Response of soybean (Glycine max L.) to application of lime and phosphate fertilizer in an acid soil of western Kenya

Article *in* Archives of Agriculture and Environmental Science · December 2020

DOI: 10.26832/24566632.2020.050406

Peter Opala
Maseno University

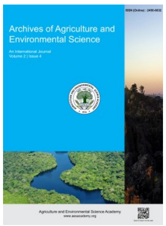
Archives of Agriculture and Environmental Science 5(4): 470-475 (2020)
https://doi.org/10.26832/24566632.2020.050406

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



ORIGINAL RESEARCH ARTICLE

Response of soybean (*Glycine max* L.) to application of lime and phosphate fertilizer in an acid soil of western Kenya

Peter Asbon Opala

Department of Soil Science, Maseno University, P.O. Box, Private Bag Maseno, Kisumu County, KENYA
E-mail: ptropala@yahoo.com

ARTICLE HISTORY

Received: 07 October 2020
Revised received: 24 November 2020
Accepted: 10 December 2020

Keywords

Acidity
Kenya
Lime treatment
Phosphorus
Soybean (*Glycine max* L.)

ABSTRACT

The effect of combining lime and phosphate fertilizer on the performance of soybean (*Glycine max* L.) was investigated in a pot experiment consisting of nine treatments of three rates of lime (0, 4 and 8 t ha^{-1}) in a factorial combination with three rates of phosphorus (0, 15, and 30 kg P ha^{-1}) at Maseno University in western Kenya. There was a significant interaction between the lime and phosphorus rate on the biomass dry weight of soybean. At the rates of 0 and 4 t ha^{-1} of lime, the biomass dry weight of soybean increased with increasing rates of phosphorus but at 8 t ha^{-1} of lime, the dry weight of soybean increased from 0 to 15 kg P ha^{-1} but declined at 30 kg P ha^{-1}. There was however no significant interaction between lime and P rates on grain weight but the effects of both P and lime rate were significant. When applied without lime, 30 kg P ha^{-1} gave significantly higher grain (5.3 g pot^{-1}) weight than 15 kg P ha^{-1}(1.6 g pot^{-1}) of soybean, which was also significantly better than the control (0.0 g pot^{-1}). When applied without phosphorus, both lime rates at 4 and 8 t ha^{-1}significantly increased grain weights of soybean compared to the control, but the grain weights of soybean between the two lime rates did not differ significantly. The highest yields of soybean were obtained when 4 t ha^{-1}of lime was applied with 30 kg P ha^{-1} (19 g pot^{-1}). Therefore, this study demonstrates that the ameliorating deleterious effects of soil acidity through liming should simultaneous be accompanied by application of P fertilizer at appropriate rates.

Citation of this article: Opala, P.A. (2020). Response of soybean (*Glycine max* L.) to application of lime and phosphate fertilizer in an acid soil of western Kenya. *Archives of Agriculture and Environmental Science*, 5(4): 470-475, https://dx.doi.org/10.26832/24566632.2020.050406

INTRODUCTION

Soybean bean (*Glycine max* L. Merr.) production has in recent years been promoted as an alternative to the common bean (*Phaseolus vulgaris*) in western Kenya in endeavors to diversify food sources and enhance food security (Chianu *et al.*, 2007; Collombet, 2013). It has potentially higher yields and is richer in proteins than the common bean (Otieno *et al*, 2018). It can also be used to produce oil and biofuels among other uses and hence its economic returns are higher than those of common grain legumes (Mathu *et al.*, 2010). Soybean is also reputed to be better at fixing atmospheric nitrogen and therefore has a higher potential to replenish soil fertility than the common bean which is inherently a poor nitrogen fixer (Fageria *et al.*, 2014; Muñoz-Azcarate, 2017). However, soil acidity and phosphorus deficiencies, which often occur concurrently, constrain soybean production in western Kenya with the average yields of 0.93 t ha^{-1}reported from farmers' fields against a potential of more than 3.5 t ha^{-1} for improved varieties under optimal growth conditions (Mahasi *et al.*, 2010; Verde *et al.*, 2013). In particular, acid soils at pH of less than 5.5 impact negatively on soybean growth by accentuating Al toxicity, reducing nitrogen fixing bacterial activity, and increasing phosphorus fixation therefore reducing available P in soils **(**Matsumoto, 2000; Liao *et al.*, 2006**)**. Phosphorus is necessary for many plant processes including synthesis of phospholipids, energy transfer, and enzyme activation **(**Hawkesford *et al.*, 2012). Phosphorus is required by soybean for nodule development and functioning and hence biological nitrogen fixation (BNF) (Divito and Sadras, 2014). When phosphorus in soil is low, these processes can be inhibited and therefore limit yields.

