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Effects of Liming on Acid Ferrasols for Sustainable Crop Production in Uganda – A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Ferralsols are the predominant soil type covering about 70% of the total land area of Uganda; they are mostly found in the Central and Western regions of the country. Ferralsols are highly weathered, acidic and have inherently low nutrient reserves. Degradation of these soils has led to reduced agricultural production and productivity. Despite the increased human population and the importance of Agriculture to the majority of the households in Uganda, little or no research has been carried out on Acid Ferralsols to improve food security and sustain livelihoods. Besides, the country's research programs have not prioritized the use and management of soil fertility management strategies such as liming. Crop yields on these soils are often far less than those on research stations. This review paper focuses on the extent and effects, causes, challenges and opportunities associated with liming Acid Ferralsols and the effects on soil properties and crop yield. Many studies have shown that detrimental effects of acid soils can be ameliorated through liming, thus improving on the physio-chemical properties to improve crop production and yield. More research is anticipated to develop lime requirements for acid Ferralsols so as to meet the growing food demand in Uganda.

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1. INTRODUCTION

Ferrasols are highly weathered and leached soils of the humid tropics that are rich in Iron (Fe) and aluminum (Al). These soils are, by nature, characterized by strong acidity, have toxic levels of Al, Fe and Mn, low cation exchange capacity, low nutrient retention and low available phosphorus [1]. In Uganda, about 70% of the total land area is under Ferralsols; the soils are very old, highly weathered, inherent low in fertility and have a pH below the critical value of soil pH 5.5 [2] (Mubiru *et al.,* 2017). Many small-scale farmers across Uganda depend on these soils for sustaining their economic and social livelihoods. However, the productivity of these soils is low; for example, soybean yields on these soils are often only a small fraction of the potential yields, with average yields on smallholder farms in Central Uganda being 0.5t/ha, Northern Uganda 0.519t/ha and Eastern Uganda 0.321t/ha, all of which are less than the potential yield of 2-3t/ha (Personal communication).

The low crop productivity on these soils is attributed to many management problems, among which is soil acidity. Acid soil is a key problem contributing to reduced agricultural productivity worldwide [3]. According to MAAIF (2020), about 46% of Uganda's soils are degraded and 10% are highly degraded. Besides, about 65% of the agricultural soils in Sub-Saharan Africa (SSA) are degraded due to poor management practices which induce decline in soil biological, chemical and physical quality and lead to reduced capacity of these soils to support crop production and provide ecosystem services [4]. Long-term solutions such as approaches that build Organic Matter (OM) and organic nutrient pools, in addition to inorganic fertilizer applications, are an essential component to achieving sustainable soil fertility in Uganda [5]. Lime and inoculants are also an effective amendment for improving soil fertility, increasing microbial activity and generally improving crop yield [6]. Furthermore, most of the Ugandan farmers are resource-limited and the population continues to grow at the rates of 3.0% [7]; this puts more pressure and constraints on agricultural land through continuous cultivation, resulting into nutrient mining and soil acidification; this has in turn led to widespread negative macro nutrient balance sheets, which point to depletion of soil nutrient stocks [8]. Adoption of generated research findings such as liming strategies are also low among farmers in SSA.

Uganda has one of the highest soil nutrient depletion rates in the world, with the lowest inorganic fertilizer application of 1.8 Kg/ha [9]. World Bank has estimated that the value of replenishing these depleted soil nutrients could be 20% of the average rural household income [9]. Liming can however shift these nutrient depleted soils towards nearly neutral soil pH levels and improve on the availability of mineral nutrients to enhance plant growth [10], thereby enabling farmers save on the cost of purchasing inorganic mineral fertilizers. When soil pH is lower than 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 micronutrient elements. Acidic soils limit or reduce crop production primarily by impairing root growth, thereby reducing nutrient and water uptake [11]. The most recognized effect of soil acidity is observed in plant roots, since exchangeable Al^{3+} impairs the development of the root system and interferes with P, Ca and Mg absorption and movement by plants [12]. Soil pH is known to influence a variety of soil characteristics that are critical for plant growth and development (e.g., resistance against diseases, root system development, soil microbial activities, availability of nutrients and rate of photosynthesis) [13].

