E. Afri. Agri. For. J (2022,Volume 87 (1), Pg 32-40)

OVERCOMING SOIL ACIDITY CONSTRAINTS THROUGH LIMING AND OTHER SOIL AMENDMENTS IN KENYA. A REVIEW

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ABSTRACT

Food production in Kenya is constrained by low and declining soil health resulting from low soil fertility and increasing widespread soil acidity, coupled with emerging climate change effects leading to recurrent food and nutrition insecurity. The major food production areas with high crop yield potential in the country are greatly affected by soil acidity due to continuous cropping, loss of organic carbon, nutrient leaching and inappropriate use of fertilizers. While use of organic and inorganic fertilizers, improved seed varieties and crop protection have received much research attention, liming as one way of improving soil health and crop production has not received similar attention. Consequently, potential yield of hybrid crops remains constrained. Soil acidity is mainly ameliorated by applying lime or other acid-neutralizing materials, which neutralize the acidity, raises soil pH, increases the availability of plants' nutrients and adds calcium and magnesium to the soil. It also improves the environment for beneficial soil microorganisms thus enhancing rapid breakdown of organic materials in the soil and releasing nutrients for growing plants. Soil buffer capacity determines the amount of lime per unit of soil volume needed to alter soil pH. Soils with low Cation Exchange Capacity (CEC) respond rapidly to liming than soils with high CEC. But the low-CEC soils have a high capacity for rapid leaching of the added bases, thus a quicker return to original acidity unless additional liming is done. Over-liming is recommended for soils which have low CEC, such as sand which is deficient in buffering agents such as organic matter and clay. There is therefore need for appropriate attention to to ameliorate soil acidity in order to maintain good soil health for food and nutrition security. A meta-analysis of a desk study supported by field experiment was carried out in areas viewed as most affected by soil acidity. The aim of the study was to evaluate amendments that can be used for alleviating soil acidity in acidic soils. The results showed that extensive work has been done in Western and Rift valley regions of Kenya targeting soil acidity alleviation and few studies in the coastal and eastern regions due to perception that these areas do not have acidic soils. Among the soil acidity amendments, use of lime and organic sources showed positive crop response and increased yields when applied in acidic soils.

INTRODUCTION

Soil acidity is ranked as one of the major limitations to optimal crop production (Donovan *et al*., 2000; Mulungu *et al*., 2013). Soil acidity poses such a threat to crop production to an extent that about 30% of the world's total land area has acidic soils and approximately 50% of the world's arable lands are classified as acidic (Donovan *et al*., 2000; Mulungu *et al*., 2013). Main staple food crops like maize and rice are sensitive to soil acidity, their yields are negatively affected to a tune of 20% and 13% respectively by acidic soils worldwide (Donovan *et al*., 2000; Mulungu *et al*., 2013). In developing countries like Kenya where fertilizer use is low, maize production is made worse by soil acidity. Acidic soils occupy about 13% of the total land area, which translates to approximately 63% of Kenya's arable land Kenya (Kanyanjua *et al.,* 2002; Kanyanjua and Ayaga, 2006); however, the latest soil analysis for mapping maize suitability in Kenya shows that soil acidity has expanded to new areas not previously classified as acidic (NAAIAP, 2014). This implies that acidic areas are rapidly expanding to areas classifies as non-acidic.

Acidic soils contain higher levels of active hydrogen and/or aluminum in relation to calcium and magnesium. The

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degree of acidity is expressed in terms of pH which is defined as the negative log of hydrogen ion concentration (-log [H^+]). A pH of 7.0 is neutral. Below 7.0 is acidic and above 7.0 is alkaline (Table I).

TABLE I -DESCRIPTIVE RANGES SOIL PH IN SOILS

pH range	
Ultra acid < 3.5	Neutral 6.6-7.3
Extremely Acid 3.5-4.4	Slightly alkaline 7.4-7.8
Very strongly acid 4.5-5.0	Moderately alkaline 7.9-8.4
Strongly acid 5.1-5.5	Strongly alkaline 8.5-9.0
Moderately acid 5.6-6.0 Slightly acid 6.1-6.5	Very strongly alkaline > 9.0