Phosphorus deficient acid soils can effectively be ameliorated by application of phosphate fertilizers and agricultural lime. The appropriate rates of lime and P for soybean in western Kenya are however not well established. There is therefore a likelihood of farmers mismanaging application of these inputs which could lead to poor crop performance (Boke and Fekadu, 2014). Over liming has been reported to increase deficiencies of micronutrients such as Zn, Cu and Mn while under liming is not effective in ameliorating the deleterious effects of acidity (Sanchez, 2019). Furthermore, lime could interact with the applied phosphate fertilizer to either negatively or positively impact on soybean performance. At very high pH, P can be fixed as calcium phosphate by the applied lime but when the pH is raised to around 6.5, phosphorus and most other nutrients become available thus enhancing crop growth (Penn and Camberato, 2019). There is however paucity of information on these interactive effects on performance of soybeans in western Kenya. The objective of this study was therefore to determine the effects of lime and phosphate fertilizer and their interaction on the growth and yield of soybean in a greenhouse pot experiment. The results of the study provide useful information to researchers and agricultural extension workers on the appropriate combination of lime and phosphate fertilizer to be used for optimum productivity of soybeans in western Kenya.

MATERIALS AND METHODS

Experimental site and soil

A greenhouse pot experiment was conducted from January to April 2019 at Maseno University 0°00'17.36°S latitude and 34° 30'01.62'E longitude in western Kenya. The soil that was used in the study was a Ferralsol obtained from a farmer's field and whose initial properties (Table 1) were determined before the establishment of the experiment. The soil was very acidic (pH < 5), low in available P, N, cation exchange capacity (CEC) and exchangeable bases. It however had an adequate amount of organic matter, likely because it had been under natural vegetation for several years.

Experimental design and management

The soil was collected randomly from various spots from a farmer's field at a depth of 0-20 cm. It was subsequently air-dried, sieved through a 4 mm mesh, homogenized by hand mixing and applied in all the pots, which consisted the experimental units at a rate 4 kg of soil pot^{-1}. Nine treatments consisting of three levels of lime (0, 4 and 8 t ha^{-1}) in a factorial combination with three rate of P (0, 15, and 30 kg P ha^{-1}) (Table 2) were imposed and replicated thrice in a completely randomized design. Agricultural lime with 70% calcium carbonate ($CaCO_3$) equivalent and triple superphosphate (46% P_2O_5) were used as the sources of lime and P respectively. Calcium ammonium nitrate and muriate of potash were applied to all the treatments at the rate of 20 kg ha^{-1} and 60 kg ha^{-1}to supply N and K which are often limiting in these soils. All the fertilizers and lime were incorporated and thoroughly mixed with the soil at the time of planting. Four soybean seeds were planted per pot and later thinned to two at one week after emergence. Soil moisture content was maintained at around field capacity by regular watering. Other agronomic practices such as weeding and pest control were done at appropriate times.

