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*Review*

# Recent advances towards understanding and managing Kenyan acid soils for improved crop production

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**This review focused on the efforts made to understand and manage Kenyan acid soils by use of inorganic, organic materials (OMs) and crop germplasms tolerant to soil aluminium (Al) toxicity and/or low soil available phosphorus (P). Kenyan acid soils which occupy 13% of the total land area were developed through parent materials of acid origin, leaching of base cations and use of acid forming fertilizers. They are high in Al (>2 cmol Al/kg and > 20% Al saturation) and low in soil available P (< 5 mg P/kg soil) due to moderate-high (107-402 mg P/kg) P sorption, hence crops recover only 9.6 to 13.5% of the P fertilizer. Application of lime, P fertilizer and OMs increases soil pH, available P and reduces Al toxicity on Kenyan acid soils. Lime, P fertilizers and OMs have increased maize grain yield by 5-75, 18-93 and 70-100%, respectively on Kenyan acid soils. Similarly, deployment of crop cultivars tolerant to Al toxicity and/or low soil available P increases crop yields. However, lack of knowledge on the importance of lime, credit to purchase farm inputs, crop varieties tolerant to soil acidity constraints and inadequate amounts of OMs limits crop yield on Kenyan acid soils.**

**Key words:** Acid soils, lime, phosphorus, organic materials, tolerance to soil acidity.

## INTRODUCTION

Soil acidity is a widespread limitation to crop production in many parts of the world (van Straaten, 2007). The total area covered by acid top soils is estimated to vary from 3.777 × $10^9$ to 3.950 × $10^9$ ha (Eswaran et al., 1997; von Uexkull and Mutert, 1995), which represents 30% of the total land area of the world. Most acid soils are found in South and North America, Asia and Africa. They occupy about 40% of the total arable land area in the world, most of which are found in the tropical and subtropical regions (Haug, 1984). About 43% of tropical land area comprising 68, 38, and 29% of Tropical America, Tropical Asia and Tropical Africa, respectively, are acidic (Panday et al., 1994). Acid soils occupy about 13% (7.5 million ha) of the Kenyan total land area (Figure 1) (Kanyanjua et al., 2002). Strong soil acidity is associated with Al, H, iron (Fe) and manganese (Mn) toxicities to plant roots in the

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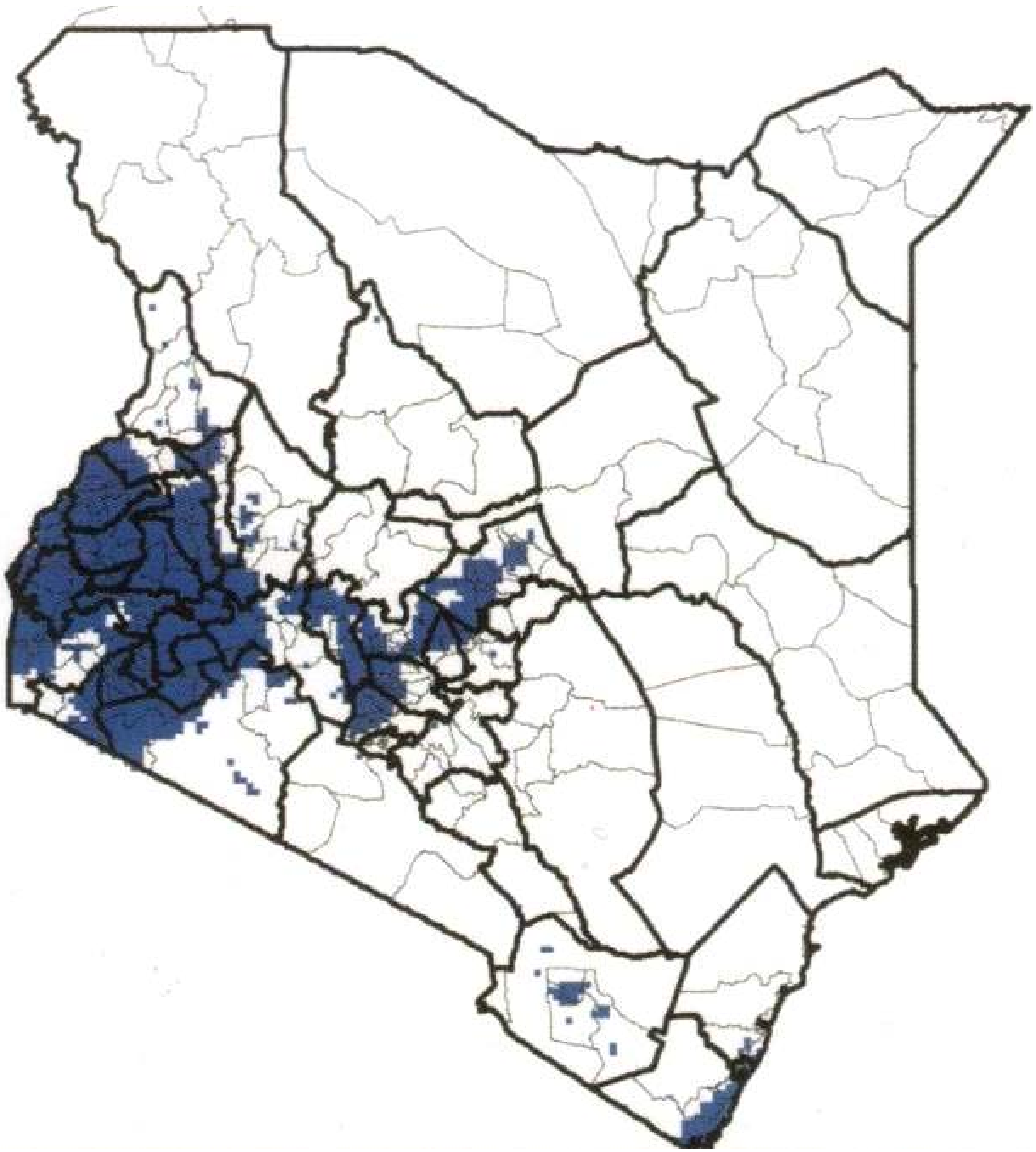

**Figure 1.** Map of Kenya with shaded areas showing acid soils. Sources: Kanyanjua et al. (2002).

soil solution and corresponding deficiencies of the available P, molybdenum (Mo), calcium (Ca), magnesium (Mg) and potassium–(K) (Giller and Wilson, 1991; Jorge and Arrunda, 1997).