Source: Soil Survey Division Staff, 1993

Acidic soils retard plant growth through either H^+ and Al^{3+} ionic effects, mineral ion toxicity or interfering with mineral availability indirectly. Soil nutrients solubility and availability is affected by soil pH. Soils with pH <5.5 have a weak buffering capacity; low P bioavailability due to high P fixation capacity; toxicities of Al, Fe, Mn (occasionally H); deficiencies of Ca, Mg, K, Zn, S, and Mo; and low cation exchange capacity (CEC), which act together to limit plant growth (Clark, 1982; Clark *et al.,* 1988). Most of these acidic soils are mainly found in Rift Valley and western Kenya regions (Obura, 2008; Kisinyo, 2011). These are high rainfall, medium to high potential agricultural areas where most crops are grown (Jaetzold and Schmidt, 1983) and often classified as Kenya's food basket. As a result of high rainfall, most base cations in these soils have been leached hence the predominant exchangeable cations are H^+, $Al^{3+,}$ Fe^{2+} and Mn^{2+} ions (Obura, 2008; Kisinyo, 2011); making the soils acidic. Inappropriate use of ammonium based fertilizers and reclamation of peat soils such as Gleysols has aggravated soil acidification. The Kenyan acid soils were developed from non-calcareous parent materials such as syenites, phonolites, trachytes, olivines, older basic tuffs and nepholites which are acidic in nature (Jaetzold *et al.*, 2005). Most acidic soils in the highland east of Rift Valley and western Kenya are strongly acidic (pH 4.5 – 5.0) due to high exchangeable Al^{3+} and AI saturations (Kisinyo and Opola, 2014). The high exchangeable Al^{3+} is associated with low levels of available phosphorus for crop uptake in such soils due to high phosphorus sorption by either aluminum oxides and hydroxides or clay colloid (Obura, 2008; Kisinyo *et al.*, 2013). Ways of improving crop production in such soils has been exploited and include the application of inorganic and organic fertilizers, liming and breeding acid tolerant crops (Atiwag, 1992; Ligeyo, 2014; Obura, 2008 and Kisinyo *et al.*, 2013). Among all the options explored, liming continued to receive low attention from policy makers, fertilizer manufacturers and distributors, consequently low application by smallholder farmers. As a result, crop yields remained low in areas with high soil acidity. Figure 1 shows areas in Kenya where the soil pH is low or high soil acidity.

Soil Liming

Liming raises soil pH, Ca and Mg contents, and reduces aluminium concentration in the soil. Adequate liming eliminates soil acidity and toxicity of Al, improves availability of Ca, P, Mg, and reduces loss of cations through leaching. Lime requirement depends on both initial soil pH and soil acidity buffer capacity. However, pH can be used to predict lime requirement within a certain soil type. According to Kanyanjua *et al.* (2002), lime is widely known as the most effective means of correcting soil acidity. Application of agricultural lime containing Ca and/or Mg compounds to acid soils increase Ca^{2+} and/or Mg^{2+} ions and reduces Al^{3+}, H^+, Mn^{4+} , and Fe^{3+} ions in the soil solution. This leads to increased soil pH and available P due to reduction in P sorption and reduction of Al toxicity (Kamprath, 1984; Tisdale *et al.*, 1990; Kanyanjua *et al.*, 2002; The *et al.*, 2006; van Straaten, 2007; Opala *et al.*, 2010a, b; Kisinyo, 2011). In addition to neutralization of soil acidity, lime enhances root development, water and nutrient uptakes (Raij and Quaggio, 1997; van Straaten, 2007; The *et al.*, 2006). According to Kisinyo (2011), use of burnt lime at 2, 4, and 6 t/ha increased soil pH, available P, maize grain yield, P use efficiency and reduction in exchangeable Al^{3+} in acidic soils of Rift Valley highlands. In western Kenya, higher rates of lime (4 and 6 tons/ha) have a higher capacity to increase soil pH, available P and grain yield by lowering levels of exchangeable Al^{3+} than the lower rate (2 tons/ha) (Kisinyo *et al.*, 2014). As a result of lime applications of 4 t/ha, up to 75% maize yield increments were reported (Gudu *et al.*, 2005; Kisinyo, 2011). This review paper seeks to shed more light on the effects of soil acidity, prevalence, causes and remedies; benefits of liming and how to tackle soil acidity through liming and other soil amendments in Kenya.