Data collection

Soil was sampled at 14 weeks after planting (WAP) immediately after harvesting the soybean from each treatment and analyzed for soil pH, exchangeable acidity and available phosphorus using standard procedures as described by Okalebo *et al.* (2002). Soil pH was determined potentiometrically using water as the extractant (2.5:1 soil: water ratio) and exchangeable acidity with 1M KCl extractions followed by titration with NaOH. Available phosphorus was determined by the Olsen method (sodium bicarbonate extractant at pH 8.5) which has been reported to correlate well with crop yields in acid soils of western Kenya although it was developed for alkaline soils (Nyambati and Opala, 2014). Plant heights were measured weekly up to seven WAP while the grain yields were determined at physiological maturity. The biomass dry weights were determined by harvesting the aerial parts of the plants, placing them in paper bags and then oven drying them at 70°C to a constant weight.

Statistical analysis

Data for soil analyses, plant heights, biomass dry matter and grain yields were subjected to analysis of variance using the GENSTAT Discovery Edition 3 statistical package. Where significant, the least significant difference between means (LSD) was used to separate the treatment means at the significance level of $p \leq 0.05$.

Table 1. Initial characteristics of the experimental soil.

Soil parameter	Value
pH (H_2O)	4.65
Exchangeable acidity (cmol kg^{-1})	1.95
Exchangeable Al (cmol kg^{-1})	1.88
Total N (%)	0.16
Acid saturation (%)	69.20
Organic C (%)	2.42
Bicarbonate extractable P (mg kg^{-1})	2.20
Exchangeable K (cmol kg^{-1})	1.30
Exchangeable Ca (cmol kg^{-1})	0.24
Exchangeable Mg (cmol kg^{-1})	0.30
CEC	3.68
Clay (%)	46.90
Sand (%)	35.60
Silt (%)	17.60

Table 2. Description of different treatments combinations used in the study.

Treatment number	Treatment combination	Treatment code
1	0 t ha^{-1}lime, 0 kg P ha^{-1}	0L0T
2	0 t ha^{-1}lime, 15 kg P ha^{-1}	0L15T
3	0 t ha^{-1}lime, 30 kg P ha^{-1}	0L30T
4	4 t ha^{-1}lime, 0 kg P ha^{-1}	4L0T
5	4 t ha^{-1}lime, 15 kg P ha^{-1}	4L15T
6	4 t ha^{-1}lime, 30 kg P ha^{-1}	4L30T
7	8 t ha^{-1}lime, 0 kg P ha^{-1}	8L0T
8	8 t ha^{-1}lime, 15 kg P ha^{-1}	8L15T
9	8 t ha^{-1}lime, 30 kg P ha^{-1}	8L30T

RESULTS AND DISCUSSION

Soil pH, exchangeable acidity and available phosphorus

There was no significant effect of phosphorus rate or lime x phosphorus rate on soil pH (Table 3). The effect of lime on soil pH was however significant. In general pH increased with increasing lime rate but the difference between 4 and 8 t ha^{-1} lime rates was not significant. Exchangeable acidity in contrast decreased with increasing lime rate irrespective of the P rate but again the difference between 4 and 8 t ha^{-1}lime rates was not significant (Table 3). When applied with no lime, P at 15 and 30 kg ha^{-1} significantly lowered the exchangeable acidity compared to treatments with no P application but there was no significant difference between the two P rates (15 and 30 kg ha^{-1}).

The observed increase in pH with lime application and concurrent decrease in exchangeable acidity is to be expected. Lime is known to increase the soil pH by releasing OH^- ions which react with Al^{3+} in soil solution and therefore precipitate aluminum as $Al(OH)_3$ (Caires *et al.*, 2002; Hue, 2004). This has the effect of reducing exchangeable acidity which comprises $Al^{3+}$and H^+. The lack of significant differences in exchangeable acidity among the lime treatments is likely due to the fact that the entire aluminum was precipitated with application of lime at both rates, and the exchangeable acidity that was determined was therefore entirely due to H^+ (Opala, 2017).