Excess $H^+$ ions in acid soils are toxic to plant roots, negatively affect root membrane permeability thus interfering with ion transport and could lead to loss of the previously absorbed cations and organic constituents (Foy, 1984). However, the main constraint to crop production in highly acid soils is not high $H^+$ ions *per se*, but the increased concentration of highly toxic $Al^{3+}$ ions at pH < 5.5 (Sale and Mokwunye, 1993). Aluminium toxicity in acid soils inhibits root development which leads to reduced water and mineral uptake resulting in an overall

**Table 1.** Soil pH, exchangeable $Al^{3+}$ and percent Al saturation.

| Region | Location (latitude and longitude) | Sampling site | Soil pH (1: 2.5; soil: water) | Exchangeable $Al^{3+}$ (cmol/kg) | % Al Saturation |
|---|---|---|---|---|---|
| Western Kenya | 0° 14.466"N and 34° 13.415"E | Sega | 4.65 | 2.07 | 33 |
| | 0° 18.910'N and 34° 13.231''E | Bumala | 4.62 | 2.01 | 27 |
| | 0° 36.781'''Nand 35° 18.280''E | Kuinet | 4.55 | 2.24 | 34 |
| Highlands east of RV | 0° 25.004''S and 37° 30,062''E | Kavutiri | 4.07 | 4.29 | 71 |
| | 0° 40.883''S and 36° 56.097''E | Kangema | 4.69 | 3.32 | 45 |
| | 0° 28.181'N and 35° 15.752''E | Kerugoya | 4.85 | 2.71 | 42 |

Source: Kisinyo (2011).

poor plant growth and low crop yields (Kochian, 1995; Kanyanjua et al., 2002; Ligeyo and Gudu, 2005). Al toxicity reduced root growth in Al toxicity sensitive maize inbred lines than the tolerant ones grown under similar conditions (Ouma et al., 2013). Kenya acid soils contain high Al (normally > 20% Al saturation), low P (< 5 mg P/kg soil) and N (< 0.2% total N) reduce maize yield by 16, 28 and 30%, respectively (Okalebo et al., 1997; Kisinyo, 2011; Ligeyo, 2007). As a result, maize grain yield are low and has been declining over the years (Ayaga, 2003). This review focuses on the efforts made so far to understand and manage the Kenyan acid soils by use of inorganic, organic materials (OMs) and germplasm tolerant to Al toxicity and/or low soil available P crop cultivars for improved crop production in acid soils of Kenya.

## TOWARDS UNDERSTANDING THE KENYAN ACID SOILS

Attempts have been made towards understanding the extent and behaviour of Kenya acid soils. According to Kanyanjua et al. (2002) acid soils occupy about 13% of the Kenyan land area. Most of these soils are found in the highlands east of Rift Valley (RV) and western Kenya regions (Kisinyo, 2011; Obura, 2008). Because of high rainfall, they are found in the medium to high potential agricultural areas where most crops are grown (Jaetzold and Schmidt, 1983). However, due to high rainfall, most base cations in these acid soils have been leached hence the predominant exchangeable cations are $H^+$, $Al^{3+}$, Fe and $Al^{3+}$ and $Mn^{2+}$ ions (Kisinyo, 2011; Obura, 2008). Continuous use of acidifying fertilizers and reclamation of peat soils such as Gleysols (e.g. Yala swamp) has also led to soil acidification (Sombroek et al., 1982; Kanyanjua et al., 2002). To a large extent, most 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 (Sombroek et al., 1982).

Acid soils in the highland east of RV and western Kenya are strongly acidic (pH 4.5 to 5.0), have high exchangeable $Al^{3+}$ ions and % Al saturations (Table 1) (Kisinyo, 2014). Exchangeable $Al^{3+}$ ions > 2.0 cmol /kg are considered excess for many crops (Landon, 1984) while Al saturation > 20% cannot be tolerated by most improved maize germplasm in Kenya (Ligeyo, 2007). At soil pH < 5.0, Al minerals hydrolyse to form octahedron hex hydrate ($Al^{3+}$) and mononuclear hydroxides [$Al(OH)^{2+}$ and $Al(OH)_2^+$] which are responsible for P sorption (Kinraide, 1991; Kochian, 1995). High exchangeable $Al^{3+}$ in the Kenya acid soils has led to P sorption in these soils (Kisinyo et al., 2013; Obura, 2008). The predominant clay minerals in the Kenyan acid soils include kaolinite, gibbsite, goethite, Al and Fe oxides (Obura, 2008; Otinga, 2012). These minerals are common in tropical acid soils and are responsible for high P sorption (Buresh et al., 1997; Obura, 2008; Tisdale et al., 1990; Uehabra and Gillman, 1981). Phosphorus sorption in the Kenya acid soils range from moderate to high (Obura, 2008; Kifuko et al., 2007; Kisinyo et al., 2013; Opala et al., 2010a) as P sorptions of 100 to 400 and > 400 mg P/kg are classified as moderate and high, respectively (Buresh et al., 1997). Kenyan acid soils have different P sorption capacities. The acid soils found in the highlands east of RV have higher P sorption (343 to 402 mg/kg soil) than those found in western Kenya (107 to 294 mg/kg soil) probably due to high exchangeable Al in the former region compared to the latter (Table 2) (Kisinyo et al., 2013).