There is limited understanding of problems and management strategies for ameliorating acidic soil conditions in Uganda. Athanase et al*.* [14] found out that lack of awareness, lack of appropriate lime recommendations, limited studies done and unknown agricultural lime quality were some of the problems associated with liming practices for crop production in SSA.

There is also limited literature on the performance of different crop species on the different soil types in Uganda when lime is applied. A perception survey involving farmers was carried out in the Northern and Eastern regions of Uganda to determine the fertility status of farmers' fields and the results showed that soil fertility status in Northern Uganda was medium while those in the Eastern region was poor with yields below those cultivated fields in northern region (Tanyima, 2015). The perceptions of these 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 Ferralsols to determine fertility management strategies such as liming. The gap in experience can be learned from other countries that have successfully worked on mitigating the challenges associated with strongly acidic soils. For instance, studies have shown the experience of the Cerrado region in Brazil which saw the conversion of large areas of acid soils to productive use through integrated soil fertility management that can be adopted in Uganda. Brazil has been able to develop over 60 million ha of the Cerrado region with crops and improved pasture with implementation of appropriate technologies and inputs, infrastructure and policy support [15]. 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 understand the extent and effects, distribution, causes, challenges and opportunities associated with liming Acid Ferralsols. The effects of liming on soil properties and crop yields will also be discussed.

2. EXTENT AND DISTRIBUTION OF ACID FERRASOLS

Acidic soils include Ferralsols (Oxisols), Acrisols and to a smaller extent Plinthisols, Alisols and Nitisols (IUSS Working Group WRB, 2015). Acrisols cover 87.8 million ha or 2.9% and Ferralsols (Oxisols) cover about 312.4 million ha or 10.3% of the total land area of Africa [16]. The chemical fertility of ferralsols is poor; weatherable minerals are scarce or absent and cation retention by the mineral soil fraction is weak [17].

Approximately, 50% of the world's arable soils are acidic and are prone to the effects of Aluminum (Al), Iron (Fe) and Manganese (Mn) toxicity [18]. 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 abundant element after oxygen and silicon and forms approximately 7% of the total solid matter in soils [19]. Major areas affected by these acid soils include East and Central Africa (Uganda, Kenya, Tanzania, Ethiopia, Rwanda, Brundi, Malawi, Central African Republic and the Democratic republic of Congo), West Africa (Ghana, Nigeria, Ivory Coast, Liberia, Sierra Leone and Guinea) and Southern Africa (South Africa, Zimbabwe and Mozambique) [20]. In central Uganda, the soils are highly weathered and have low inherent soil fertility; many years of continuous cropping, erosion and poor soil management have contributed to further degradation of these soils [21]. A study carried out in Eastern Uganda by Woniala and Nyombi [22] showed low pH (5.2) and low available phosphorus across farmers' fields, suggesting the use of lime as a management requirement. The low fertility status of these soils due to soil acidification among others, affects their productive capacity, as yield**s** on farmers' fields remained at an all-time low. Despite recommendations by researchers, relevant stakeholders in the sector are yet to institute measures on Improve Acid soil Management Practices (IASMP). It is well documented that as soil pH declines, so does the supply of several essential plant nutrients, including calcium, magnesium and phosphorus [23,24]. In many soils, this decline occurs alongside an undesirable increase in aluminum to levels toxic to plants [24]. Besides, acidic soils such as Ferralsols contain toxic levels of Al and Mn, which lead to low nutrient availability [25]. The low nutrient content of these Ferralsols is due to the presence of 1:1 clay minerals and Fe and Al oxides [26].