The available P levels were generally low (Table 4). There was a significant interaction between phosphorus and lime whereby when no phosphorus was applied, lime rates of 4 and 8 t ha^{-1} gave significantly higher amounts of available phosphorus than 0 t ha^{-1} lime but when phosphorus was applied at 15 and 30 kg ha^{-1}, there was no significant difference in available phosphorus among the lime rates. When averaged across P rates, the available P at 4 and 8 t ha^{-1} were similar but significantly higher than 0 t ha^{-1}. When averaged across lime rates, the available P at 0 and 15 kg ha^{-1} were similar but significantly lower than at 30 kg ha^{-1}. Although the available phosphorus generally increased with increasing phosphorus rates, the highest value was still below the critical level of 10 mg kg^{-1} that is considered adequate for most crops in Kenya (Okalebo *et al.*, 2002). The inability of the applied phosphorus to increase the available phosphorus beyond this critical value is partly attributed to P fixation which is common in Ferralsols in western Kenya (Opala *et al.*, 2010; Kisinyo *et al.*, 2014) and therefore higher rates of phosphorus may be required to maintain the available phosphorus above the critical level in this soil. Both rates of lime increased available soil phosphorus when no phosphate fertilizer was applied, implying that lime primed the fixed P. The reported effects of liming on P availability are however contradictory, with some indicating increased availability while others show no effects or even reductions in available P. Antoniadis and Koutroubas (2015) found that liming was only effective in increasing available P where the initial total soil P was high. On the other hand, Jaskulska *et al.* (2014) reported that regular application of lime to acidic soils resulted in an increase in plant available phosphorus. This is attributed to the fact that liming increases soil pH, which enhances the release of phosphate ions fixed by Al and Fe ions into the soil solution (Ameyu, 2019). At high soil pH values, however the precipitation of insoluble calcium phosphates can decrease phosphate availability which may explain the lower mean P values at 8 t ha^{-1} compared to at 4 t ha^{-1}.

Soybean growth and yields

Plant growth increased with time for all the treatments except for the control (0L0P) which only increased in the first two weeks and thereafter stopped (Figure 1). Similarly, increase in height for treatment 0L15P declined drastically after 4 WAP. The tallest plants at all sampling were observed in treatment 4L30P followed by the 8L30P. The difference between the two was more pronounced at 6 and 7 WAP. Lime at a rate of 4 or 8 t ha^{-1} applied with P at 15 kg ha^{-1} had similar plant heights and were better than 0P4L and 0P8L which had similar growth patterns. The effect of applying 30 P kg ha^{-1}without lime was significantly better than 15 P without lime kg ha^{-1}. However, these two treatments had shorter plants at the 7 WAP compared to lime (at both rates) without P inputs.

The better growth when lime was applied at 4 t ha^{-1} compared to 8 t ha^{-1} is attributed to possible over liming at 8 t ha^{-1} where the average pH was 6.74. Sanchez (2019) pointed out that variable charge soils of the tropics such as those of the present study should not be limed to pH above 6.0 because growth and yield could decrease. At higher lime rates, deficiencies of micronutrients such as Zn, Mn and Cu may occur (Fageria, 2009) and lead to poor growth. Application of 30 P kg ha^{-1} without lime gave significantly taller plants than 15 P without lime kg ha^{-1}. However, these two treatments had shorter plants at the 7 WAP compared to lime (at both rates) without P inputs. This suggests that soil acidity was more limiting to soybean growth than P deficiency in this soil.

Table 3. Effect of lime and phosphorus rates on soil pH and exchangeable acidity.

	pH				**Exchangeable acidity (cmol kg^{-1})**			
	Lime rate (t ha^{-1})				**Phosphorus rate (kg ha^{-1})**			
	0	**15**	**30**	**means**	**0**	**15**	**30**	**means**
0	4.72	4.67	4.91	4.77	2.42	1.91	1.92	2.08
4	5.56	5.64	6.33	5.84	0.40	0.30	0.30	0.32
8	6.86	6.61	6.76	6.74	0.30	0.26	0.16	0.24
Means	5.72	5.64	6.00	5.78	1.04	0.82	0.79	0.88
LSD								
Lime rate		0.73				0.29		
P rate		0.75				0.28		
Lime × P rate		1.27				0.50		

Table 4. Effect of lime and phosphorus rates on available phosphorus.

