al., 2020).

Treatment $L_{2.5}$+PD_{50} tended to show the most pronounced effect on soybean vegetative growth. The optimum 'agronomic' rate of poultry manure for the sandy-loam soil investigated is 20-25 t ha^{-1} (Ogunezi et al., 2019; Onah et al., 2023). So, the $L_{2.5}$+PD_{50} represents co-application of synthetic limes at moderate rates of ≤ 2.5 t ha^{-1} and poultry-droppings manure at ≤ double the subsisting 'agronomic' rate. Treatment $L_{2.5}$+PD_{50} outperforming $L_{5.0}$+PD_{50} indicates the negative effect of over liming on plant growth. Coarse-textured acid tropical soils may thus require low application rates of synthetic limes in the presence of high rates of effective animal manures.

3.2 Treatment effects on above-soil biomass, soil pH and available P, and plant P content

At the end of six-week growth phase, above-soil biomass of the soybean plant as well as soil pH, available P and plant P content were assessed (Table 1). Lime effects on soybean above-soil biomass 6 WAS were such that treatments L_0+PD_0 and $L_{2.5}$+PD_0 were similar and lower than L_5+PD_0, unlike poultry-droppings manure effect that showed significant increases with application rate. Treatments L_0+PD_{25} and $L_{2.5}$+PD_{25} were similar unlike L_0+PD_{50} that produced lower than $L_{2.5}$+PD_{50} and L_5+PD_{50} for which values were similar. These results imply that synthetic lime may not be necessary with poultry-droppings manure at the so-called 'agronomic' rate, but at about the double of this application rate when the lime also needs not be applied beyond the moderate rate of 2.5 t ha^{-1}. Notably, merging L_0+PD_{50} and the control-like $L_{2.5}$+PD_0 gave rise to $L_{2.5}$+PD_{50}, while merging L_0+PD_{50} and L_5+PD_0 both of which were similar gave L_5+PD_{50}. From the standpoint of both the economy of agronomic production and the synergy of lime and manure over sole use of either, therefore, $L_{2.5}$+PD_{50} was the optimal lime-manure combination in this study.

Where the adoption of $L_{2.5}$+PD_{50} is cost-inhibitive, the resource-poor farmer can opt for the runner-up treatment being L_0+PD_{50} or L_5+PD_{25}, whichever is more viable. Halving manure and adding CaO lime which the second of these two treatments is to the first has similarly been reported to be equivalents in soybean production in low-fertility tropical soils (Verde et al., 2013). The next in performance was L_5+PD_0 and it was similar to L_0+PD_{25}.

Table 1

Treatment effects on above-soil biomass of the indeterminate soybean plant, soil pH, soil available P, and plant P content, all assessed at six weeks of age of the plants (*n* = 27)

Treatment	Above-soil biomass (g 2.5-kg^{-1} potted-soil)	Soil pH_{water}	AvP (mg/kg)	% Plant-P
$L_{5.0}$+PD_{50}	18.50	7.4	27.98	0.28
$L_{5.0}$+PD_{25}	14.20	7.2	27.98	0.19
$L_{5.0}$+PD_0	11.87	6.7	9.33	0.15
$L_{2.5}$+PD_{50}	17.19	7.3	48.50	0.33
$L_{2.5}$+PD_{25}	11.40	7.0	22.38	0.16
$L_{2.5}$+PD_0	9.63	6.6	7.46	0.14
L_0+PD_{50}	13.00	7.1	29.85	0.32
L_0+PD_{25}	10.97	6.8	20.52	0.16
L_0+PD_0 (Control)	8.27	5.8	5.60	0.12
F-LSD$_{(0.05)}$	*1.47*	*0.06*	*0.16*	*0.01*

L_0, $L_{2.5}$ and $L_{5.0}$ – lime at 0, 2.5 and 5 t ha^{-1}, respectively; PD_0, PD_{25} and PD_{50} – poultry-droppings manure at 0, 25 and 50 t ha^{-1}, respectively; AvP – available phosphorus; Plant-P – plant P content.

