EFFECT OF LIMING ON ACID FERRASOLS FOR SUSTAINABLE CROP PRODUCTION IN UGANDA : A REVIEW

ABSTRACT

Ferralsols are the most dominant soil (25%) type in Uganda characterized with high levels of acidity and low levels of cation exchange capacity (CEC). The soils are weathered, mineral fractions are weak, acidic and infertile, have low nutrient reserves rendering them incapable of supplying plant nutrients. The degradation of these soils has necessitated decline in crop yield at a time population in the region is rapidly increasing. Despite the never-ending increased in human population and the importance of Agriculture to the households of the country, little research has been conducted on Ferrasols with the use of lime such as calcium carbonate to improve fertility. Besides, the country's research programs rarely emphasized the use of soil fertility management strategies such as liming. Crop production on these soils is low. For example, average bean grain and maize yields on smallholder farms, which on average are less than 1 ha, are less than 30% of their potential yields with maize estimated to range from 3.8 to 8.0 ha^{-1} and beans 2.0 t ha^{-1}. There is also limited literature on the effect of Agricultural lime on these acid Ferrasols to determine crop performance. Few studies have been carried out in the region to evaluate different rates of limestone on Ferrasols to improve the availability of plant nutrients for sustainable crop production. However, those studies failed to determine liming requirements for these acid Ferrasols. This review paper focuses on the extent and effects, causes, challenges and opportunities associated with liming Ferrasols to improve their productive capacity. Soil lime fertility management strategy is vital to ameliorate these acid Ferrasols to meet the growing demand of food production for the over 70% household in the region depending directly or indirectly on agriculture production as a source of livelihood.

Key words: Ferrasols, soil acidity, liming materials, soil fertility, crop yield

INTRODUCTION

"Ferralsols are the most dominant (25%) soil type in Uganda" (Bamutaze, 2015). The soils are weathered and leached with strong acidity containing toxic levels of Al^{3+}, Fe^{2+},

Mn^{2+}, low available phosphorus and has a pH (5.2) below the critical soil pH of 5.5 (Jaetzold *et al.,* 2012, Drake et al., 2017). "The capacity of these soils to supply plant nutrients and retain cation exchange capacity (CEC) are both low. The low retention capacity has marked consequences for fertilizer management. The worldwide extent of Ferralsols is estimated at 750 million ha, almost exclusively in the humid tropics on the continental shields of South America and Africa" (WRB, 2014). "Many small-scale farmers in the region depend on the success of these soils to sustain their economic and social livelihoods. However, crop production on these soils remains low. The low crop production is attributed to many management problems in addition to soil acidity. Besides, soil acidity is expanding both in areas across Sub Saharan Africa (SSA). Major areas affected by soil acidity include East and Central Africa (Uganda, Kenya, Tanzania, Ethiopia, Rwanda, Brundi, Malawi, Central African Republic, Democratic republic of Congo), West Africa (Ghana, Nigeria, Ivory Coast, Liberia, Sierra Leone, Guinea) and Southern Africa (South Africa, Zimbabwe, Mozambiqu)" (Leenaars et al. 2014). "Notably, 65% of the agricultural land (2.3 billion ha) in Africa is degraded primarily due to poor soil fertility management practices, soil erosion, and soil acidification" (Zingore et al., 2015). The productivity of these agricultural land in Africa ranks amongst the lowest in the world. According to the Ministry of Agriculture, Animal Industry & Fisheries of Uganda, about 46% of Uganda's soils are degraded and 10% is very degraded. Reversing this situation will require the use of liming material in adequate, and proper proportion to reverse the problem.

"Uganda has one of the highest soil nutrient depletion rates in the world with the lowest inorganic fertilizer application of 1.8Kg/ha" (Kiweewa, 2021). "World Bank calculated that the value of replacing these depleted soil nutrients could be 20% of the average rural household income" (Kiweewa, 2021). Liming can however shift these nutrient depleted soils towards near neutral levels and improve on the availability of mineral elements to enhance crop performance (Holland et al., 2018). "When soil pH is lowered than the optimal pH 5.5, it reduces the solubility of nutrients needed for plant growth and usually leads to Al^{3+} and Mn^{2+} toxicity plus deficiency in N, P, K, Mg, Ca, and various micronutrients" (Marschner, 2012).