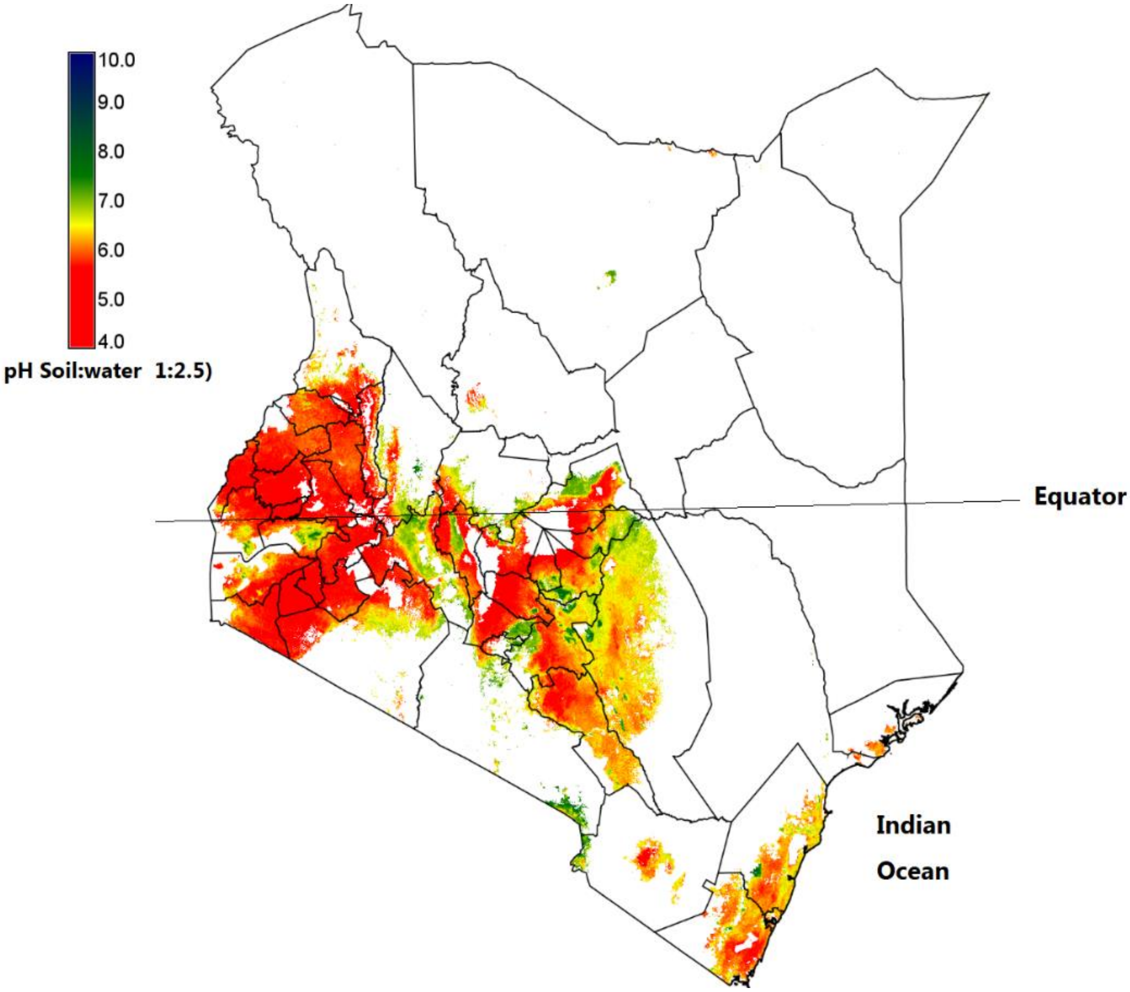

Figure 1: Distribution of acidic soils in Kenya. Source (Africa SoilGrids, 2015)

MATERIALS AND METHODS

This was a desk study on the previous work done in Kenya on prevalent, causes, coping and amending soil acidity. The materials were purposely collected targeting liming work done in Kenya in libraries, online and personal communications with persons directly involved with liming and soil amendment work in Kenya. Table II indicate the key papers that were reviewed. The collected information was reviewed and synthesized and meta-analysis done to come up with the best scenarios. This review article presents the prevalence, causes and remedies for soil acidity in Kenya

TABLE II- LIST OF KEY PAPERS REVIEWED

Title	Authors	Year
Recent advances towards understanding and managing Kenyan acid soils for improved crop production.	Kisinyo, P.O *et al*	2014
Response of maize top cross hybrids to low phosphorous in acid soils of western Kenya.	Ligeyo D. O *et al*	2014
Soil Suitability Evaluation for Maize Production In Kenya.	NAAIAP, KARI	2014
Phosphorus Sorption and Lime Requirements of Maize Growing Acids Soil of Kenya.	Kisinyo P.O *et al*	2013
Comparison of effects of phosphorus sources on soil acidity, available phosphorus and maize yields at two sites in western Kenya.	Opala P.A., *et al*	2013
Enhancing Maize Grain Yield in Acid Soils of Western Kenya Using Aluminium Tolerant Germplasm.	Ouma E *et al*	2013
Effects of soil properties on bioavailability of aluminium and phosphorus in selected Kenyan and Brazilian soils.	Obura, P. A.	2008
Acid soils in Kenya: Constraints and remedial options.	Kanyanjua, *et al*	2002