Lime rate (t ha^{-1})	**Phosphorus rate (kg ha^{-1})**			
	0	**15**	**30**	**Means**
	Available P mg kg^{-1}			
0	4.19	6.15	7.38	5.91
4	6.49	6.70	9.19	7.46
8	6.38	6.76	8.37	7.17
Means	5.69	6.54	8.31	6.85
LSD				
Lime rate		1.16		
P rate		1.14		
Lime × P rate		2.01		

Table 5. Effect of lime and phosphorus rates on soybean grain weight and biomass dry weight.

	Grain weight (g/pot)				**Biomass dry weight (g/pot)**			
	Lime rate (t ha^{-1})				**Phosphorus rate (kg ha^{-1})**			
	0	**15**	**30**	**means**	**0**	**15**	**30**	**means**
0	0.0	1.6	5.3	2.3	3.0	9.6	12.	68.4
4	6.2	14.8	19.0	3.3	18.6	40.8	53.4	37.6
8	7.5	13.3	17.3	12.6	17.4	53.4	45.7	33.0
Means	2.3	10.0	13.9	9.4	13.0	28.8	37.2	26.3
LSD								
Lime rate		1.6				5.7		
P rate		1.6				5.7		
Lime × P rate		2.6				9.9		

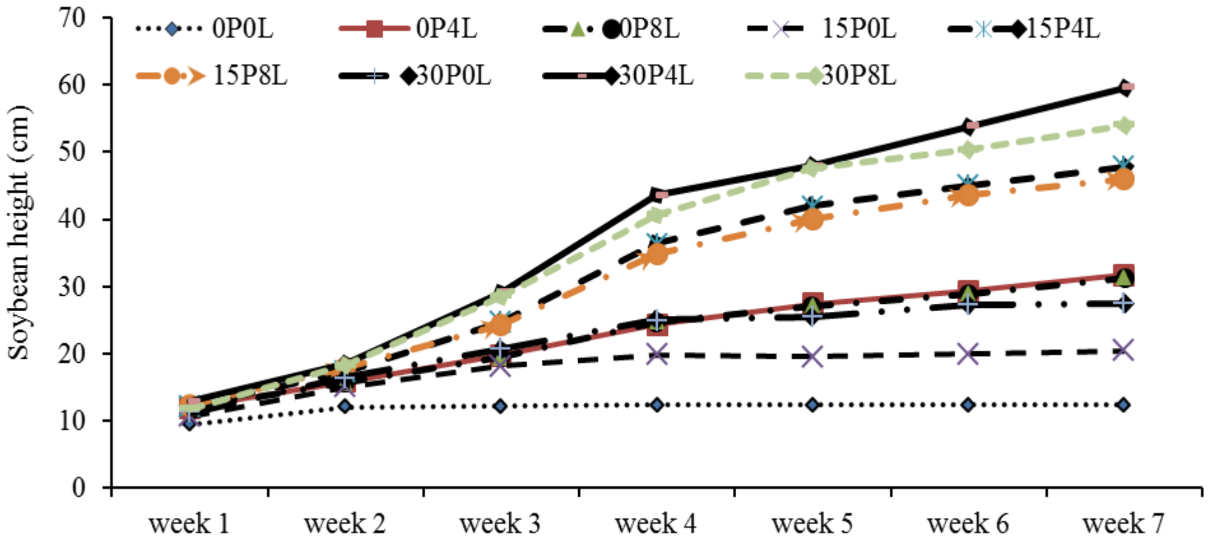


Figure 1. *Soybean heights as affected by lime and phosphate fertilizer rates.*

The effects of treatments on grain weight of soybean are presented in Table 5. The grain weights ranged from 0 g pot^{-1} for the control treatment to 19 g pot^{-1} (4L30P). There was no significant interaction between lime and P rates on grain weight. However, the effects of both P and lime rate were significant. When applied without lime, 30 kg P ha^{-1} gave significantly higher grain weights than 15 kg P ha^{-1}, which was also significantly better than the control. When applied without phosphorus, both lime rates significantly increased grain weights compared to the control, but the grain weights between the lime rates did not differ significantly.