Treatments $L_{2.5}+PD_{50}$ and $L_{5.0}+PD_{50}$ being similar in plant above-soil biomass could be attributed to the low clay content of the soil and the overall environmental setting of the study, lime and manure types used and their application rates tested, and/or the short-duration nature of the study (Moreira et al., 2015; Kabango et al., 2022; Akpan et al., 2023). The present observation indicates that CaO lime is required at ≤ 2.5 t ha^{-1} in the presence of a P source for growing arable crops in acid loamy soils of the humid tropics (Opala, 2017). Beyond this rather moderate rate of lime, the corresponding rate of manure (about double the 'agronomic' rate) needed to maintain production at optimal levels would initially remain unchanged. However, an inverse lime-manure rate relationship might later set in. From the study site, Nnadi et al. (2020) reported increases in sweet potato yields due to co-application of CaO lime at 10 t ha^{-1} and poultry-droppings manure at 20 t ha^{-1}. By its liming/SOM-enhancing effects in this soil, $L_{2.5}+PD_{50}$ would improve soil fertility (Umeugokwe et al., 2021), aggregation/structure (Obalum et al., 2024), or both (Ogunezi et al., 2019; Obalum et al., 2020; Ogumba et al., 2024), leading to increased crop vegetative growth (Ebido et al., 2021). For soybean, however, any improvements in soil aggregation/structure most unlikely contributed to the highest vegetative growth due to this $L_{2.5}+PD_{50}$ treatment (Obalum et al., 2011b; Osakwe et al., 2023).

Treatment affected soil pH, available P and plant P content. Soil pH was highest and lowest in L_5+PD_{50} and L_0+PD_0 (control), respectively, with generally higher values with (7.0 - 7.4) than without (6.6 - 7.1) combination of lime and manure (Table 1). Soil available P and plant P content were highest in $L_{2.5}+PD_{50}$, followed by L_0+PD_{50}, while the lowest values were from the control. Liming indirectly influences mineralization of manure-added nutrients by increasing soil pH which creates favourable conditions for microbial activities (Dada & Ewulo, 2011), and this leads to increases in plant uptake of the nutrients (Islam et al., 2021). Notably, treatments L_5+PD_0 and L_0+PD_{25} bearing only lime and only manure, respectively were similar in above-soil biomass, soil pH and plant P content but differed widely in soil content of available P. By this observation, 5 times the application rate of CaO lime would be needed of poultry-droppings manure to produce a similar effect on soil pH, implying that this manure's equivalent of CaO lime for the soil studied is 20%. Again, the observation indicates dependence of agronomic response to lime-manure amendments on soil pH-regulated bioavailable P rather than soil available P.

The main effects of treatment showed that both lime and manure contributed to the variations in the four plant and soil variables just presented. Soybean above-soil biomass and soil pH decreased with lime application rate ($L_{5.0} > L_{2.5} > L_0$), unlike soil available P ($L_{2.5} > L_5 > L_0$) and plant P content ($L_{5.0} = L_{2.5} > L_0$); while all four variables decreased with manure rate ($PD_{50} > PD_{25} > PD_0$). The increases in soil pH with an increase in lime rate can be associated with a decrease in hydrogen ions by its neutralization effect and an increase in hydroxyl ions following application of lime (Bolan et al., 2003; Antoniadis et al., 2015; Li et al., 2019). Lime effect on soil available P suggests a lime-induced precipitation of Fe and Al as insoluble compounds (Antoniadis et al., 2015) and hence decrease of Fe and Al binding/fixation of P at the optimal rate of lime, beyond which Ca fixation of P occurs (Amsalu & Beyene, 2020). Also, the deprotonation of Fe and Al hydroxides and the accompanying increases in negative surface charge with increasing soil pH contributes to an increase in available P (Opala, 2017). The higher Plant P content in limed potted soils could be explained by enhanced release of soil nutrients including P, making it available for plant uptake.

Increasing soil pH with increase in manure rate in this study could be attributed to the release of cations following the mineralization of SOM. The increased presence of cations counters acidity and decreases exchangeable Al in soils amended with manure. Addition of manure has severally been reported to increase soil pH (Soremi et al., 2017; Ogunezi et al., 2019; Okebalama et al., 2020; Ndzeshala et al., 2023; Onah et al., 2023; Chukwuma et al., 2024). Increases in P availability with poultry droppings rate can be attributed to the mineralization of organic P in the manure. Organic acids from SOM adhering to sorbing surfaces can inhibit phosphate adsorption via adsorption site competition, whereby they mask and prevent fixation sites from interacting with phosphate ions in solution (Borggaard et al., 2005; Brady & Weil, 2008). Also, these negatively charged organic molecules adsorb or complex Fe and Al ions in acid soils (Haynes & Mokolobate, 2001; Brady and Weil, 2008). This could inhibit their crystallization and decrease their role in P sorption or precipitation. The phenomenon of increases in soil available P as a result of poultry manure application has severally been reported for the coarse-textured soils of the study area (Ogunezi et al., 2019; Obalum et al., 2020; Okebalama et al., 2020;

Umeugokwe et al., 2021; Ndzeshala et al., 2023; Onah et al., 2023; Chukwuma et al., 2024).