Several studies have shown that intensive farming and leaching of basic cations (Ca^{2+}, K^{+}, Mg^{2+},) influenced by tropical rainfall has replaced these cations with acid ones (Al^{3+}, H^{+}) and has subsequently intensified the chemical degradation of these arable lands resulting in reduced capacity to produce crops sustainably (Kisino et al., 2014). These soils might have probably reached the last stages of weathering with limited nutrient replenishment (Glatzel et al., 2014) caused by continuous nutrient mining, soil erosion and leaching (Verde et al., 2013). " Years of continuous cropping followed by erosion and poor soil management have contributed to soil acidification thereby constraining average farm sizes to about 0.8 to 1.2 hectares per household in many farming communities with subsistence farming being unavoidable " (Bulyaba et al., 2020; FAO, 2015). Crop yields on these soils are often only a small fraction of the potential yields. For example, average bean grain and maize yields on smallholder farms, which on average are less than 1 ha, are less than 30% of their potential yields with maize estimated to range from 3.8 to 8.0 ha^{-1} while and beans is 2.0 t ha^{-1} (Okoboi et al., 2012, Otunge et al., 2010, Sebuwufu et al., 2014). The gap in yield is attributed to many management problems in addition to soil acidity coupled with low nutrient. Woniala and Nyombi (2013) reported low soil pH (5.2) and low phosphorus availability across farmers' fields in Eastern Uganda suggesting the use of lime as a management requirement. Similarly, Tanyima (2015) evaluated soil fertility variability in Northern and Eastern Uganda and found the accumulative pH (5.2) to be acidic. Besides, Lance et al. (2017) evaluated improved production systems for legume on Ferralsol in South-Central Uganda and found the soil pH (5.2) to be below the critical level at pH 5.5 and yet most crops grow best between pH 5.5 to 6.5.

Athanase et al. (2013) attributed the lack of awareness, lack of appropriate lime recommendations, limited studies done and unknown agricultural lime quality as some of the problems associated with liming practices for crop production in SSA. A perception survey involving farmers was carried out in the Northern and Eastern regions of Uganda to determine the fertility status of farmers' fields, that is; good, medium and poor (Tanyima, 2015). The perception survey showed that soil fertility status in Northern Uganda was medium while Eastern Uganda was poor with yield below those cultivated in northern Uganda. The perceptions of those farmers could be attributed to the knowledge gaps that still exist about the state of soil fertility in the region. It could also be that research programs in the country had not placed emphasis on the identification, distribution and characterization of acid Ferrasols to determine fertility management strategies such as liming. The gap in experience could be learned from other countries that have successfully worked to mitigate the challenges associated with strongly acidic soils. For instance, “numerous studies have shown the experience of the Cerrado region in Brazil which saw the conversion of large areas of acidified soils to productive use through an integrated solution could be integrated and adopted in Uganda. Brazil has been able to develop over 60 million ha of the Cerrado region with crops and improved pasture with the implementation of appropriate technologies and inputs, infrastructure, and policy support” (Klink, 2014). This review paper attempts to capture the many lessons learned in other countries about the management of acidic soils and how those best practices could be integrated into the Uganda context. The objective of this review paper therefore is to generally understand the extent, effects and characteristics, distribution, causes, challenges and opportunities associated with liming acid Ferrasols.

EXTENT AND DISTRIBUTION OF FERRASOLS

“Acid soils belong to Ferralsols and Acrisols and to a smaller extent the Plinthisols, Alisols and Nitisols” (IUSS Working Group WRB, 2015). “Acrisols covered 87.8 million ha or 2.9% and Ferralsols about 312.4 million ha or 10.3% of the total land area of Africa” (Tully *et al.* 2015). “The chemical fertility of Ferralsols is poor; weatherable minerals are scarce or absent, and cation retention by the mineral soil fraction is weak” (Fungo *et al.,* 2011). “Approximately, 50% of the world’s arable soils are acidic and are subjected to the effects of aluminum (Al), iron (Fe), and manganese (Mn) toxicity of which the tropics and subtropics account for 60%” (Kochian *et al.* 2015). “In fact, Al^{3+} toxicity has been reported in 67% of the world’s acidic soils (Lin et al. 2012), and is considered the third most element after oxygen and silicon, and forms approximately 7% of the total solid matter in soils” (Frankowski, 2016). “In Ferralsols with a low pH, liming is a means of raising the pH of the rooted surface soil. Liming combats Al toxicity and raises the effective CEC. On the other hand, it lowers the anion exchange capacity, which may lead to collapse of microstructural elements and slaking at the soil surface" (IUSS Working Group WRB 2015). "Furthermore, strong retention (fixing) of P is a characteristic problem in Ferralsols" (IUSS Working Group WRB 2015). "The low nutrient content of these Ferralsols is also attributed to the predominance of 1:1 clay mineral, Fe and Al oxides in the fraction" (de Sant-Anna et al. 2017). Despite recommendations by researchers, relevant stakeholders in the sector are yet to institute measures on Improve Acid Soil Management Practices (IASMP) to begin addressing the problem of acid Ferrasols in Uganda.