3. CAUSES OF ACID SOILS

Heavy rainfall enhances leaching; this results into the removal of basic cations (Ca^{2+}, K^+ and Mg^{2+}), with replacement of acidic cations (H^+ and Al^{3+}) over a long period of time. This can exacerbate soil acidity by leaving toxic and insoluble compounds of Al and Fe in soils [27]. The nature of these compounds is acidic and its oxides and hydroxides react with water and release hydrogen (H^+) ions in soil solution. As the soil gets gradually depleted of its exchangeable bases through constant leaching, it gets de-saturated and becomes increasingly acid [28]. Rainfall is very effective in making soils acidic; if a lot of water moves through the soil profile, this accelerates the leaching of bases [29]. In productive agricultural systems, the most important source of soil acidity is the application of chemical fertilizer based on ammonium N. Added to soil, N-fertilizer is nitrified and if the resulting NO_3^- isn't taken up by the crops, it gets leached, thereby causing acidification [23]. Also, application of acidifying fertilizers such as diammonium phosphate which is used to cater for P deficiencies, has become a noticeable cause of increased soil acidity [30]. Different management practices such as application of lime and organic matter to agricultural acid soils have been widely adopted as an amelioration strategy for many years to improve crop productivity [31]. However, lime is rarely used in many areas of agricultural land in Uganda. Limited knowledge on the use of lime and the inability of research programs to begin prioritizing the use of lime by farmers as one of the key requirements for ameliorating acidic soils have left most of the soils challenged across farming systems in Uganda. Liming can turn acid soils to nearly neutral pH levels and improve the availability of Ca^{2+}, Mg^{2+} and other plant nutrients which are essential for plant growth; liming can hence neutralize the toxicity effects of H^{+}, Al^{3+} and Mn^{+2} [10,32].

Parent materials (rocks types) from which soils are formed is also another factor that can cause 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 [33]. 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. Besides, humus materials in soils occur as a result of microbiological decomposition of Organic Matter and contain different functional groups such as carboxylic (-COOH), phenolic (-OH) etc. which are capable of attracting and dissociating hydrogen ions hence carbon dioxide (CO_2) produced by these decaying organic materials react 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 (Paul, 2020), affecting agricultural soils.

4. EFFECTS OF SOIL ACIDITY ON CROP PRODUCTION

Crop plants need 17 kinds of nutrients to complete their life cycle; of these, 14 should be present in the soil in adequate quantities and proportions for healthy plant growth (Fageria et al., 2009). However, the availability of these nutrients is influenced by soil pH. In general, 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 [34]. This would imply that soil acidity and its associated low nutrient availability are among the major constraints to attaining sustainable crop production and achieving food security. FAO and ITPS [35] reported ten main soil threats globally among which are soil acidification, soil contamination, loss of soil biodiversity, soil salinization etc. Healthy soil is fundamental to increasing food production and achieving food security, but the challenge is soil acidity [10]. Soil acidity and its associated low nutrient availability is common in all regions where precipitation is high enough to leach appreciable amounts of exchangeable bases from the top soil surfaces (Achelous et al., 2012). When soil pH is < 5.5, it affects the growth of crops due to high concentrations of aluminum (Al) and manganese (Mn) and deficiency of Phosphorus (P), Nitrogen (N), Sulfur (S) and other nutrients [36]. Soil acidity affects large-scale farms by reducing yield and quality of cash crops such as coffee, tea, pineapple, oil palm, rubber and sisal, which are important sources of foreign exchange for several African countries [37]. Generally, soil acidification has become a global threat towards future agricultural production and achieving food security in SSA. This has created an enormous reduction in farm size and yield output across the region, with farmers being subjected to subsistence or peasant farming. Solubility of nutrients in these soils is greatly affected and usually leads to Al^{3+} and Mn toxicity plus deficiency in N, P, K, Mg, Ca, and various micronutrients [11].