The effect of both phosphorus and lime rates on biomass dry weight of soybean was significant ($p < 0.001$) (Table 5). The interaction between the lime and phosphorus rate was also significant ($p = 0.02$). At the rates of 0 and 4 t ha^{-1} of lime, the biomass dry weight increased with increasing rates of phosphorus but at 8 t ha^{-1} of lime, the dry weight increased from 0 to 15 kg P ha^{-1} but declined at 30 kg P ha^{-1}. The highest biomass dry weight was obtained with 4L30P. This treatment had its pH (6.3) within the optimum range for soybean (pH 6.0-6.5) and also had the highest available P (9.19 mg kg^{-1}). The lowest was dry weight was obtained with control (OL0P). The cessation of growth and subsequent lack of grain for OL0P is attributed to the high Al saturation (69.2%) which cannot be tolerated by soybean as acidic soil reaction with an Al saturation level above 50% has been found to be potentially toxic to soybean (Wijanarko and Taufiq, 2016). The better, though non-significant growth compared to the control, observed for the other treatments without lime but with P fertilizer application is attributed to the slight reductions in exchangeable acidity observed for this treatments (Table 3). Phosphorus from the applied fertilizer can react with Al during the fixation process hence removing it from the soil solution. Similar reductions in Al due to application of phosphate fertilizers have been reported (Iqbal *et al*., 2010). However the effect of P on Al is dependent on the source of P fertilizer and therefore these results should be treated with caution. For example, prolonged use of acidifying phosphate fertilizers such as diammonium phosphate has been shown to increase the exchangeable acidity and hence Al levels in soils (Rengel, 2003). Averaged across lime rates, 30 kg P ha^{-1} gave significantly higher dry weights than 15 kg P ha^{-1}. This is consistent with the higher levels of available P in the 30 kg P ha^{-1}than the 15 kg P ha^{-1}treatments and confirms the need to apply higher P fertilizer rates in this soil as it is responsive to P.

The positive effect of liming on growth and grain yield even without phosphorus compared with the control with no phosphorus is attributed partly to the increased available phosphorus that was observed when lime was applied without phosphorus but the main reason is the reduction of exchangeable aluminum in soil. This resulted in elimination of aluminum toxicity, consequently allowing the soybean to utilize the soil nutrients more efficiently than when lime was not applied. Similar positive effects of liming on soybean yields have been reported in other studies (Ameyu and Asfaw, 2020; Wijanarko and Taufiq, 2016; Keino *et al*., 2015). The yield increase with liming is also attributed to improvement of the calcium soil content, biological N_2 fixation and enhancement net mineralization of organic N (Fageria and Baligar, 2003; Edmeades, and Ridley, 2003).

Conclusion

Application of lime without phosphate fertilizer or phosphate fertilizer without lime only slightly increased the growth and yield of soybean compared to the control with no inputs. Generally, soybean growth and grain weight increased with increasing phosphorus rate signifying that it is beneficial to apply higher rates of phosphorus in this soil. However, at the same phosphorus rate, there were no significant differences between the lime rate of 4 and 8 t ha^{-1} and there may therefore no need to apply lime beyond 4 t ha^{-1}. Application of lime without phosphorus did not produce soybean grains because of Al toxicity and severe phosphorus deficiency. Ameliorating the harmful effects of soil acidity must therefore concomitantly be accompanied by measures to mitigate phosphorus deficiency in this soil.

REFERENCES

Ameyu, T. (2019). A Review on the potential effect of lime on soil properties and crop productivity improvements. *Journal of Environment and Earth Science*. 9: 17-23.