High P sorption in the Kenya acid soils leads to low recovery of applied P fertilizer. For example, only between 9.6 to 13.5% of P fertilizers applied at the rates of 26 to 52 kg P/ha are recovered (Table 2) (Kisinyo et al., 2014). Similarly, crop P fertilizer recoveries of 10 to 25% have been reported in tropical acid soils due to high P sorption by Al and Fe oxides (Keerthisinghe et al., 2001). Consequently, Kenyan acid soils have low soil available P (< 5 mg P/kg) which is partly responsible for low crop yields (Gudu et al., 2005; Okalebo et al., 1997;

**Table 2.** Langmuir parameters of Kenyan acid soils in the highlands east and west of Rift Valley.

| Region | Location (latitude and longitude) | Sampling site | q (mg/kg) | k (mg/L) |
|---|---|---|---|---|
| West Kenya | 0° 14.466"N and 34° 13.415"E | Sega | 258 | 3.89 |
| | 0° 18.910''N and 34° 13.231''E | Bumala | 107 | 0.63 |
| | 0° 36.781'''N and 35° 18.280''E | Kuinet | 137 | 1.02 |
| | 0° 34.997"N and 350 18.561"E | Vihiga | 294 | 1.80 |
| | 0° 10.614"N and 340 45.225"E | Ikolomani | 250 | 1.67 |
| | 0° 03.112"N and 340 23.658"E | Siaya | 204 | 1.22 |
| | 0° 47.574"S and 340 51.446"E | Kisii | 155 | 0.86 |
| | 0° 17.773"S and 350 16.350"E | Kericho | 191 | 1.18 |
| Highlands east of Rift Valley | 0° 25.004''S and 37° 30,062''E | Kavutiri | 402 | 7.94 |
| | 0° 40.883''S and 36° 56.097''E | Kangema | 343 | 6.63 |
| | 0° 28.181'N and 35° 15.752''E | Kerugoya | 388 | 8.73 |

q = P sorbed per unit soil mass at equilibrium concentration of 0.2 mg/L and k = constant related to the energy of bonding between soil phosphate ions and the surface of soil particles (mg P/L). Sources: Kisinyo (2011) and Obura (2008).

Schulze and Santana, 2003; Kisinyo, 2011).

## MANAGEMENT OF ACID SOILS

Crop production in acid soils with Al toxicity and low soil available P may be improved by use of lime and /or fertilizers with liming effects, organic materials (OMs), crop germplasms tolerant to Al toxicity and/ or low soil available P (Baligar et al., 1997; Ouma et al., 2013; Viterello et al., 2005). Use of the above technologies to manage the Kenyan acid soils forms the discussion of this review.

### Liming and use of P fertilizers

Lime is widely known as the most effective means of correcting soil acidity (Kanyanjua et al., 2002; The et al., 2006). 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 increase in soil pH and available P due to reduction in P sorption (Kamprath, 1984; Kanyanjua et al., 2002; Kisinyo, 2011; van Straaten, 2007; Tisdale et al., 1990; The et al., 2006). In addition to neutralization of soil acidity, lime enhances root development, water and nutrient uptakes~~,~~ necessary for healthy plant growth (Raij and Quaggio, 1997; van Straaten, 2007; The et al., 2006). Several studies have shown that lime reduces Al toxicity, increases soil pH, available P, Ca, Mg, uptake of N and P thus improving crop productivity in Kenya acid soils (Kanyanua et al., 2002; Kisinyo, 2011; Opala et al., 2010a, b). Nekesa (2007) reported increased soil pH and available P in western Kenya acid soils by application of agricultural lime containing 21% calcium oxide (CaO). At one of the sites, three rates of lime (96, 192 and 287 kg lime/ha) raised and maintained soil available P above 10 mg P/ kg soil in 57, 118 and 178 days after planting, respectively. In four year experiment, Kisinyo (2011) reported increased soil pH, available P, maize grain yield, P use efficiency and reduction in exchangeable $Al^{3+}$ on highlands of RV Kenya acid soil. In these trials burnt lime with 92.5% calcium carbonate equivalent at the rates of 0, 2, 4 and 6 tons/ha were used. Higher rates of lime (4 and 6 tons/ha) increased and maintained higher soil pH, available P and grain yield than the lower rate (2 tons /ha) (Figures 2 and 4) (Kisinyo, 2011). In a trial on a western Kenya acid soil, higher rates of lime reduced and maintained lower levels exchangeable $Al^{3+}$ than the lower rates (Figure 3) (Kisinyo et al., 2014). The benefits of lime on crop production are enormous with maize grain yield increments of 5 to 75% reported on Kenya acid soils with applications of 0.77 to 6.18 tons lime/ha (Gudu et al., 2005; Kisinyo, 2011). These benefits were attributed to reduction in soil acidity related constraints making conducive environment for healthy plant growth.