Regional soil acidity

Soil acidity is more prevalent in the medium altitude areas with marginal rainfall. In these areas, maize yields are very low, with averages of 1.0-1.5 t /ha. The development of the acidity is majorly attributed either leaching of base cations due to high rainfall, use of acid forming fertilizers and parent materials, among others (Obura, 2008). Acid soil in the highlands east of Rift Valley have high Al (2.71 to 4.29 cmol Al /kg soil and 27 to 34% Al saturation) compared to western Kenya (2.01 to 2.24 cmol Al /kg soil and 42 to 71% Al saturation) (Kisinyo, *et al*., 2013). Due to higher Al levels, highlands east of Rift Valley tend to have high P sorption (343 to 402 mg P/kg) than western Kenya (107 to 294 mg P/kg). Consequently, crops can only recover 9.6 to 13.5% of the applied P fertilizer (Kisinyo *et al*., 2013). In high rainfall areas like central highlands (Nyandarua, Nyeri and Kiambu had pH of 4.8, 4.1 and 4.4, respectively), western (Kakamega, Vihiga, Bugoma, Busia, Siaya, Kisii, Nyamira, Migori (pH between 4.1 to 4.8), Rift valley (Nandi, Baringo, Kericho, Uasin Gishu (pH between 4.3 to 4.5) and some parts of the coastal region (Kilifi, Taita Taveta (pH of 4.2 and 4.8), respectively) recorded low soil pH (NAAIAP, 2014). Soil acidity in the country shows that even the coastal parts which is considered to have less acidic soils has recently showed that the acidity is spreading (NAAIAP, 2014). Areas with low rainfall like the ASALs soil pH ranged from neutral to alkaline except a few pockets of higher rainfall or with irrigated agriculture. However, areas in higher rainfall regions had soil pH ranging 5.5 to 8.5 examples found in Thika and some low rainfall areas with pH less than 5.5 like Makueni (NAAIAP, 2014). They cover over one million hectares of land under maize, legume, tea and coffee crops, grown by over 5 million smallholder farmers (Gudu *et al*., 2005). Basically areas with high levels of rainfall exhibit more acidic soils. However, some ASAL areas had pH as low as 3.8 - 4.0, while at the coastal region pH as low as 4.18 was recorded (NAAIAP, 2014). Central Kenya highlands being the main export commodity zone, the soils showed widespread soil acidity; some areas had pH as low as 3.9 (NAAIAP, 2014). From the meta-analysis studies, not all the sites recorded acidic soils in western and rift valley regions contrally to the general belief that soils in Western and Rift Valley regions are acidic.

Breeding for Acidity Tolerance

Breeding for soil acidity tolerant has been done on maize, sorghum and rice (Ouma *et al*., 2013; Ligeyo *et al.,* 2014). However, this process is slow and crop specific. In a study carried out in Rift Valley, the results showed that majority of the Al tolerant lines are derivatives of the breeding line 203B which could form parental material for breeding (Ligeyo, 2007). Many of the Kenyan maize lines that exhibited high root growth under Al stress expressed low activities of the ZmMATE1 gene (< 2 fold) showing that introgression of this gene could further improve their Al tolerances (Ligeyo, 2007; Ouma *et al.,* 2013; Kisinyo *et al*., 2014; Ligeyo *et al.,* 2014). Thus, Kenyan maize germplasm are likely to carry new sources of Al tolerance genes. According to Ligeyo (2007), nutrient culture screening for Al toxicity can predict field selection under Al toxic soils by between 24% - 35% depending on the Al saturation of the particular soil and the levels of available phosphorus. This implies that plant breeders should employ an integrated approach of using both solution culture and field screening conditions when selecting cultivars for tolerance to Al toxicity. Apart from maize, sorghum has also been screened for for Al toxicity tolerant and /or P use efficient. (Ouma *et al*., 2013; Too, 2011; Matonyei, 2010; Ligeyo, 2007). However, there are no commercial maize/ sorghum or other crop varieties available to farmers that are adapted to soil acidity (Ligeyo, 2007). Considering most of the smallholder farmers practice intercropping, some of the intercropped crops like beans may not tolerate acidic soils when acid tolerant crop varieties are targeted to improve productivity. Therefore, amending the soil pH to suit a wide variety of crops is more commendable.

Interventions to reduce soil acidity

Several interventions to reduce soil acidity have been explored. The main ones, and of particular interests of this review include use of organic matter and application of liming materials. These are discussed below.