Ameyu, T. and Asfaw, E. (2020). Effect of lime and phosphorus fertilizer on soybean [*Glycine max* L. (Merrill)] grain yield and yield components at Mettu in South Western Ethiopia. *International Journal of Environmental Monitoring and Analysis*, 8: 144-154.

Antoniadis, V and Koutroubas, V.A. (2015). Phosphorus availability in low-P and acidic soils as affected by liming and P addition. *Communications in Soil Science and Plant Analysis*, 46: 1288-1298.

Boke, S. and Fekadu, A. (2014). Lime and NPK effect on soil acidity and yield of barley in different acid soils of southern region, *Ethiopia International Journal of Natural Sciences Research*, 2: 113-122.

Caires, E.F., Feldhaus, I.C., Barth, G. and Garbuio, F.J. (2002). Lime and gypsum application on the wheat crop. *Scientia Agricola*, 59: 357–364.

Chianu, J., Vanlauwe, B., Mukalama, J., Adesina, A. and Sanginga, N. (2007). Farmer evaluation of improved soybean varieties being screened in five locations in Kenya: Implications for research and development. *African Journal of Agricultural Research*, 1: 143-150.

Collombet, R.N. (2013). Investigating soybean market situation in Western Kenya: constraints and opportunities for smallholder producers. Minor thesis in Plant Production Systems, Wageningen University, The Netherlands.

Divito, G.A. and Sadras, V.O. (2014). How do phosphorous, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture egumes? *Field Crop Research*, 156: 161–171.

Edmeades, D.C. and Ridley, A.M. (2003). Using lime to ameliorate topsoil and subsoil acidity. In: Rengel Z., ed. Handbook of soil acidity. New York, Marcel Dekker. pp. 297- 336.

Fageria, N.K. (2009). The use of nutrients in crop plants. Boca Raton, CRC Press, pp.430.

Fageria, N.K. and Baligar, V.C. (2003). Fertility management of tropical acid soil for sustainable crop production. In: RENGEL, Z., ed. Handbook of soil acidity. New York, Marcel Dekker, pp.359-385.

Fageria, N.K., Melo, L.C. and Ferreira, E.P.B. (2014). Dry matter, grain yield, and yield components of dry bean as influenced by nitrogen fertilization and rhizobia. *Communication in Soil Science and Plant Analysis*, 45: 111–125.

Hawkesford, M., Horst, W., Kichey, T., Lambers, H., Schjoerring, J., Møller, I.S. and White, P. (2012). Functions of macronutrients. In: Marschner P, ed. Marschner's *Mineral nutrition of higher plant*s, 3rd edn. San Diego: Academic Press, 135-189.

Hue, N.V. (2004). Responses of coffee grainlings to calcium and zinc amendments to two Hawaiian acid soils. *Journal of Plant Nutrition*, 27: 261–274.

Iqbal, T., Sale, P. and Tang, C. (2010), "Phosphorus ameliorates aluminium toxicity of Al sensitive wheat seedlings," in Proceedings of the 19th World Congress of Soil Science, Soil Solutions for a Changing World, pp. 92–95, Brisbane, Australia, August 2010.

Jaskulska, I. Jaskulski, D. and Kobierski, M. (2014). Effect of liming on the change of some agrochemical soil properties in a long-term fertilization experiment. *Plant and Soil Environment*, 60: 146–150.

Keino, L., Baijukya, F., Ng'etich. W., Otinga, A.N., Okalebo, J.R. and Njoroge, R. (2015). Nutrients Limiting Soybean (*Glycine max l*) Growth in Acrisols and Ferralsols of Western Kenya. PLoS ONE 10(12): e0145202, https://doi.org/10.1371/journal.pone.0145202

Kisinyo, P.O., Opala, P.A., Gudu, S.O., Othieno, C.O., Okalebo, J.R., Palapala, V. and Otinga, A.N. (2014). Recent advances towards understanding and managing Kenyan acid soils for improved crop production. *African Journal and Agricultural Research*, 9: 2397-2408.