Use of P fertilizer increases the soil available P in P deficient tropical acid soils (Kisinyo et al., 2014; The et al., 2006). Application of P fertilizer increased soil available P and maize grain yield, with higher rate (52 kg P/ha) increasing and maintaining higher levels than the lower rate (26 kg P/ha) on Kenya acid soil (Kisinyo et al., 2011) (Figure 4). Similar increases on soil available P and resultant high maize production have been reported in acid soils of western Kenya due P fertilizer application (Opala et al., 2007). The P fertilizer sources with liming effects achieve better results than those without. Use of different P fertilizer sources such as triple superphosphate

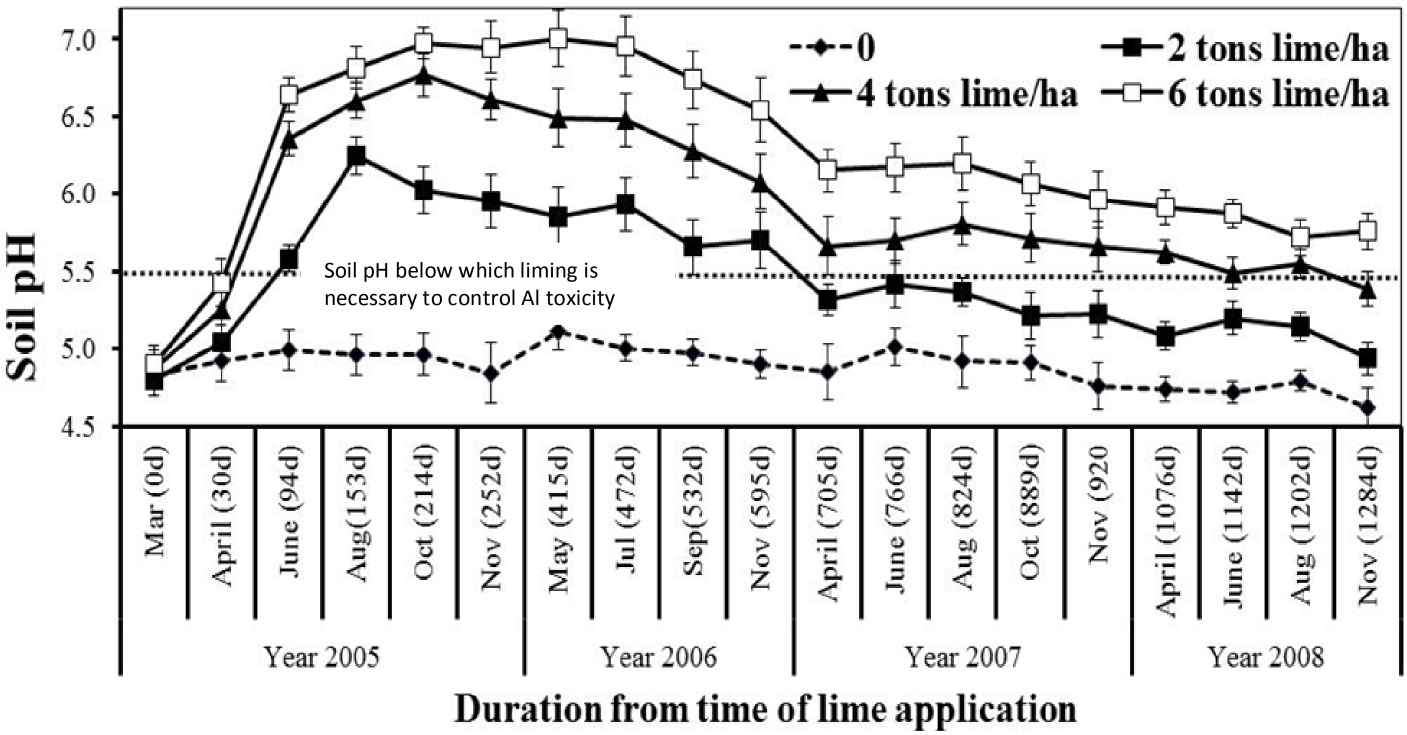


**Figure 2.** Effect of lime on soil pH during the cropping period at the highlands of RV, Kenya acid soil; d = days from the time of lime application and error bars indicate standard errors of means (SEM). Source: Kisinyo (2011).