Use of Organic Materials (OM)

Organic materials like animal manure (cattle or goat) have been used to amend soil acidity. In some cases, the use of organic manure raised the soil pH from 4.2 to 6.3 over a period of two months (Kisinyo *et al.,* 2006; Opala *et al.,* 2013). Other materials found useful in amending soil acidity were Minjingu Phosphate rock and Tithonia (Opala *et al.,* 2013). The organic sources buffer soil acidity by providing organic carbon while rock phosphate contains a substantial amount of calcium. There are some challenges associated with use of OM to manage acid soils and enhance soil fertility. Many farmers do not have enough good quality organic materials. Due to their low nutrient content, large amounts have to be applied thus increasing the labour cost (Nyambati and Opala, 2014; Opala *et al*., 2007, 2010b; Kisinyo *et al*., 2006; Jama *et al*., 1997). Applications of high volumes of OMs such as high quality farmyard (FYM) was found to be economically attractive under most smallholder farms (Opala *et al*., 2007, 2010b, 2013). This highlights the need for high quality OMs for provision of plant nutrients as well as acidity amelioration and creating conducive environment for microbial activities.

Application of liming materials

Liming of acidic soils helps to lowers the toxic levels of aluminum and manganese and overcomes the potential for calcium deficiencies. Additionally, soil microbes are active at specific soil pH; thus building the right soil pH increases some microbial activity-decomposition, symbiotic nitrogen fixation in legumes and availability of phosphorus and molybdenum. Equally, the right soil pH helps in buildup of soil organic matter, which helps improve water retention in the soil, palatability of forages, soil structure and organic content and consequent uptake of N, P and K (Obura, 2008; Kisinyo *et al.,*2014).

Agricultural lime and other liming materials are used to alter the soil pH to suit the intended crop. However, this has been slowed down by the need to carry out soil analysis before applying the lime. The soil pH and exchangeable acidity also determines the amount of soil amendment materials to be used (Obura, 2008). Across the grain basket (western and central Rift Valley), most of the studies recommended the use of lime at the rate ranging from 4 to 6 t/ha (Kisinyo *et al*., 2013; Hijbeek *et al*., 2021). From the studies, the results showed that application of lime can be repeated every five to six seasons when 4 or 6 tons/ha of lime were applied, respectively. However, the quality of the liming material and the soil pH played a great role in determining the amount of lime needed for better crop response. (Kisinyo *et al.,* 2013). A case study of a meta-analysis of results of soil amendment studies carried out in Kenya is presented in Table III. From the meta-analysis results, the soils pH under maize ranged between 4.1 and 5.5; an indication that the soils were acidic. The rainfall in the area ranged between 1100 and 2000 mm per annum (Kanyanjua *et al.,* 2002). The analyzed data was collected from different soil types. The dominant soil types in the area were Nitisols and ferralsols. The liming materials used were: Gypsum, Agricultural lime and Phosphate rocks (Minjingu (MPR) and Busumbu). (Opala *et al.,* 2013). Other materials believed to have liming effects analyzed here were farmyard manure (FYM) and Mavuno fertilizer (Obura *et al.,* 2008; Opala *et al.,* 2014). As seen from the literature search materials, very limited liming studies were carried out in the ASALs and the Coastal region probably due to the perception that the soils in these regions are less acidic. Apart from lime, other materials evaluated for liming effects were Mavuno fertilizer, Farmyard manure (FYM) and Minjingu Phosphate Rock (MPR). Lime applied at 4 t/ha had the highest benefit cost ration because the cost of lime is low, however, this is not sustainable because crops needs macro and micro nutrients at balanced levels for optimal crop production. The BCR for lime at 4 t/ha alone was attainable against a no fertilizer application (Control) yield of 0.53 t/ha. Application of TSP 40 kg P/ha + CAN 75 kg N/ha + Lime 0.5 t/ha recorded the highest yield. This shows that soil acidity is not the only parameter that limited crops yields but other nutrients like P and N were necessary for increased yields. Application of N and P (DAP being the source) without liming had high BCR but lower yields than when lime is added. Application of Mavuno fertilizer at 20 kg P/ha recorded high yield and BCR. This is associated with the fact that Mavuno has both macro and micro nutrients and liming effects (Table III). From the results (Table III), it's deduced that lime alone or application of soil nutrients alone may not be a solution but a combination of liming and nutrients application offers a visible solution to higher maize production and possible food security.