CAUSES OF SOIL ACIDITY

"The replacement of basic cations (Ca^{2+}, K^{+} and Mg^{2+}) with acidic cations (H^{+} and Al^{3+}) from the topsoil to the subsoil due to precipitation contributes to soil acidity over a long period of time. This exacerbates soil acidity by leaving the toxic and insoluble compounds of Al and Fe in the soils" (Zhang et al., 2016). "The nature of these compounds (Al and Fe) is acidic and its oxides and hydroxides react with water to release hydrogen (H^{+}) ions in soil solution" (Zhang et al., 2016). "As the soil gets gradually depleted of its exchangeable bases through constant leaching, it gets de-saturated and becomes increasingly acid" (Lesch et al., 2012). "In productive agricultural systems, the most important source of soil acidity is the application of chemical fertilizer based on ammonium N" (Goulding, 2016). "Added to soil, N-fertilizer is nitrified (Goulding, 2016), and if the resulting NO_3^- isn't taken up by the crops, it gets leached causing acidification" (Goulding, 2016). "Studies have showed that, application of diammonium phosphate, an acidifying fertilizer which is used to improve the deficiencies of phosphorous has become a noticeable cause to increase soil acidity" (Mosissa, 2018). "Removal of cations, especially from soils with small reservoir of bases due to the harvest of high-yielding crops contributes immensely to soil acidity" (Vitousek et al., 2009)

"Parent materials (rocks types) from which soils are formed is also a determining factor contributing to soil acidity. Parent materials containing excess of quartz or silica as compared to their content of basic materials or basic elements are categorized as acid rocks; for example, granite and rhyolite. Soils that develop from weathered granite are likely to be more acidic than those developed from shale or limestone" (Loganathan et al., 2012). Soils developed from sand stones are poor sandy soils and are chemically inert whereas the inherent soil fertility developed over basic parent materials is relatively high.

Studies have shown that, decaying organic matter produces H^+ which is also responsible for acidity. During the process of decaying, carbon dioxide (CO_2) is produced which reacts with water in the soil to form a weak acid called carbonic acid. This is the same acid that develops when CO_2 in the atmosphere reacts with rain to form acid rain naturally affecting agricultural soils.

Liming can however shift these soils towards near neutral levels and improve the availability of Ca^{2+} or Mg^{2+} concentrations and other plant minerals which are essential to plant growth (Holland *et al.,* 2018; Ronner *et al.,* 2016). As crop yields increase, more of these lime-like nutrients are removed from the fields in which they are cultivated. Soil acidification continues until a balance is reached between removal and replacement of the basic cations. With further increase in rainfall, a point is reached at which the rate of removal of bases exceeds the rate of their liberation from non-exchangeable forms.

EFFECT OF SOIL ACIDITY

" Plants need 17 kinds of nutrients to complete their life cycle, of that, 14 nutrients should be present in the soil in adequate quantity and proportion for healthy plant growth " (Fageria et al., 2009). " However, the availability of these nutrients is influenced by chemical reactions like acidity or alkalinity in the soil. Generally, soil acidity elevates aluminum (Al^{3+}) concentration within the soil solution to a level toxic to plants, limits the availability of essential plant nutrients, and restricts crop performance " (Alvarez et al., 2020). " This implies that soil acidity and its associated low nutrient availability are among the major constraints toward attaining sustainable crop production and achieving food security. Soil acidity is affecting large-scale farms by reducing the yields of cash crops such as coffee, tea, pineapple, oil palm, rubber and sisal, which are important sources of foreign exchange for several African economies " (Vlek et al. 2010). Studies have shown that excess Al^{3+} injures the root apex and inhibits root elongation of agricultural crops. This poor root growth affects water uptake by plants at all levels. Successful crop production on these soils will however require both macro and micronutrients in forms that will support growth.

BENEFICIAL EFFECTS OF LIMING ACID SOILS

"One of the major effects of limed acid soils is an increase in plant available nutrients. Addition of lime to acid soils, supplies Ca^{2+} and Mg^{2+} ions and displaces H^{+}, Fe^{2+}, Al^{3+}, Mn^{4+} and Cu^{2+} ions from the soil adsorption sites resulting into an increase in soil pH (Andric *et al.*, 2012), directly improving soil microbial activity and increasing crop performance" (Badole *et al.,* 2015). "Lime has also been found to increase microbial activity, change the makeup of microbial community, increase the population of acid-sensitive microorganisms, improves soil respiration and boost microbial development" (Goulding, 2016). "Liming encourages the proliferation of microorganisms already present in the soil and facilitates the formation of a more extensive root system, increases the plants' ability to absorb water and nutrients from the soil" (Li et al., 2019).