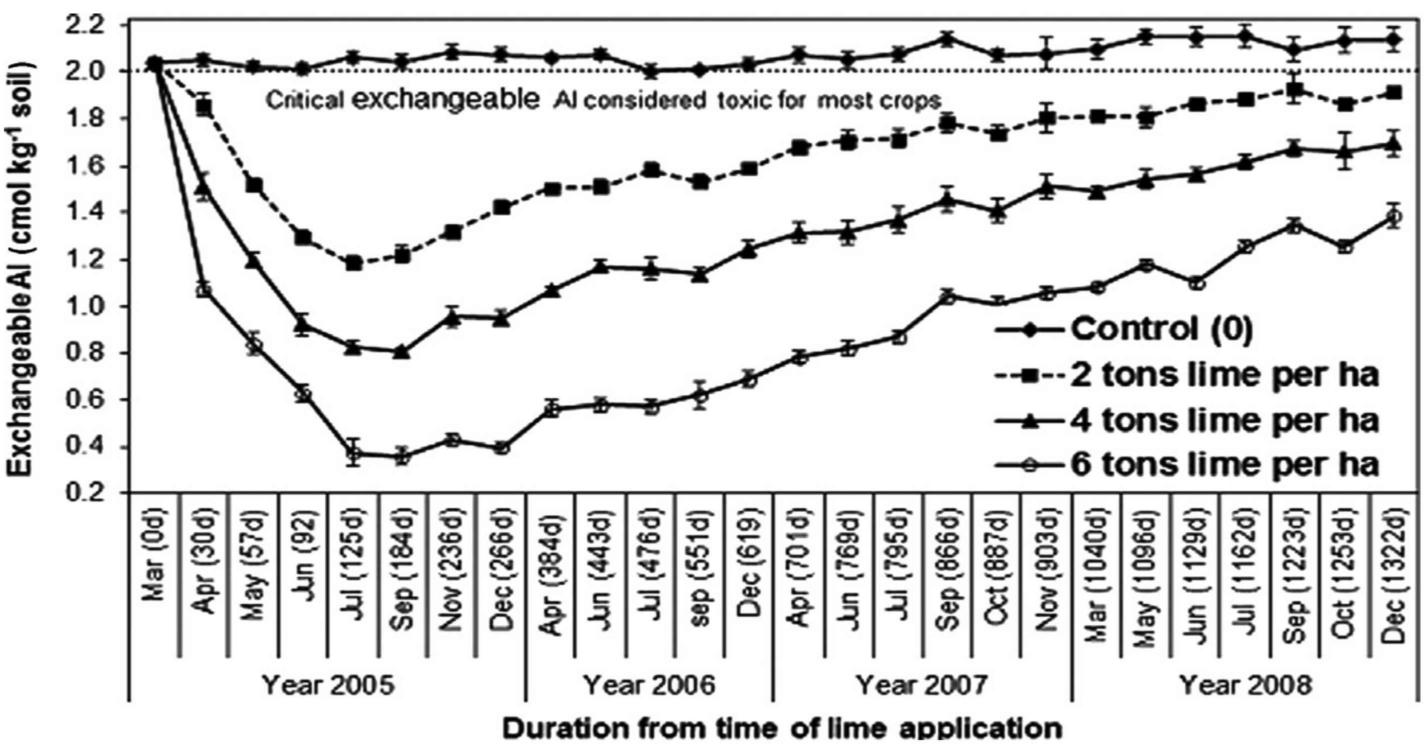


**Figure 3.** Effect of lime on exchangeable $Al^{3+}$ during the cropping period on a western Kenya acid soil; d = days from the time of lime application and error bars indicate SEM. Source: Kisinyo et al. (2014).

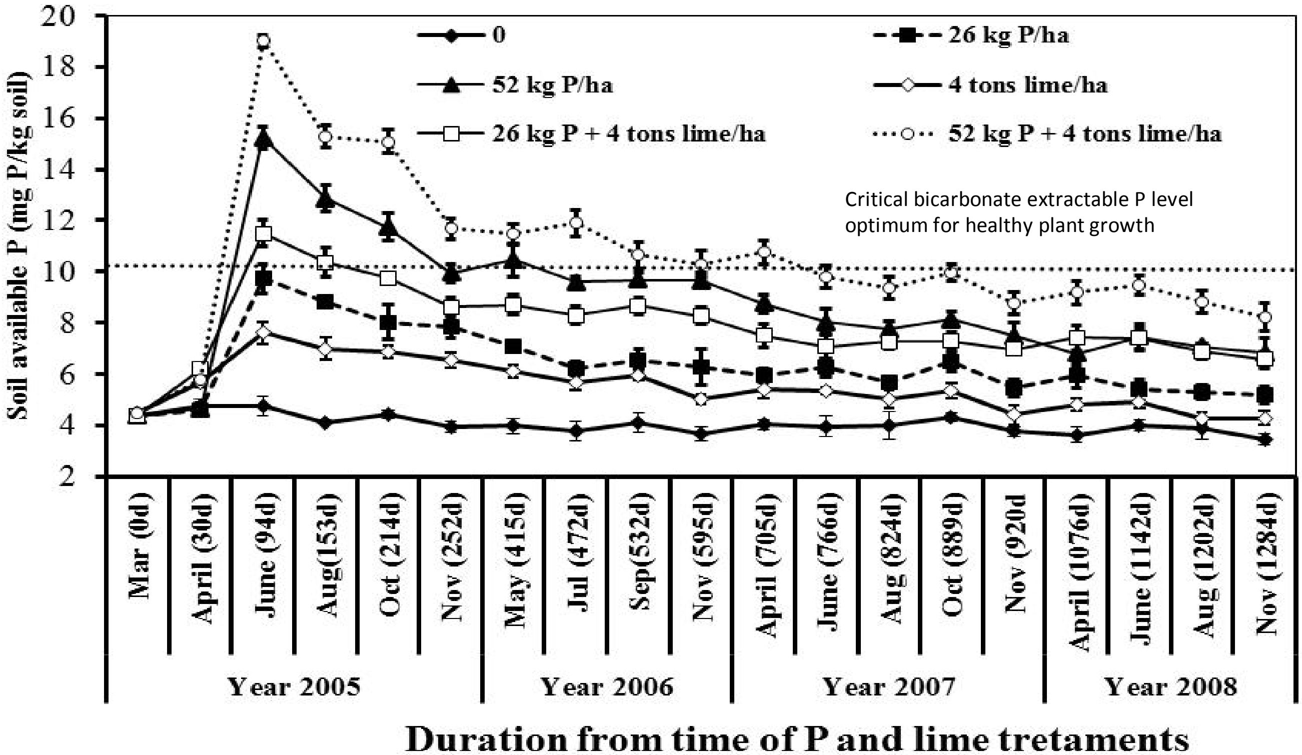


**Figure 4.** Effect of lime and P fertilizer on soil available P during the cropping period at the highlands of RV, Kenya acid soil; d = days from the time of lime application and error bars indicate SEM. Source: Kisinyo (2011).

(TSP), Busumbu phosphate rock (BPR) and Mijingu phosphate rock (MPR) at the rates of 60 kg P/ha increased soil available P and maize grain yield in western Kenya acid soils (Opala et al., 2010a). Soil available P and grain yield response followed the increasing older of BPR→TSP→MPR. The MPR produced the highest grain yields due to neutralization of soil acidity because of its liming effect in addition to increasing soil available P. The BPR produces the lowest response due to its low reactivity to release P into the soil. Maize grain yield increments of 17.5 to 93% has been reported due to applications of 26 to 60 kg P/ha on Kenya acid soils (Gudu et al., 2005; Opala et al., 2010a, Kisinyo, 2011). The increments were attributed to improvement soil available P necessary for healthy plant growth.