5. BENEFICIAL EFFECTS OF LIME ON ACID SOILS

One of the major effects of lime on acid soils is an increase in crop productivity. Liming has shown a synergistic interaction with applied nutrients (through fertilizers) and increased plant nutrient uptake by changing soil chemical and physical properties (Chintala, 2012). These changes in soil characteristics depend on the interaction of numerous other factors, including climate, soil type and intrinsic soil properties [38]. Adding liming materials to acid soils helps to reduce acidity by neutralizing acid reactions in the soil. Lime has been found to enhance microbial activity, changing the makeup of the microbial community and increasing the population of acid-sensitive microorganisms and soil respiration when soil acidity restricts microbial development [23]. Liming material is capable of altering numerous geochemical and biological properties of soil and provides a variety of benefits [13]; for example, it reduces soil acidity and solubilization of hazardous elements, namely aluminum (Al) and manganese (Mn). Besides, it aids in the rise of Calcium (Ca) and Magnesium (Mg) levels and availability of Phosphorus (P) and Molybdenum (Mo), all of which plays crucial roles in plant growth and development [39].

Liming encourages the proliferation of microorganisms already present in the soil and facilitates the formation of a more extensive root system and increases plants' ability to absorb water and nutrients from the soil [13]. Liming enhances a conducive environment for leguminous plants and associated microorganisms and increases availability of plant nutrients by raising the pH and precipitating exchangeable aluminum [40]. Liming is essential in providing optimum conditions for biological activities that include nitrogen-fixation; mineralization of nitrogen, phosphorus and sulfur in soils which improve soil conditions for plant growth, especially for soybean, by increasing grain yield, shoot dry mass, number of pods per plant and soil quality [23]. According to Hoben et al. [41], nitrogen is a critical limiting element for plant growth and is key to agriculture development [42]. Legume growth can be limited under low nutrient availability partly because of low N supply; this reduces plant photosynthesis and BNF capacity [43].

Abubakari [44] showed that soybean grown in lime-applied acid soils significantly increased nodule number, volume and dry weight per plant as compared to the un-limed treatment in legume crops; Temesgen et al. [45] reported the positive effect of lime application on acid soil resulting into an increase in barley grain yield during the first trail and the same study showed that yield reduction in the final year was as a result of re-acidification of the soil. In Croatia, Andric et al. [46] also reported increased soybean yield by 44% as a result of lime application over the control/un-limed treatments; Workneh et al. [47] reported significant increase in straw yield of soybean by 16.3% due to application of lime to acid soil at the rate of 2.6tha^{-1}; Achalu et al. [48] reported an increased in plant height, fresh biomass, dry biomass, grain yield, harvest index and P-uptake of barley in limed acid soils. These increments in plant growth, yield and yield components are as a result of an increase in soil fertility and the reduction of the toxic concentration of acidic cations in acid soils. These studies showed significant influence of applied lime to acid soils for sustainable crop production. It is important to note that liming is the most commonly utilized long-term technique for soil acidity amelioration and its effectiveness has been thoroughly established in the literature [49].

6. 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 [50]. 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 [46], which directly improves microbial activity and increased crop growth and performance [51]. In Croatia, Andric et al. [46] reported increased soybean yield by 44% as a result of lime application in acid soils. In a study carried out in Western Kenya, Nekesa *et al.* [6] found positive response of soybean grain yield to lime application either alone or in combination with P fertilizer.

Determination of soil acidity and amount of lime requirement is associated not only with the soil pH but also with the buffer capacity of the soil or CEC [52]. Lime neutralizes both active acidity and some reserve acidity. As active acidity is neutralized by lime, reserve acidity is released into the soil solution, hence preserving active acidity or pH. The ability of a soil to tolerate variations in pH is referred to as buffering capacity and it is mostly determined by reserve acidity. 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, the land use history and the initial pH prior to lime application [53].