Liao, H. Wan, H., Shaff, J., Wang, X., Yan, X. and Kochian, L.V. (2006). Phosphorus and aluminum interactions in soybean in relation to aluminum tolerance. Exudation of specific organic acids from different regions of the intact root system. *Plant Physiology*, 141: 674–684.

Mahasi, J.M., Vanlauwe, B., Mursoy, R.C., Mbehero, P. and Mukalama, J. (2010). Increasing productivity of soybean in western Kenya through evaluation and farmer participatory variety selection. In Wasilwa, L.A., Ouda, J. Kariuki, I. W. Mangale, N.S., Lukuyu, M.N. (Eds), Transforming Agriculture for Improved Livelihoods through Agricultural Product Value Chain. Proceedings of the 12th KARI Biennial Scientific Conference. November 8-12, 2010. Nairobi, Kenya.

Mathu, R.W., Nandokha, T., Riungu, T.C., Matere, S. and Bendera, N.K. (2010). The potential of soybean to increase agricultural productivity in dry areas of central Kenya. In Wasilwa, L.A., Ouda, J. Kariuki, I. W. Mangale, N. S., Lukuyu, M.N. (Eds), Transforming agriculture for improved livelihoods through agricultural product value Chain. Proceedings of the 12th KARI Biennial Scientific Conference. November 8-12, 2010. Nairobi, Kenya.

Matsumoto, H. (2000). Cell biology of aluminium toxicity and tolerance in higher plants. *International Review of Cytology*, 200: 1-46

Muñoz-Azcarate, O., González, A.M. and Santalla, M. (2017). Natural rhizobial diversity helps to reveal genes and QTLs associated with biological nitrogen fixation in common bean. *AIMS Microbiology*, 3:435-466.

Nyambati R.O. and Opala, P.A. (2014). The Effect of minjingu phosphate rock and triple superphosphate on soil phosphorus Fractions and Maize Yield in Western Kenya. ISRN Soil Science, (4): 1-9, http://dx.doi.org/10.1155/2014/920541

Okalebo, J.R., Gathua, K.W. and Woomer, P.L. (2002). Laboratory methods of soil and plant analysis. A working manual. TSBF-CIAT, SACRED Africa, KARI, SSEA. Second edition. Nairobi.

Opala P.A. (2017). Influence of Lime and Phosphorus Application Rates on Growth of Maize in an Acid Soil. *Advances in Agriculture Volume 2017*, pp 1-5, http://dx.doi.org/10.1155/2017/7083206

Opala, P.A., Okalebo, J.R., Othieno, C.O. and Kisinyo, P. (2010). Effect of organic and inorganic phosphorus sources on maize yields in acid soils in western Kenya. *Nutrient. Cycling in Agroecosystems*, 86: 317–329.

Otieno, H.M.O, Chemining'wa, G.N. and Zingore, S. (2018). Effect of farmyard manure, lime and inorganic fertilizer applications on soil pH, nutrients uptake, growth and nodulation of soybean in acid soils of Western Kenya. *Journal of Agricultural Science*, 10: 199-208.

Penn, C.J. and Camberato, J.J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*, 120: 2-18.

Rengel, Z. (2003). Handbook of Soil Acidity. University of Western Australia Perth, Western Australia.

Sanchez, P.A. (2019). Properties and management of soils in the tropics, second edition. Cambridge University Press.

Verde, B.S., Danga, B.O. and Mugwe, J.N. (2013). Effects of manure, lime and mineral P fertilizer on soybean yields and soil fertility in a humic nitisol in the Central Highlands of Kenya. *International journal of Agricultural Science Research*, 2: 283-291.

Wijanarko, A. and Taufiq, A. (2016). Effect of lime application on soil properties and soybean yield on tidal land. *Agrivita*, 38: 14-23.