Study done by Abubakari (2016) showed that "soybean grown in limed acid soils significantly increased nodule number, nodule volume and nodule dry weight per plant as compared to un-limed treatment in legume crops". Temesgen et al. (2017) reported "positive effect of lime application on acid soil resulting to an increase in barley grain yield". In Croatia, Andric et al. (2012) also reported "increased soybean yield by 44% as a result of lime application over the control/unlimed treatments". Workneh et al. (2013) reported "significant increase in straw yield of soybean by 16.3%, due to soil lime at the rate of 2.6 t ha^{-1}". Workneh et al. (2013) also reported "highest nodule number, nodule volume and nodule dry weight per plant in soybean when lime was applied". Similarly, Achalu et al. (2012) reported "an increased in Plant height, fresh biomass, dry biomass, grain yield, harvest index and P-uptake of barley in limed acid soils". "Studies done in Kenya, showed positive effects of liming on soybean yield and yield components" (Keino et al., 2015). "In Ethiopia, the effects of lime on agricultural output have been researched for a variety of crops. Yields for different crops increased by applying lime above the control (no liming); 2.8-4.5, 3.01-3.09, 2.01- 2.55, 1.6-3.3, 1.9-2.6, and 2.1-2.5 t ha^{-1} for barley, maize, malt, barley, faba bean, common bean, and soybean respectively" (Abu, 2021).

The general reaction that explains the interaction of a liming material such as $CaCO_3$ with water to form OH^-ions is $CaCO^3+H_2O \rightarrow Ca^{2+}+HCO_3^-+OH^-$ (Thomas and Hargrove, 1984).

The OH^- reacts with indigenous H^+ or H^+ formed from the hydrolysis of Al^{3+}. The overall reaction of lime with an acid soil can be expressed as: 2Al-soil+$3CaCO_3+3H_2O \rightarrow$3Ca-soil+2Al $(OH)_3+3CO_2$.

Liming neutralizes soil acidity by dissolving and releasing a base (HCO_3^- , OH) into the soil solution, which reacts with acid (H^+, Al^{3+}). The chemical reaction of dolomitic lime with soil acidity is as follows:

$CaMgCO_3 + H_2O \rightarrow Ca^{++} + Mg^{++} + 2HCO_3^- + 2OH^-$
Calcium Magnesium Carbonate + Water ➔ Calcium + Magnesium + Bicarbonate + Hydroxide

" It is good to note that liming is the most commonly utilized long-term technique of soil acidity amelioration, and its effectiveness has been thoroughly established in the literature" (Junior *et al.,* 2020). " It is the least expensive and widely used alkali in agriculture since limestone deposits are extensively available globally, and a large percentage of the population has easy access to this material" (Ferreira et al., 2019).

LIMING MATERIALS

Lime in a broad sense is any material containing calcium (Ca^{2+}) or magnesium (Mg^{2+}) that tends to neutralize soil acidity by making soluble nutrients insoluble for plant uptake. Liming materials include $CaCO_3$, CaMg $(CaCO_3)_2$, Ca $(OH)_2$, CaO *etc*. which vary according to their degree of fineness and neutralizing capacity (TSO, 2010). Determination of soil acidity and amount of lime requirement is associated not only to the soil pH but also to the buffer or CEC (Nelson and Su, 2010). Lime neutralizes both active acidity and some reserve acidity. As active acidity is neutralized by lime, reserve acidity is released into the soil solution thus preserving active acidity or pH (Abu, 2021). In a strongly buffered soil, more lime is required to counteract acidity than in a less buffered soil. The amount of lime required to raise soil pH is dictated by the type of lime used, history of the land use, and initial pH prior to liming (Abu, 2021).

OVER LIMING AND COMPLEXITIES OF LR DETERMINATION

Over liming have however 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 soil acidity. It is therefore practical to acknowledge the pH of the affected soils before making an inform decision on liming requirement. Liming has been noted to improve soil structure, porosity, aggregation, bulk density and water transmissivity. According to Erkki and Hedlund (2016), lime stabilizes organic matter content through enhanced nutrients mineralization. Among the nutrients stimulated and made available in the soil include: N, P, K, Ca and Mg. Additionally, Al^{3+} and Mn^{2+} solubility or their toxicities in soil including Al^{3+} and H^{+} exchange are reduced (Adeli et al., 2017) and this boosts CEC activity. It is also true that the response of a particular crop to lime treatment varied from site to site. Proper measures are essential to safeguard the effective use of lime on acid soil to improve crop performance.

LIME REQUIREMENT METHODS

Many lime requirement methods have observed to raise soil pH to a level desirous of plant growth. Different lime buffer methods include: procedure by Shoemaker, McLean, and Pratt (1961), Single Buffer Method of Woodruff (1947), Single-Buffer Method of Mehlich (1976), New Woodruff Single-Buffer Method (Brown et al., 1977), Single-Buffer Method of Adams and Evans (1962), Double-Buffer Method of Yuan (1974), and the incubation method of Trans and Van Lierop (1981).