Keino et al. [54] observed positive effects of liming on soybean yield. Over liming has 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 acidity [55]. It is therefore prudent to acknowledge the pH of the affected soils before making an informed decision on the lime requirement of a given soil. Amendment of lime on soil has been noted to improve soil structure, porosity, aggregation, bulk density and water transmissivity [56]. According to Erkki and Hedlund [57], lime stabilizes organic matter content through enhanced nutrient mineralization. Among the nutrients stimulated and made available in the soil include N, P, K, Ca and Mg. Additionally, Al and Mn solubility or their toxicities in soil, including Al and H exchange, are reduced [58] and this subsequently increases the CEC of the soil. It is also true that the response of a particular crop to lime treatment varied from site to site. Proper measures are required to ensure effective use of lime on acid soil for improved crop growth and yield enhancement.

7. OVER LIMING

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 [57], 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 [58] 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.

8. 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 [59], Single-Buffer Method of Mehlich [60], New Woodruff Single-Buffer Method [61], Single-Buffer Method of Adams and Evans [62], Double-Buffer Method of Yuan [63], and the incubation method of Trans and Van Lierop [64].

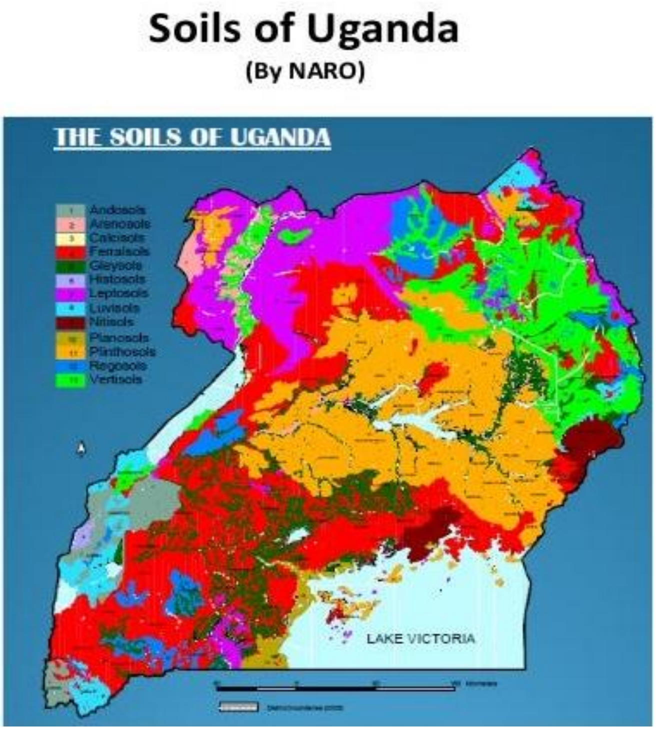

Fig. 1. Major soil types of Uganda (NEMA, 2010, http://maps.nemaug.org/maps/. downloaded on 05/02/2023). Each soil type has its own chemical properties suitable for different purposes. For instance, Ferrasols are highly weathered soils with low supply of nutrients, characterized by low pH and low available phosphorus. Calcisols on the other hand are soils characterized with high accumulation of CaCO3 and have serious problems with trace elements deficiencies for elements such as Zn, Cu, Fe and Mn