The increases in plant P uptake and content due to poultry-droppings manure addition are attributed to increased availability of P as a result of organic matter mineralization. Manure is known to be a reservoir of essential macronutrients, and the nutrients are released upon decomposition and mineralization (Ogunezi et al., 2019; Nnadi et al., 2021). Improved availability of soil nutrient contents following poultry manure addition was reported to increase uptake and hence concentrations of nutrients in plant tissues (Ewulo et al., 2008; Ogunezi et al., 2019).

3.3 Relationships among soybean growth, soil pH, soil available P, and plant P content

The coefficients of the bivariate correlations among growth/productivity indices of soybean, soil pH in water, soil available P, and plant P content are presented (Table 2). There were positive correlations among growth/productivity indices, all of which were significant except that between above-soil biomass and number of leaves. Soil pH, soil available P and soybean plant P content all had significant positive correlations with plant height, leaf area and above-soil biomass, but non-significant positive correlation with number of leaves. Also, soil pH correlated positively with soil available P and plant P content, both of which were also positively correlated. Soil pH often shows weak correlations with available P in the absence of soil acidity-ameliorating amendments in Nigeria (Obalum et al., 2012; Obalum and Chibuike, 2017; Ukabiala et al., 2021). Therefore, soil pH correlating with soil available P here could be attributed to the lime-manurial amendments' alteration of the former (Sato & Comerford, 2005; Ogunezi et al., 2019; Chukwuma et al., 2024) and/or to the use of one soil type of similar texture (Ifeanyi-Onyishi et al., 2024). As found here, P extractable from soil can be directly related to P concentrations in plants (Bolan et al., 2003).

Soybean growth/productivity indices were regressed on soil pH, soil available P and plant P content (Table 3). Plant height was predicted by soil available P and leaf area by plant P content. Number of leaves per plant was not predicted any of the three independent variables, understandably because it was the only plant growth index that had no correlations with these indices. Instead, it was influenced by plant height. Soybean above-soil biomass was predicted by soil pH. However, repeating this regression analysis with plant height, leaf area and number of leaves included among the independent variables showed the soil available P-controlled plant height to be an alternative, equal-strength predictor of above-soil biomass. This points not just to the inter-relationships among plant height, above-soil biomass, soil pH and soil available P, but also to the underlying influence of soil pH on available P's control of biomass production in coarse-textured, low-fertility soils of the humid tropics.

Table 2

Matrix of the coefficients of correlations (*r*) among growth/productivity indices of soybean†, soil pH in water, soil available P and plant P content (*n* = 9)

	Plant height	Leaf area	No. of leaves	Above-soil biomass	Soil pH_{water}	Soil AvP	Plant-P
Plant height	-						
Leaf area	0.85**	-					
No. of leaves	0.83**	0.74*	-				
Above-soil biomass	0.86**	0.85**	0.57	-			
Soil pH_{water}	0.82**	0.76*	0.66	0.86**	-		
Soil AvP	0.83**	0.90**	0.66	0.81**	0.80*	-	
Plant-P	0.72*	0.92**	0.59	0.81**	0.72*	0.86**	-

†For plant height, leaf area and number of leaves, mean values for the five consecutive sampling times (2, 3, 4, 5 and 6 weeks after sowing) were used for the correlations. AvP – available phosphorus; Plant-P – plant P content; * and **significant at $p \leq 0.05$ and 0.01, respectively.

Table 3

Results of multiple linear regressions of growth/productivity indices of soybean† on soil pH, soil available P and plant P content (*n* = 9)

Regression models	R^2	Adj. R^2	SEE
Plant height = 39.986 + 1.502AvP	0.692	0.648	14.559
Leaf area = 2.037 + 55.062plant-P	0.852	0.831	1.998
Number of leaves = 7.205 + 0.213plant-height‡	0.684	0.639	3.788
Above-soil biomass = –27.948 + 5.922soil-pH	0.735	0.697	1.853
Above-soil biomass = 4.484 + 0.118plant-height‡	0.742	0.705	1.827

†For plant height, leaf area and number of leaves, mean values for the five consecutive sampling times (2, 3, 4, 5 and 6 weeks after sowing) were used for the regressions. ‡Plant growth parameters were included among the independent variables. AvP – available phosphorus; Plant-P – plant P content; SEE – standard error of the estimate. All the regressions are significant at $p \leq 0.01$.