Residual benefits of lime and P fertilizer have been reported in Kenyan acid soils (Kisinyo, 2011; Nekesa, 2007; Opala et al., 2010a). Similar results were reported on an acid soil of Hawaii by Mahilum et al. (1970) where 2 tons $CaCO_3$ $ha^{-1}$ kept exchangeable Al below 1.0 cmol $kg^{-1}$ from the original 3.0 cmol $kg^{-1}$ for 5 years. Due to its slow reactivity, not all the benefits of lime may be realized during the first year of its application (Halvin et al., 2006). Elsewhere in tropical acid soils, residual effect of P fertilizer has been reported to persist for as long as 5 to 10 years or more, depending on the initial P rate applied crop removal and the soil buffering capacity (Tisdale et al., 1990). Combined application of both lime and P fertilizer has increased soil available P, seedlings growth and crop yields more than either of them alone in Kenyan acid soils (Kisinyo, 2011, Kisinyo et al., 2012; Kanyanjua et al., 2002). In low P acids soils with high P sorption, use of both P fertilizer and lime have been suggested for maximum soil available P and efficient utilization of the P fertilizers by plants (Kisinyo et al., 2014; The et al., 2006). Many studies have reported improved soil available P and its utilization due to combined applications of both lime and P fertilizer on Kenyan acid soils (Kanyanjua et al., 2002; Kisinyo, 2011; Kisinyo et al., 2012; Opala et al., 2014). Therefore, it is imperative that combined application of both P fertilizer and lime are important for both short and long term management of P deficient acid soils such as found in Kenya.

Despite the enormous benefits, use of lime and inorganic fertilizers face a number of challenges. Most Agro-Chemical Dealers do not stock lime as a result it is not readily accessible to farmers. Lime application is labour intensive; particularly hand broadcasting and subsequent spreading are expensive for small holder

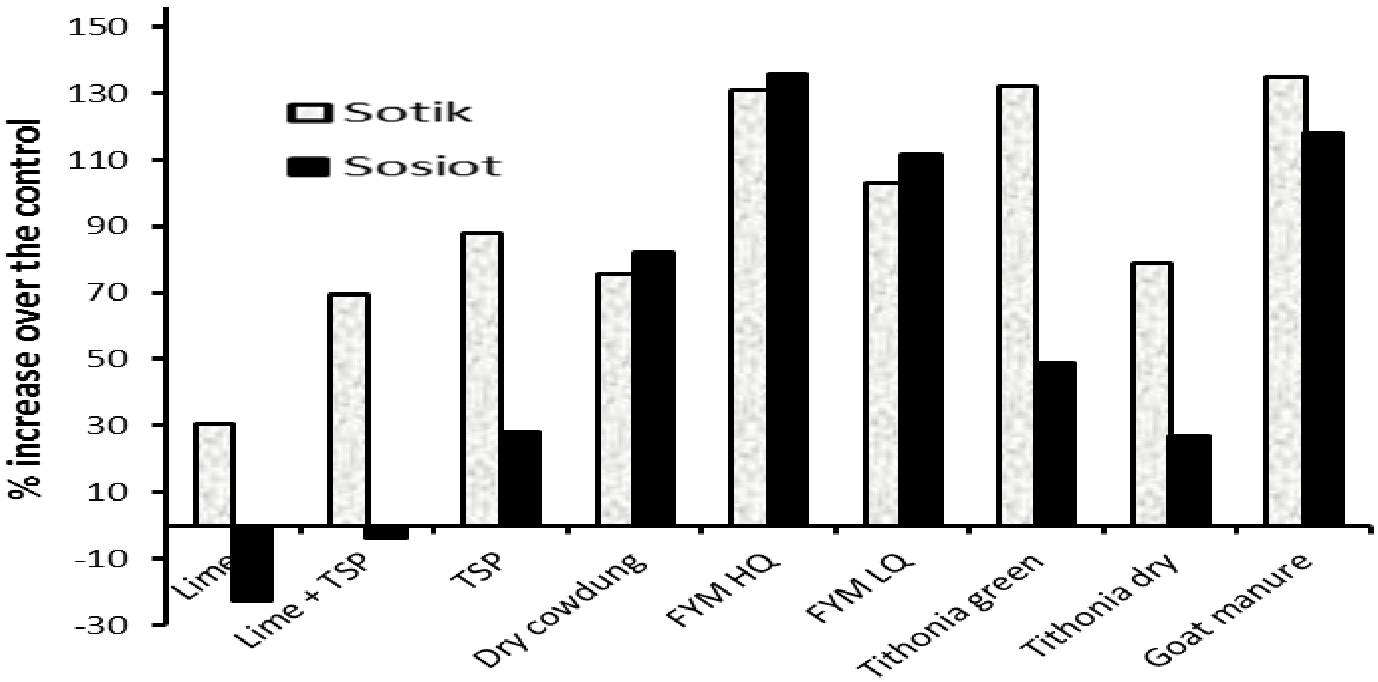


**Figure 5.** Percent increase in drymatter yield over the control at Sosiot and Sotik. TSP = triple superphosphate, FYM HQ = farmyard manure of high quality (> 1.5% N), FYM LQ = farmyard manure of low quality (< 1.0% N). Source: Opala et al. (2014).

farmers who lack the credit to hire labour. Also low demand for lime by farmers in Kenya as a result of lack of knowledge on its importance hinders its use by farmers. Fortunately, Kenya has large lime deposits and many companies such as Homa Lime, Athi River Mining are producing liming materials. Therefore, use of lime has the potential to improve crop production in Kenya acid soils and hence the need to create awareness among farmers on its importance. This will help create demand for the Agro-Chemical Dealers to stock so that farmers may access it easily. Like many parts of SSA, most small holder farmers in Kenya rarely use the recommended rates of inorganic fertilizers (N and P) due to their high cost and lack of credit (Okalebo et al., 1997, 2006; Sanchez et al., 1997). Due to these challenges, there is need to explore alternative management options discussed below to improve crop production in the Kenyan acid soils.