The incubation lime requirement method becomes appropriate for field experiments. The method is useful for determining field lime requirement for soils believed to be acidic. For example, Trans and Van Lierop (1981) incubated soils with different rates of a chemically pure $CaCO_3$ ground to pass a 400-mesh sieve. The incubation LRs (to achieve pH 6.5) were obtained by graphing the applied liming rates against the ensuing soil pH after incubating the soils for 8 weeks. Soil pH was determined six times during the first month of incubation, and it was found to have stabilized within that time.

The incubation methods involving adding incremental rates of $CaCO_3$ to a soil suspension and allowing the mixture to equilibrate for a period of 8 weeks or more, and then measure soil pH biweekly as described by Trans and Lierop (1981) can also be used to calculate the lime requirement rates to raise the pH to the desire pH levels (5.5, 6.0 and 6.5) with the use of the below equation as described by (Van reeuwijk, 1992).

$$LR\ CaCO_3\ (kgha^{-1})\ \frac{cmol\ (+)\ EA\ of\ soil*0.15m*10^4\ m^2*BD\ (mg/m^3)*1000}{2000\ kg} * 1.5$$

CONCLUSION

Soil acidity is becoming an increasing problem in Uganda. Varied studies indicated the use of lime to obtain adequate crop yields. Correcting acidic soil condition is vital to agricultural sustainability. The practice of liming to reduce toxic levels of Al, Fe and Mn has been recognized as necessary for optimal crop production in acidic soils. Additionally, lime should be considered as a soil amendment to raise soil pH suitable for nutrient availability, plant growth and crop yield.

Significant reduction in crop yield is reported on farmers' fields in the region. The paper notes the declining soil fertility trend in Ferrasols of Uganda. Soil fertility is declining at an alarming rate thus constraining farmers to shift from one place to another in search of arable farming land. These shifting practices are affecting soil productivity and ecosystem services.

This puts crop production in an unstainable path since Ferrasols are weathered with low nutrients reserve.

Farmers are not aware of the increasing benefits associated with the use of lime. Soil research in the country has not placed more emphasis on the use of lime to reverse the problem of soil acidity. The current soil fertility management practices that smallholder farmers are using in the region namely, recycling of crop residues, addition of cow manure, short fallow and biomass transfer appear to be inadequate to counter soil acidity.

Considering the increase in human population, this poses a huge challenge to stakeholders in the sector to address the downward soil fertility trend.

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Soils of Uganda

(By NARO)

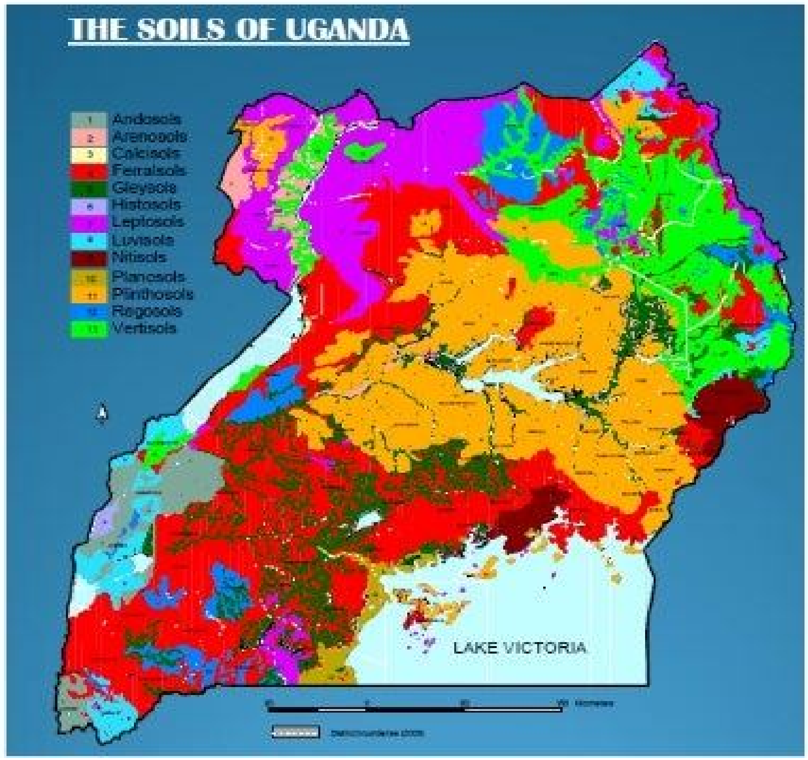

Figure 1: Major soil types of Uganda (NEMA, 2010, http://maps.nemaug.org/maps/ downloaded on 9/23/2022). Each soil type has its own chemical properties suitable for different purposes. For instance, Ferrasols are highly weathered soils with low supply of nutrients, characterized by low pH and low available phosphorus. Calcisols on the other hand are soils characterized with high accumulation of $CaCO_3$ and have serious problems with trace elements deficiencies for elements such as Zn, Cu, Fe and Mn