TABLE III - A META-ANALYSIS SHOWING MEANS OF MAIZE GRAIN YIELD AND BENEFIT COST ANALYSIS COMPARING LIMING AND OTHER SOIL HEALTH INPUTS IN WESTERN KENYA

Soil health amendments	(t/ha)	BCR
Lime 4 t/ha	2.84	95.02
Mavuno 20 kg P/ha	3.36	11.53
Lime 2 t/ha + DAP 20 kg P/ha	3.06	9.82
Lime 2 t/ha + Mavuno 20 kg P/ha	2.91	9.50
DAP 40 kg P/ha	3.25	7.76
FYM 2 t/ha + TSP 20 kg P/ha	3.47	7.47
FYM 2 t/ha	1.88	6.79
Minjingu Phosphate Rock (MPR) 40 kg P/ha	3.64	4.36
Lime 4 t/ha + TSP 40 kg P/ha	2.18	3.68
FYM 2 t/ha + MPR 40 kg P/ha	2.84	2.07
TSP 40 kg P/ha + CAN 75 kg N/ha + Lime 0.5 t/ha	3.66	1.79
TSP 50 kg P/ha + CAN 75 kg N/ha + MOP 30 kg K/ha + Lime 0.5 t/ha	3.61	1.55
No inputs	0.53	0.00

Source: Kenya Soil Health Consortium database.

When to Re-apply Lime

According to Kisinyo *et al.* (2014), the frequency of application depends upon leaching of basic cations. If crop rotation is being made from a more tolerant crop to a less acid-tolerant crop (e.g., from potato to wheat), then liming may be necessary. Banding or application of lime in planting holes may require lime applications on a seasonal or annual basis. Sandy soils should be sampled every two years. Medium-textured soils (e.g., loams) and fine-textured soils should be sampled and the pH determined every three years. In Kenya the latest liming recommendations is application of lime at 6 t/ha and reapplication three years later, or 4 t/ha that will require another application two and a half years later and at 2 t/ha will require application every two years under medium-textured soils. However, liming needs to be soil specific and supported by soil analysis results. This is because even within the same farm some portions of the farm have lower soil acidity than others.

Obstacles and limitations to Liming

Challenges associated with use of lime are several. First, there is limited knowledge and awareness of important of lime and financial resources to purchase lime and other inorganic inputs (KSHC, 2014). Secondly, the quantities required per unit area are large, for example 2 t/ha and hence expensive in terms of transportation and quite labor intensive at farm level application. Due to the large quantities required per unit area, lime and most of the liming materials are bulky, occupies a large storage area; and thus expensive in terms of transporting and storage space (Kisinyo *et al*., 2014; Ligeyo *et al.,* 2014). Another huge limitation to use of lime is lack of pelleted lime in Kenya market, the current liming materials are in powder form and hence prone being blown away by wind during application. Additionally, it should be noted that different crops have different levels of soil acidity tolerance, therefore liming should be limited to levels where most of crops tolerate. In addition, few staple food crops varieties have been improved to tolerate acidic soils (Ligeyo, 2007; Ouma *et al.,* 2013). However, these acid tolerant crops may not be accessible to a majority of smallholder farmers. Finally, organic materials have been found to improve soil acidity, however, they are not adequate due to fast decomposition and competition for other domestic uses (Kanyanjua *et al.,* 2002; Kisinyo *et al.,* 2014; Kimiti *et al.*, 2021). Despite these challenges, liming acidic soils remain an important activity among the farming communities facing soil acidity challenges. Therefore, overcoming soil acidity should not be the only goal when it comes to the need to improve crop production in acidic soils. Limited soil nutrients pose a greater challenge in acidic soils when not appropriately applied. Thus appropriate addition of both macro and micro nutrients should be incorporated in liming strategies.

CONCLUSIONS

Liming is able to improve the soil quality of acidic soils by adjusting pH to the levels appropriate for soil microbial activities and crop to be grown and hence improve crop yields. To improve crop production, lime should be applied together with other soil nutrients necessary for crop production. Application of lime should be limited to acidic soils and not a blanket application. Inorganic fertilizers with both macro and micro nutrients enhanced with liming capacity stand a good chance in improving soil health and hence crop production. Organic materials like manure are a good source of nutrients and can help in soil acidity reduction. More research needs to be done to check the effects of acids released by organic materials during decomposition.

RECOMMENDATIONS

This paper recommends use of lime to lower soil acidity only after soil tests showing the need for liming and hence application at the right quantities according to recommendations. Liming should be appropriately combined with multi-nutrient inorganic fertilizers for higher crop production in acidic soils. The cycle for lime application is determined by the level of soil acidity and quantities applied per unit area. Lime is immobile, thus to lower the pH of top soil, it should be applied between 0 - 30 cm soil depth. Growing of soil acidity tolerant crops in absence of lime may help in attaining higher crop yields but to maintain a healthy soil, liming and use of organic sources of nutrients is paramount. Policy support is needed in production of pelleted lime that can be applied using mechanized implements. Effective liming materials applied at the right rate and time will help alleviate crop growth restrictions caused by soil acidity.