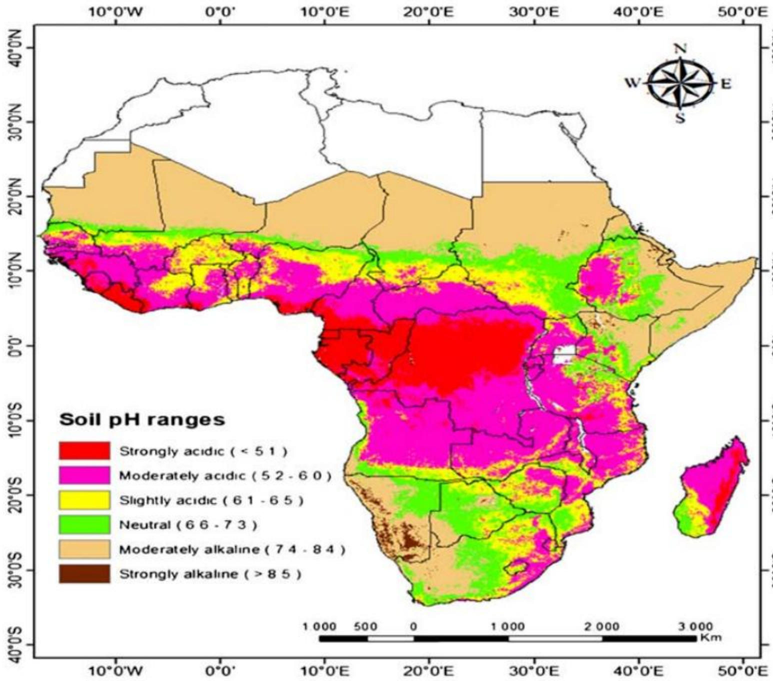

Fig. 2. Extent and distribution of soil acidity in Sub-Saharan Africa (SSA) extracted from Horneck et al. [67]; Leenaars et al. [20]

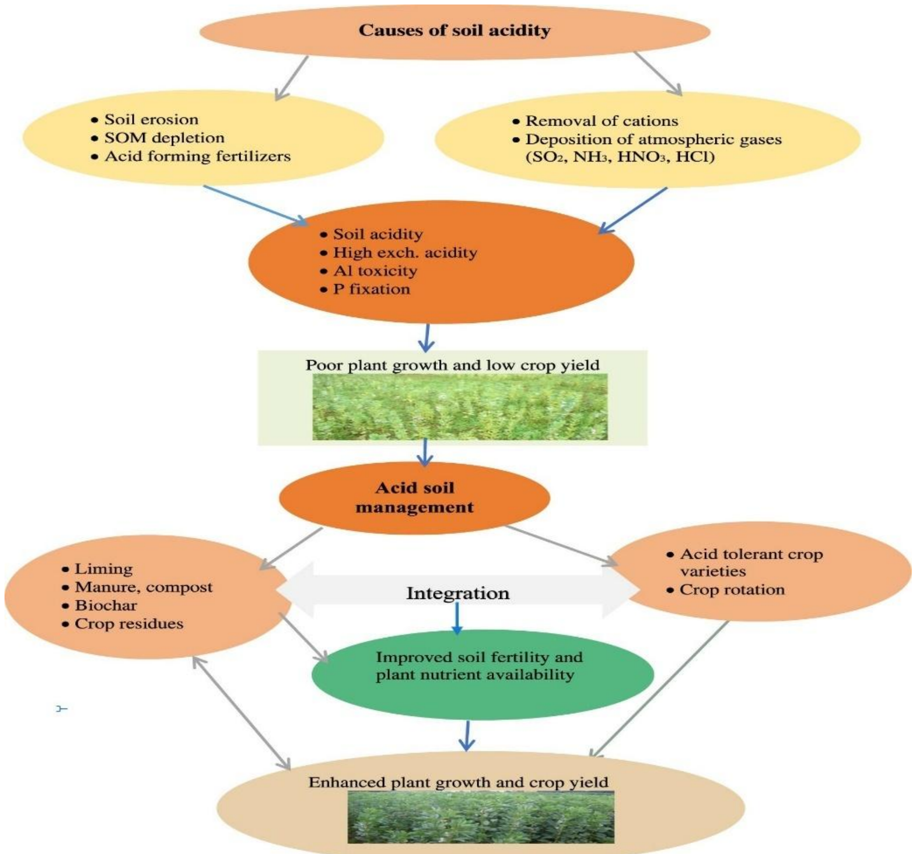

Fig. 3. Causes of soil acidity Agegnehu et al. [3]