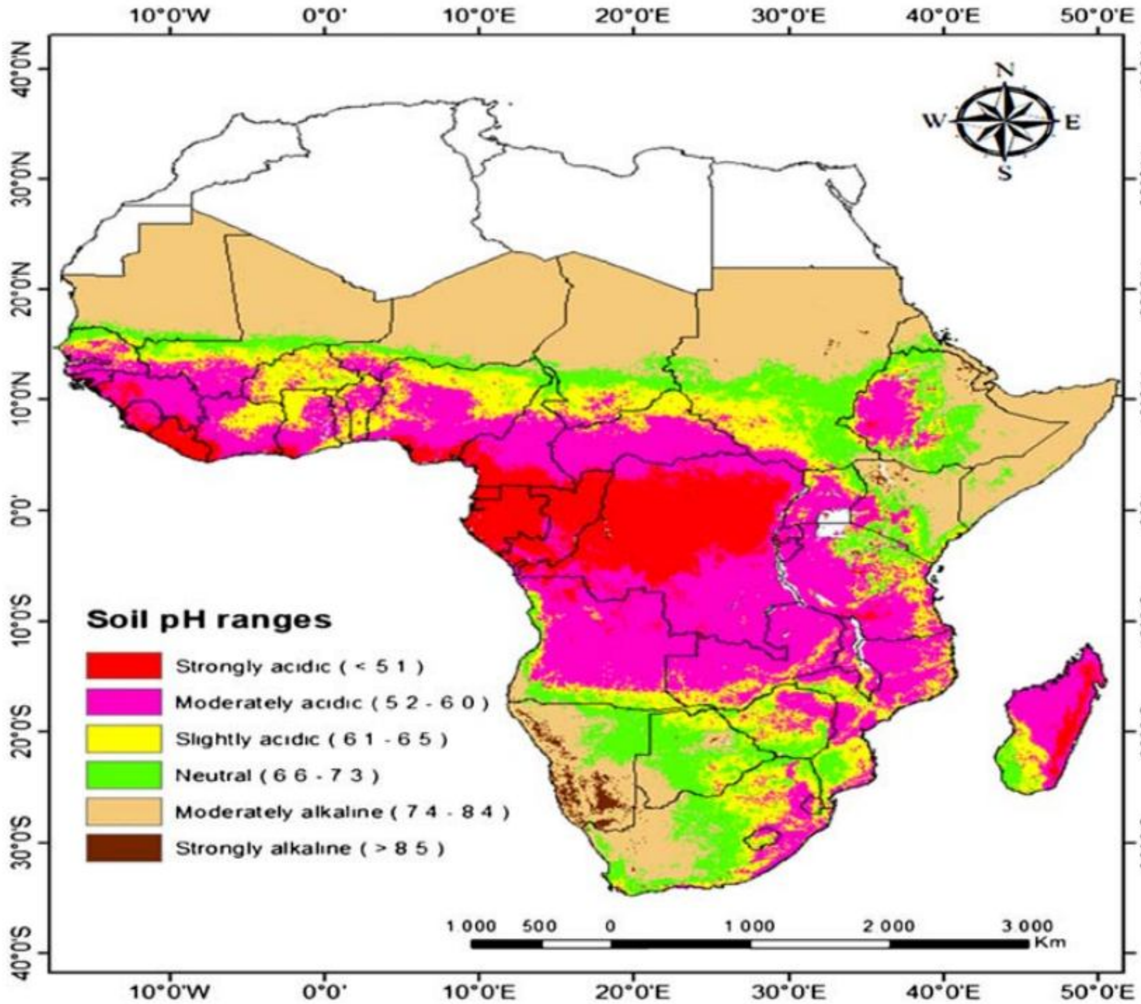

Figure 2: Extent and distribution of soil acidity in Sub-Saharan Africa (SSA) extracted from Horneck et al. (2011); Leenaars et al. (2014).