ACKNOWLEDGMENT

The authors are grateful to European Union (EU), and International Fund for Agricultural development (IFAD) for funding the activity through the Kenya Cereal Enhancement Programme (KCEP) – Climate Resilient Agricultural livelihood (KCEP-CRAL) Programme. Additionally appreciation goes to all the KALRO staff who participated.

REFERENCES

Africa SoilGrids, 2015. SoilGrids - Global digital soil mapping

Atiwag, J.A. (1992). Response of snap bean (Phaseolus vulgaris Linn.) to lime and phosphorus, Philippines *Journal of Crop Science* (Philippines). 17 ((Supplement No.1), 21.

Clark R.B. (1982). Plant response to mineral element toxicity and deficiency. In Plant response to mineral element toxicity and deficiency (Eds MN Christiansen, FC Lewis) pp. 71–73. (John Wiley and Sons: New York, NY).

Clark R. B., Flores C.I. and Gourley L. M. (1988). Mineral element concentrations in acid soil tolerant and susceptible genotypes. *Comm. Soil Sci. Plan*. 19, 1003-1017.

Donovan, C., Damaseke, M. Govereh, J. and Simumba, D.. (2002). Framework and Initial Analyses of Fertilizer Profitability in Maize and Cotton in Zambia.

Gudu S. O., Okalebo J. R., Othieno C. O., Obura P. A., Ligeyo D. O., Schulze D. and Johnson C. (2005). Response of maize to nitrogen, phosphorus and lime on acid soils of western Kenya. In: Tenywa J.S. *et al*., (Eds). African Crop Science Conference Proceedings, 5 - 9th Dec. 2005. Kampala, Uganda, pp. 1109-1115.

Hijbeek R., M.P. van Loon, W. Ouaret, B. Boekelo, M.K. van Ittersum (2021). Liming agricultural soils in Western Kenya: Can long-term economic and environmental benefits pay off short term investments?,Agricultural Systems, Volume 190, (2021), 103095, ISSN 0308-521X, https://doi.org/10.1016/j.agsy.2021.103095. (https://www.sciencedirect.com/science/article/pii/S0308521X21000482)

Jaetzold R. and Schmidt H. (Eds) (1983). Farm management handbook of Kenya, Vol. IIA Western Kenya and Vol. II B (Central Kenya): Natural conditions and farm management information. Ministry of Agriculture/GAT

Nairobi and GTZ/Eschborn.

jaetzold, R., Schmidt, H., Hornetz, B. and Shisnya, C. (2005).Farm management handbook of Kenya, Revised Edition Vl 2. National conditions and farm management information, Ministry of Agriculture/German agency for Technical cooperation, Nairobi, Kenya

Kanyanjua, S. M., Ireri, L., Wambua, S. and Nandwa, S. M. (2002). Acid soils in Kenya: Constraints and remedial options. KARI. Technical Note, 11:24.

Kanyanjua S. M., Ayaga G. O. (2006). A guide to choice of mineral inorganic fertilizers in Kenya. KARI Technical Note. 2006;17:1-17.

Kenya Soil Health Consortium (KSHC), (2014). Soil health inputs for increased agricultural productivity in Kenya.Policy Brief No. 1. Kenya Soil Health Consortium Collating, Harmonizing, Disseminating Soil Health Innovations.www.kenya.soilhealthconsortium.org

Kimiti, W.W., Mucheru-Muna, P.W., Mugwe, J., Ngetich, K.F., Kiboi, M.N. and Mugendi, D.N. (2021). Lime, manure and Inorganic Fertilizer Effects on Soil Chemical Properties, Maize Yield and Profitability in Acidic Soils in Central Highlands of Kenya. *Asian Journal of Environment and Ecology.*

Kisinyo J. A. and Opile W. R. (2014). Immediate and residual effects of lime and phosphorus fertilizer on soil acidity and maize production in western Kenya. *Expl. Agric.* 50(1): 128-143. http://dx.doi.org/10.1017/S0014479713000318

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 of Agricultural Research* 9(31):2397-2408.