The dependence of soybean growth/productivity on soil pH, available P, and plant P content was expected because of treatment-mediated influence of soil pH on P availability in the soil studied (Ogunezi et al., 2019; Chukwuma et al., 2024), especially with its not varying in soil texture (Ifeanyi-Onyishi et al., 2024). It was also because of soil pH's underlying influence on plant's preferential uptake of P from this soil for increased crop productivity (Ndzeshala et al., 2023). Similar to our data, Ndzeshala et al. (2023) and Ugwu et al. (2024) reported that about 88% of the variations in maize growth responses to nutrient-supplying organic amendments in potted coarse-textured, low-fertility soils of the study area to be in line with soil available P content. Treatment $L_{2.5}$+PD_{50} being the optimal lime-manure combination, lime main effect on soil available P being $L_{2.5} > L_5 > L_0$, and soybean P nutrition playing a prominent role in its productivity are in unison.

With the role of soybean P nutrition in its biomass productivity in this study highlighted, the major mechanism behind $L_{2.5}$+PD_{50}'s effectiveness was most likely decreased Fe-Al fixation of P with increasing soil pH (Amsalu & Beyene, 2020). This $L_{2.5}$+PD_{50} could not outperform L_5+PD_{50}, suggesting that the poultry-droppings manure component of these treatments, being above the optimum 'agronomic' rate of 20-25 t ha^{-1} for this soil (Ogunezi et al., 2019; Onah et al., 2023), supplied P in excess of soybean requirement. So, the liming above the optimal rate of 2.5 t ha^{-1} in treatment L_5+PD_{50} probably led to Ca fixation of the excess P from the poultry-droppings manure component of this treatment (Amsalu & Beyene, 2020), such that it would not contribute to further P nutrition and hence biomass accumulation by the plant.

Therefore, $L_{2.5}$+PD_{50} is adopted as the optimal lime-manure combination for arable crops in the study area and similar humid tropical agro-environments. The lime-manure ratio in $L_{2.5}$+PD_{50} is 0.05. This is rather low compared to the most effective ratio of 0.13 from a field-based evaluation of soybean responses to dolomite lime and cattle-dung manure effects in a clayey Brazilian Oxisol (Moreira et al., 2015). The use of potted soils in our study and differences in environmental setting, soil type, and lime-manure types may explain the lower ratio in the adopted $L_{2.5}$+PD_{50}.

4. Conclusions

As a test crop, soybean showed interesting agronomic responses to the effects of co-application of CaO lime and/or poultry-droppings manure in the acid sandy-loam soil of this study. Co-application of these synthetic and organic amendments at the rates of 2.5 and 50 t ha^{-1}, respectively to the soil enhanced the vegetative growth and above-soil biomass of the crop better than the other rate-varying options of lime-manure combinations. The increases in soybean productivity due to this lime-manurial amendment option were largely a reflection of the increased availability of soil P and plant uptake of same.

The application of synthetic lime and/or animal manure to acid coarse-textured soils of the humid tropics can influence arable crops production in the region. Increasing the agronomic productivity of these soils would require the use of CaO lime at moderate rates with poultry-droppings manure at about double the optimum 'agronomic' rates. The increases would be due to ameliorated soil acidity and hence elevated soil fertility status evidenced by increased P bioavailability. For the acid sandy-loam soil studied and similar coarse-textured soils of the Derived Savannah, arable crops production would benefit specifically from co-application of CaO lime at 2.5 t ha^{-1} and poultry-droppings manure at 50 t ha^{-1}. This viable soil fertility management option is, therefore, suggested for coping with soil acidity and related P-fixation problems in arable crops production.

Long-duration field trials on agronomic evaluations of the immediate and residual effects of the suggested option on the overall soil/environmental quality in this and similar agro-environments are, however, needed to comment on its sustainability and validate its adoption. Such future studies can involve various lime and manure types and can explore the relative contributions of organic and inorganic P to the enhanced P bioavailability due to appropriate lime-manure combination.

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Ethical Implications

This article has no ethical implications.

Conflict of Interest

The authors declare no conflicts of interest in this study.

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