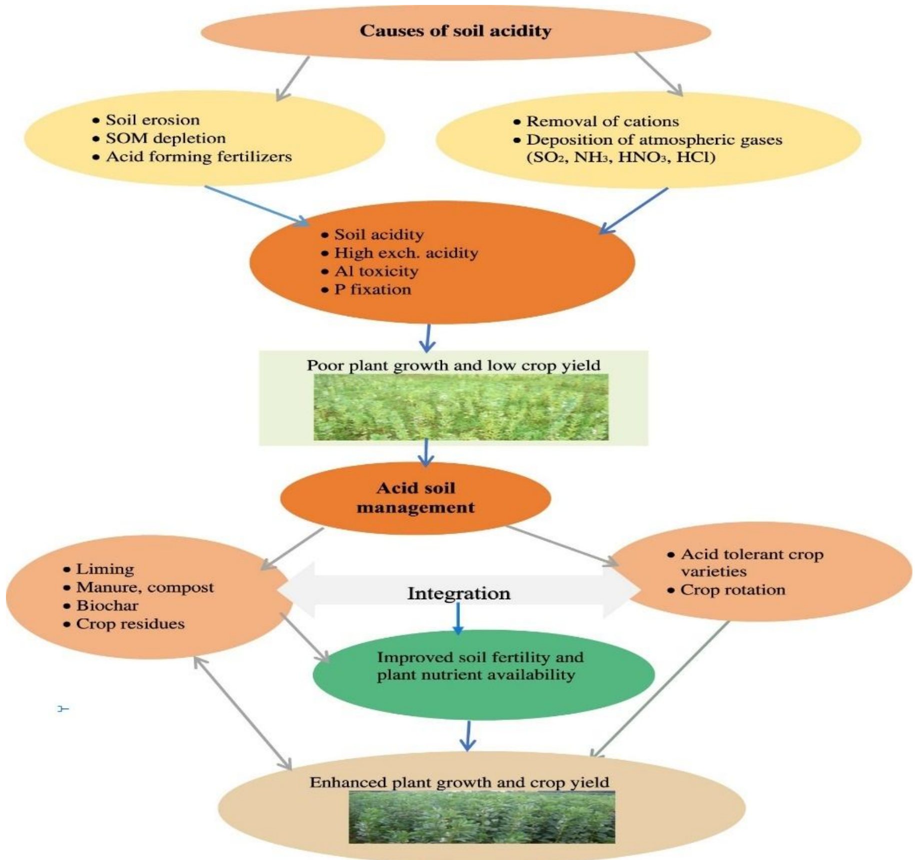

Figure 3: Causes of soil acidity Agegnehu et al., (2021)

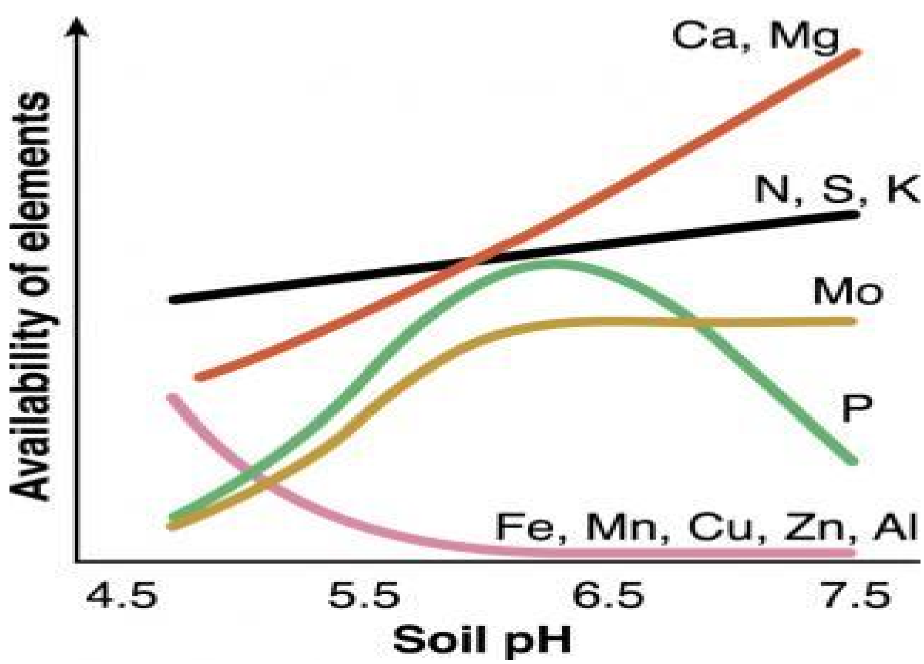

Figure 4: A representation of the relationship between soil pHCa and nutrient availability (Chris Gazey, 2018). In acidic soils, some nutrients may be insufficiently available for optimal plant growth and aluminum may become toxic.

Table 1. Estimation of lime requirements for different soil pH ranges using BC method