Kisinyo P.O., Othieno C.O, Gudu S.O., Okalebo J.R., Opala, P.A., Maghanga J.K, Ng'etich W.K., Agalo J.J, Opile W.R, Kisinyo J.A. and Ogola B.O. (2013). Phosphorus Sorption and Lime Requirements of Maize Growing Acids Soil of Kenya. Sustain. Agric. Res. 2(2): 116-123. http://dx.doi.org/10.5539/sar.v2n2p116

Kisinyo P. O. (2011). Constraints of soil acidity and nutrient depletion on maize (*Zea mays* L.) production in Kenya. Ph.D thesis, Moi University, Kenya.

Kisinyo P.O., Othieno C.O., Okalebo J.R., Opala P.A., Osiyo R.J., Kipsat M., Serem A. and Maghanga J.K. (2006). Combined use of organic and inorganic fertilizers to replenish nitrogen and phosphorus in smallholder farmers in tropical Africa. Proceedings of the 23rd Soil Science Society of East Africa. Masaka Uganda 20th – 24th November 2006. pp. 17-21.

Ligeyo D. O. (2007*).* Genetic analysis of maize (*Zea mays L.*) tolerance to aluminium toxicity and low phosphorus stress and development of synthetics for use in acid soils of western Kenya. Ph.D. Thesis. Moi University, Eldoret, Kenya.

Ligeyo D. O., Ouma E., Gudu S.O., Kisinyo P.O., Matonyei T., Okalebo J.R. and Othieno C.O. (2014). Response of maize top cross hybrids to low phosphorous in acid soils of western Kenya. *East. Africa. Forestry. J.* 2014; 80(1):25-30.

Mulungu K., Tembo G. and Stephen Kabwe S. (2013). An Economic Analysis of Precision Application of Lime at Reduced Rates *Journal of Economics and Sustainable Development* www.iiste.org ISSN 2222-1700 (Paper) ISSN 2222-2855 (Online) Vol.4, No.17, 2013

National Accelerated Agricultural Inputs Access Programme (NAAIAP) (2014). Kenya Agricultural Research Institute (KARI) Department of Kenya Soil Survey. Soil Suitability Evaluation for Maize Production in Kenya, Nairobi, Kenya

Obura, P. A. (2008). Effects of soil properties on bioavailability of aluminium and phosphorus in selected Kenyan and Brazilian soils. Ph. D Thesis, Purdue University, USA. pp. 1-57.

Opala P.A., Jama B.J, Othieno C.O and Okalebo J.R. (2007). Effect of phosphate fertilizer application methods and nitrogen on maize yields in western Kenya. An agronomic and economic evaluation. *Exp. Agric.* 43: 477-487. http://dx.doi.org/10.1017/S0014479707005315

Opala P.A., Okalebo J.R. and Othieno C.O. (2013). Comparison of effects of phosphorus sources on soil acidity, available phosphorus and maize yields at two sites in western Kenya. *Arch. Agron. Soil Sci.* 59(3): 327-339. http://dx.doi.or g/10.1080/03650340.2011.627681.

Opala P.A., Okalebo J.R., Othieno C.O. and Kisinyo P. (2010a). Effect of organic and inorganic phosphorus sources on maize yields in an acid soil in western Kenya. Nutr. Cycl. Agro-ecosyst. 86: 317-329.

Opala P.A., Othieno C.O., Okalebo J.R. and Kisinyo P. (2010b). Effects of combining organic materials with inorganic phosphorus sources on maize yield and financial benefits in western Kenya. *Exp. Agric.* 46: 23-34. http://dx.doi.org/10.1017/S0014479709990457

Ouma E., Ligeyo D., Matonyei T., Agalo J., Were B., Too E., Onkware Gudu S.O., Kisinyo P. and Nyangweso P. (2013). Enhancing Maize Grain Yield in Acid Soils of Western Kenya Using Aluminium Tolerant Germplasm. *J. Agric. Sci. Technol.* A 3: 33-46.

Raij B, Quaggio JA (1997). Methods used for diagnosis and correction of soil acidity in Brazil: An overview. In: Monitz AC (Ed). Plant soil Interaction at low pH. Brazilian Soil Science Society, Campines, Brazil, pp. 205-214.

Soil Survey Division Staff, 1993. Soil Survey Manual. USDA Handbook 18, U.S.

The C, Calba H, Zonkeng C, Ngonkeu E. L. M, Adetimirin V. O. (2006). Response of maize grain yield to changes in acid soil characteristics after soil amendment. Plant Soil 284: 45-57. http://dx.doi.org/10.1007/s11104-006-0029-9.

Van-Straaten, P. (2007). Agrogeology: The Use of Rocks for Crops. Department of Land Resource Science, University of Guelph, Guelph, 440 p.