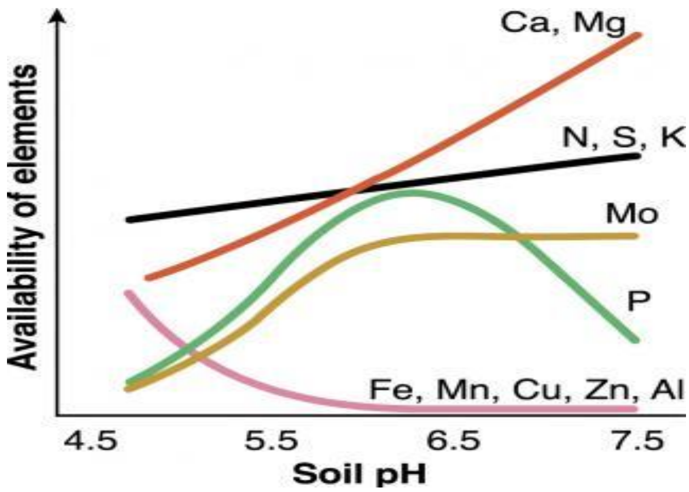

Fig. 4. A representation of the relationship between soil pHCa and nutrient availability [68]. In acidic soils, some nutrients may be insufficiently available for optimal plant growth and aluminum may become toxic

Table 1. Effect of lime and other soil fertility management practices on yield of selected crops and soil properties

Crop	Treatment ($t\ ha^{-1}$ lime)	Yield ($t\ ha^{-1}$)	Yield (% increase over control)	Effect on soil properties and nutrient uptake	Source
Wheat	0.0-2.20	0.90-2.69	94-199	Liming improved soil pH and plant P uptake	[69]
Tef	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	[70]
Soybean	0.00-2.60	1.58-2.31	29-46	Increase soil pH from 5.03 to 6.72 and reduced Al^{3+} by 0.88-1.19 meq 100 g^{-1}	[71]
Barley	0.00-7.00	2.52-4.24	52-81	Lime increased pH in the surface 15cm and reduced Al^{3+}	(Desalegn et al. 2017)
Oats/Soybean	0.0-2.0	0.96-1.48	5-54	Liming reduced H and Al contents to a depth of 0.60 m	[39]
Maize	0-2.0	1.77-4.99	111-182	Lime increased soil pH from 4.92 to 5.46 and reduced EA from 0.25 to 0.10 cmol kg g^{-1}	[72]

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 [64] 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 [64] 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 [65].

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

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→Ca^{2+}+HCO_3^-+OH^- [66].

The OH^- reacts with indigenous H^+ formed from the hydrolysis of Al^{3+}. The overall reaction of lime with an acid soil can be expressed as: 2Al-soil+3$CaCO_3$+3H_2O→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 ➜ Ca^{++} + Mg^{++} + 2HCO_3^- + 2OH^-

Calcium Magnesium Carbonate + Water ➜ Calcium + Magnesium + Bicarbonate + Hydroxide

9. CONCLUSION

Soil acidity remains a major constraint to global food production. Significant reduction in crop yield due to the acidic nature of ferralitic agricultural soils adversely affects the livelihoods of many farmers in Sub-Saharan Africa (SSA). These soils are low in available nutrients required to successfully enable plants complete their life cycles. In Uganda, most farmers believe that their soils are fertile, have high inherent ability to support plant growth to increase yield and do not need soil amendments such as lime. Besides, farmers are not aware of the increasing benefits associated with the use of lime. Up till now, soil research in Uganda has not placed emphasis on the use of lime to reverse acidity in the soils. Application of lime to acid soil should be considered an approach to optimizing soil pH and creating an enabling environment for increased soil nutrient bio-availability, thereby creating a healthy soil for crop production. The extent of soil acidification can as well be addressed through Integrated Soil Fertility Management Approaches (ISFMAs). Combined application of organic materials and lime has the capacity to enhance a buildup process for nutrient accumulation with a high residual effect, thereby reducing on the use of organic and inorganic fertilizers in successive farming seasons. More emphasis on the type of fertilizers used and the amounts applied is cardinal to the mitigation of soil acidification [73-82].

Adoption of improved soil management practices is key to the ever-increasing human population that directly depends on ferralitic acid soils for their livelihoods. Management of Acid Ferralsols across farmers' fields will require research, relevant agronomic practices and improved crop varieties so as to generate information for use by farmers.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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