## Use of organic materials (OMs)

Use of OMs has been proposed as an alternative to liming to reduce Al toxicity in acid soils (Lungu, 1993). During OMs decomposition, there is release and synthesis of organic compounds which combines with Al to form solid- organic material phase leading to reduction of Al solubility (Tang et al., 2007; Haynes and Mokolobate, 2001). Organic materials also interact with P in soils in a variety of ways that potentially influences P sorption and release reactions. Direct and indirect mechanisms have been proposed for the increase of soil available P as a result of the addition of OMs by Guppy et al. (2005). OMs are known to reduce soil acidity, Al toxicity and increase soil available P in acid soils. In western Kenya, Opala et al. (2010a) demonstrated that *Tithonia diversifolia* (tithonia) green manure is effective in increasing maize yield due to its ability to reduce exchangeable Al in soils without necessarily increasing the soil pH (Figure 5). This was attributed to the ability of the tithonia to form complex with Al. However in the same study, farmyard manure (FYM) increased the soil pH but it was less effective in decreasing the exchangeable $Al^{3+}$ compared to tithonia. It was thus concluded that the ability of an organic material to reduce Al toxicity was related to its ability to complex the Al through organic acids produced during its decomposition process. The tithonia green manure was therefore more effective because of its ability to release larger quantities of organic acids compared to the well rotten FYM which had lost most of the organic acids. This confirmed earlier findings by Ikerra et al. (2006) who found larger quantities of organic acids in soils treated with tithonia than those that received FYM in Tanzania. In another study in Kericho County in Kenya, Opala et al. (2014) tested the effect of a range of organic materials of diverse composition commonly found on small holder farms on maize dry matter production on two acid soils. These were compared to lime and triple superphosphate (TSP). Results showed that manures of high quality that is > 1.8% N increased maize dry matter yields above the control with no nutrient inputs and were generally superior to lime applied alone or in combination with TSP (Figure 5). This was attributed mainly to the ability of the OMs to ameliorate Al toxicity while providing a range of nutrients that were not provided by lime. This confirmed earlier observations by Opala et al. (2013) that some organic materials such as tithonia could substitute lime as an amendment for soil acidity. It had been previously recognized that organic materials can indeed decrease P sorption in acid soils and hence farming systems that include additions of green or animal manures may be able to increase availability of P by increasing the solubility of soil P (Ohno and Crannel, 1996). There has been intensive research in Kenya by International Centre for Research in Agroforestry, Tropical Soil Biology and Fertility, Kenya Agricultural Research Institute and Moi University in the past two decades focused on increasing available P in acid soils of western Kenya using organic materials such as tithonia, calliandra and farmyard manures with /or without inorganic P sources such as triple superphosphate or phosphate rocks. This was based on the fact that decomposing organic materials produce organic acids that solubilize P from phosphate rocks (PRs) through chelating or complexing action (Kpomblekou and Tabatabai, 1994). Use of OMs to increase the dissolution of PRs has been widely studied in East Africa region (Okalebo et al., 2006; Savini et al., 2006; Kifuko et al., 2007).

There is, however, a wide divergence of opinion as to the effect of OMs on PRs dissolution. Many of the earlier studies reported enhanced dissolution of PR when it is combined with OMs such as FYM (McLenaghen et al., 2004). There is, however, emerging evidence that some high quality organic resources, especially those with a high Ca content, e.g. tithonia, can inhibit dissolution of reactive PRs such as MPR (Smithson, 1999). Other workers have, however, suggested that organic materials enhance dissolution of unreactive PRs but inhibit dissolution of reactive PRs such as Mijingu (Zarah and Bah, 1997). Ikerra et al. (1994) observed that the agronomic effectiveness of MPR increased when it was combined with high quality FYM but not with low quality compost. Interestingly, Tian and Kolawole (1999) found increased uptake of P following incubation of low quality materials such as maize stover with PRs. More recently in Kenya, Gikonyo et al. (2006) attributed the reported declines in crop yields as a result of combination of OMs and insoluble PR to very high toxic levels of available P in the soil. According to these authors, the toxic levels of P a rose from enhanced dissolution of the PRs by the OMs and not the inhibition of PRs dissolution as reported earlier (Smithson, 1999). Though most of the results showed increased yields as a result of combining PR and OMs, it did not explain how some OMs, such as FYM, which are known to increase pH in certain cases, can at the same time increase dissolution of PR which is favoured by acidic conditions. Thus Opala et al. (2010a) hypothesized that the reported increases in crop yields as a result of combining PR and OMs could be due to the P released from mineralization of the OMs and not increased dissolution of the PR. These authors demonstrated that combining OMs (tithonia or FYM) with PR or TSP did not enhance P availability, although the maize yields obtained by the combined application of OMs and the inorganic P sources was higher than that of the inorganic P sources where the available soil P was in most cases higher. The studies however, showed large reductions in exchangeable Al in the soils treated with the OMS, particularly tithonia and concluded that the ability of an OM to reduce Al in acid soils was more effective in increasing maize yield than its ability to increase soil available P. Maize grain yield increments of 70 to 100% have been reported through use of various OMs in Kenya (Opala et al., 2010a).