pH ranges used in the curve	Curve slopes	BC (g/100 soil)	BC (kg ha−1)	Remark or recommendation on the use of BC values	Examples of lime rates to raise a given soil pH to target pH		
					pH ranges		Lime rate (kg ha−1)
					Initial	Target	
Estimation of BC values and lime rates (kg ha−1) for soils with pH between 5.0 and 5.6 to raise the pH between 6.0 and 6.5							
5.17-6.12	31.61	0.0316	644	For soils with pH 5.0-5.6	5.2	6.0	530
5.17-6.4	24.87	0.0402	844	Acceptable, but less economical for one time use	5.2	6.4	1010
Estimation of BC values and lime rates (kg ha−1) for soils with pH between 4.5 and 5.0 to raise the pH between 6.0 and 6.5							
4.65-6.0	11.21	0.0892	1873	For soils above pH 4.6	4.8	6.0	2250
4.65-6.30	8.26	0.1211	2544	Expensive	4.8	6.3	3820
4.63-5.61	12.24	0.0817	1716	Cheaper for one time use, maybe with insignificant yield reduction. The rate is not recommended for split or localized application.	4.8	5.6	1370
Estimation of BC values and lime rates (kg ha−1) for soils with pH between 3.8 and 4.5 to raise the pH between 6.0 and 6.5							
4.27-5.24	16.24	0.0616	1293	Cheap for one time use; perhaps, with some level of yield penalty.	4.27	5.24	1254
4.27-5.61	13.48	0.0742	1557	Acceptable for one time use; perhaps with	4.27	5.6	2070

pH ranges used in the curve	Curve slopes	BC (g/100 soil)	BC (kg ha−1)	Remark or recommendation on the use of BC values	Examples of lime rates to raise a given soil pH to target pH		
					pH ranges		Lime rate (kg ha−1)
					Initial	Target	
				insignificant yield reduction.			
4.27-5.84	11.23	0.0891	1871	Moderately acceptable.	4.27	5.8	2940
4.27-6.03	9.27	0.1079	2265	Expensive to bring the pH from below 4.3–6.0.	4.27	6.0	3918

Source: Extracted from Huluka (2005) and Sikora and Moore (2008).

Table 2: Effect of lime and other soil fertility management practices on yield of selected crops and soil properties.

Crop	Treatment		Yield			
	Manure (t ha^{-1})	Lime (t ha^{-1})	(t ha^{-1})	% increase over control	Effect on soil properties and nutrient uptake	Source
Wheat	0-5.0	0.0–2.20	0.90–2.69	94–199		(Asrat et al. 2014)
Wheat		0–10	2.44-4.27	34–75	Liming improved soil pH and plant P uptake.	
	N/P/K (kg ha^{-1})	**Lime (t ha^{-1})**	**Yield (t ha^{-1})**	**% increase over control**		
Tef	0-46/0-26/0	0.00–2.00	0.82–2.88	99–252	Liming increased soil pH from 5.38 to 6.17 and CEC from 14.8 to 20.7	(Abewa et al. 2014)
Soybean	18/20/0	0.00–3.75			Increased soil pH from 5.03 to 6.72, and reduced Al^{3+} from 0.68 to 0.36 cmol kg^{-1}	(Buni 2014)
Soybean	18/20/0	0.00–2.60	1.58–2.31	29–46	Increased nodule dry weight by 100%.	(Bekere et al. 2013)
Barley	50/0-30/0	0.00–2.20	2.54–4.56	52–81	Lime reduced Al^{3+} by 0.88–1.19 meq 100 g^{-1} soil, and raised soil pH by 0.48–1.1 units.	(Desalegn et al. 2017)
Barley	145/00/00	0.00–7.00	2.52–4.24	15–68	Lime increased pH in the surface 15 cm and reduced Al^{3+} only in the 0-5-cm layer.	(Tabitha et al. 2008)
Barley	41/20/0	0–4.5	1.28–1.83	4.0–41	Liming increased soil pH from 4.53 to 5.61 and reduced EA from 2.2 to 0.23 cmol kg^{-1}	(Beyene 1987)
Oats/soy bean	-	0.0–2.0	0.96–1.48	5–54	Liming reduced H^{+} and Al^{3+} contents to a depth of 0.60 m.	(da Costa and Crusciol 2016)
Maize	60/26/0	0–2.0	1.77–4.99	111–182	Liming increased soil pH from 4.92 to 5.46 and reduced EA from 0.25 to 0.10 cmol kg^{-1}.	(Opala et al. 2018)
Faba bean	18/20/0	0.0–5.0	0.81–1.47	45–53	Liming increased soil pH from 5.1 to 5.9 and reduced EA from 1.31 to 0.12 cmol kg^{-1}.	(Agegnehu et al. 2006)
Mucuna flagellipes	-	0.0–4.0	1.39–2.82	45–103	Liming increased soil pH from 4.3 to 6.1.	(Agba et al. 2017)
Potato	0/0/0/-110/ 40/100	0.0–3.5	10.03–30.67	59–332	Liming increased soil pH from 4.8 to 5.5.	(Haile and Boke 2009)
	NPK (kg ha^{-1})	**FYM/compost (t ha^{-1})**	**Yield (t ha^{-1})**	**% increase over control**		
Wheat	23/10/0	0.0–8.0	1.2-2.9	68–129	Addition of FYM increased soil pH from 5.0 to 5.6, OC, N and P.	(Agegnehu et al. 2014)
Potato	0/0/0/-110/ 40/100	0–20	17–54	134–217		(Haile and Boke 2011)