There are however some challenges in the use of OMs to manage acid soils and replenish soil fertility. The quantities and qualities of organic materials available to farmers are limiting factors to their use in Kenya. Due to their low nutrient content, large amounts have to be applied thus increasing the labour cost (Jama et al., 1997; Kisinyo et al., 2006). The high costs in some cases cannot be offset by the extra yields obtained by applying some of the organic materials including tithonia (Opala et al., 2007, 2010b), calliandra and maize stover (Nyambati and Opala, 2014; Jama et al., 1997). However, OMs such as FYM of high quality have in most cases been shown to be economically attractive under most smallholder situations (Opala et al., 2007, 2010b, 2013). This highlights the need for high quality OMs as sources of nutrients in acid soils. Nziguheba et al. (2002) concluded that OMs suitable for use as P sources should have a high P content and low cost of production. The P concentration in plant materials such as tithonia is controlled by genetics and environmental factors and can, therefore, not easily be manipulated by the farmer through management. Opportunities for increasing the quality of FYM, however, do exist. Practices such as using pits for manure storage and storing manure under shade (Murwira and Nzuma, 1999; Rufino et al., 2006) can greatly enhance the quality of FYM, therefore, making its use more profitable. Increasing the quantity of high quality FYM to resource-poor farmers in western Kenya may however be limited, particularly in the absence of large numbers of improved livestock breeds (Jama et al., 1997). Therefore, FYM and other OMs that have shown potential for use as nutrient sources while amelioration soil acidity can be applied together with appropriate inorganic P sources such as TSP and MPR in an integrated soil fertility management program on small holder farms.

### Use of acid tolerant crops

To deal with soil acidity related problems, plant breeding programs have developed germplasms tolerant to Al toxicity and/ or low soil available P (Parentoni et al., 2006; Donswell et al., 1996). The low soil available tolerant genotypes can obtain adequate P even from sparingly soluble P through enhanced microbial colonization and symbiotic association with P solubilizing microorganisms in the rhizosphere (Oliveira et al., 2006). In addition, some of the genotypes express a protein kinase gene called phosphorous starvation tolerance gene (Pstol1) which enables acquisition of P and other nutrients (Gamuyao et al., 2012) even in P deficient soils. The sensitive crop germplasms do not express this gene and hence are not able to utilize the applied fertilizers and /or fixed P with high efficiency and hence the reason for low grain yields. Incorporation of this gene to P deficiency sensitive cultivars could greatly improve crop yields in acid soils of Kenya and other regions experiencing similar constraint.

On highly acid soils (pH<5.0), aluminum toxicity is a primary limitation for crop production. Liming to mitigate its effect is not sustainable as has been stated and this has led to discovery and use of Al tolerant genotypes. A major physiological mechanism of plant aluminum tolerance involves aluminum activation of membrane transporters that mediate organic acid release from the root apex, the site of aluminum phytotoxicity, with the released organic acids forming stable, nontoxic complexes with $Al^{3+}$ in the rhizosphere (Magalhaes et al., 2007). In sorghum a multidrug and toxic compound extrusion (MATE) gene that transport citric acid was found to confer Al tolerance (Magalhaes et al., 2007) and in maize a similar gene, *ZmMATE1*, (Maron et al., 2013) was also found. The introgression of such genes into Al sensitive cultivars have been shown to improve grain yield performance in acid soils.

Although the approach of using tolerant plant germplasm is not able to reverse soil acidity conditions, it minimizes the problems experienced by farmers, especially those who do not use lime (Clark, 1997). In recent studies, Kenyan maize and sorghum germplasms tolerant to Al toxicity and /or P use efficient have been identified (Ouma et al., 2013; Ligeyo, 2007; Matonyei, 2010; Too, 2011). These elite materials provide a good foundation for breeding for tolerant cultivars to Al toxicity and/or P use efficiency in Kenya at the moment. Currently, there are no commercial maize/sorghum or other crop varieties available to farmers that are adapted to soil acidity in Kenya (Ligeyo, 2007). Therefore, there is need to develop crop varieties adapted to acid soils for enhanced crop productivity in the Kenyan acid soils.

## CONCLUSION

Acid soils occupy about 13% of the total land area in Kenya. Most of which has developed partly due to leaching of base cations by high rainfall, use of acid forming fertilizers and parent materials of acids origin. These contain low soil available P (< 5 mg p/kg soil) owing partly to high P sorption by clay minerals such kaolinite, gibbsite, goethite, and Al and Fe oxides. Acid soil in the highlands east of RV 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). Due to higher Al levels, highlands east of RV 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. In the Kenyan acid soils, improved crop productivity has been achieved through use of lime, manures, fertilizers with liming effects, crop germplasms tolerant to Al toxicity and low soil available P. Lime has increased soil pH, available P and crop yields and reduces Al toxicity in these soils. Combined application of lime and P fertilizer or use of P fertilizers with liming effects is more effective increasing soil available P and crop yields than lime alone or P fertilizer without lime. Use of organic materials reduces Al toxicity through production of organic acids that form complex with $Al^{3+}$ ions leading to high crop yields in the Kenyan acid soils. Similarly utilization of high quality OMs such as tithonia produces economic crop yields since small volumes are required compared to low quality ones. Deployment of crop germplasms tolerant soil Al toxicity and /or low available P has the potential to increase crop productivity in the Kenyan acid soil. Therefore there is need to develop crop varieties tolerant to soil Al toxicity and /or low available P to increase crop productivity in the Kenyan acid soils. However, challenges such as lack of credit to purchase inorganic inputs, knowledge on the importance of lime, improve crop varieties tolerance to soil acidity constraints and inadequate amounts of organic materials limit crop productivity on the Kenyan acid soils.

### Conflict of Interest

The authors have not declared any conflict of interest.

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