SOIL ACIDITY AND LIMING HANDBOOK FOR KENYA

Peter Opala
Maseno University

Esther Mwende Muindi
Pwani University

Samuel Gudu
Moi University

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LIST OF AUTHORS AND CONTRIBUTORS

Anthony O. Esilaba – Formerly Kenya Agricultural and Livestock Research Organization (KALRO)
Peter A. Opala – Maseno University
Dave Nyongesa – Formerly KALRO
Esther M. Muindi – Pwani University
Esther W. Gikonyo – KALRO
Angela N. Kathuku-Gitonga – African Plant Nutrition Institute (APNI)
David M. Kamau – KALRO
Michael M. Kamau – Gatsby Africa (GA)
Peter O. Kisinyo – Rongo University
John Wendt – International Fertilizer Development Center (IFDC)
James Mutegi – APNI
David Mbakaya – Formerly KALRO
Ivan Adolwa – APNI
Mercy Nyambura – Formerly IFDC
Nesbert Mangale – Formerly KALRO
Fredah W. Maina – KALRO
Samuel O. Gudu-Rongo University
Japheth M. Wanyama-KALRO
Bonventure S. Biko – GA

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Gatsby Africa
P.O Box 41472-00100
Merchant Square, Riverside Drive
Nairobi, Kenya
www.gatsbyafrica.org.uk

Kenya Agricultural and Livestock
Research Organization
Kaptagat Rd, Loresho
P.O Box 57811-00200
Nairobi Kenya
www.kalro.org

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FOREWORD

Food is one of the basic physiological needs that human beings require for survival. With an increasing global food demand, the world needs to produce sufficient food to sup¬port its populations. Additionally, agriculture is a major source of employment and incomes for households, soci¬eties, and governments the world over. This situation holds true especially for Kenya which is a predominantly agricul¬tural-based economy. Over 18 million Kenyans earn an income from agriculture. The sector significantly contributes to the Country's foreign exchange earnings through agricultural exports. The importance of this sector in Kenya can therefore not be overemphasized.

Soil acidity is a significant constraint to crop productivity in the tropics. In Kenya, soil acidity affects about 13% of the land mass, which equates to approximately 63% of the country's arable land. Most crop nutrients become unavailable in highly acidic soils, resulting in low productivity. Declining crop yields pose a serious threat to the food and nutritional security, incomes, and livelihoods of mil¬lions. Soil health remains an important factor in increasing and maintaining crop yields. To maximize agricultural productivity, farmers' understanding of soil acidity and its management is paramount. Liming has been identified as an effective method for reducing soil acidity and increasing crop yields in Kenyan regions with high acidic soils.

Recognizing the importance of having the right information, the Ministry of Agriculture and Livestock Development, research institutions, universities, the private sector, and development partners collaborated through the Kenya Fertilizer Roundtable (KEFERT) to produce this handbook as a reference source for soil acidity and liming information in the country. The overall objective of this handbook is to contribute to increased food security, nutrition, and poverty reduction by promoting appropriate use of liming tech¬nologies, innovations and management practices among small-scale farmers in Kenya.

Specifically, this handbook seeks to:

- standardize and harmonize soil acidity and liming knowledge, information, and technologies by serving as a reference point for key stakeholders.
- improve access to soil acidity and liming information for key stakeholders – policy makers, extension staff, input suppliers, researchers, and farmers, among others.
- propose policies and strategies designed to ameliorate the effects of soil acidity on agricultural production.
- inform policy changes that will enhance the profitability of the agricultural lime supply value chain
- draw attention to critical issues limiting adoption among lime users that need to be addressed.

In conclusion, the significance of food as a fundamental human need cannot be overstated and meeting the esca-lating global food demand remains a critical global challenge. Soil acidity emerges as a pressing obstacle, affecting a substantial portion of Kenya's arable land and con¬sequently jeopardizing food and nutrition security; and income stability for many. The imperative role of soil health in bolstering crop yields underscores the necessity of comprehensive knowledge dissemination among farmers.

With its multi-fold objectives ranging from standardizing knowledge to influencing policy changes, the handbook aspires to empower stakeholders, foster informed deci¬sion-making, and ultimately contribute to the advance¬ment of food security, nutrition, and poverty alleviation in Kenya.

Through the promotion of effective liming practices and targeted interventions, this initiative strives to uplift the agricultural landscape and ensure a brighter, more sus¬tainable future for farmers in the country.

Hon. Mithika Linturi
Cabinet Secretary
Ministry of Agriculture and Livestock Development

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ABBREVIATIONS AND ACRONYMS

AfSIS	Africa Soil Information Service
Ag- lime	Agricultural lime
AGRA	Alliance for a Green Revolution in Africa
Al	Aluminium
APNI	African Plant Nutrition Institute
AS	Ammonium Sulphate
ASTGS	Agricultural Sector Transformation and Growth Strategy
B	Boron
C	Carbon
Ca	Calcium
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate, Calcitic limestone
$CaMg(CO_3)_2$	Calcium magnesium carbonate or dolomitic lime
CAN	Calcium Ammonium Nitrate
CaO	Calcium Oxide
$CaSiO_3$	Calcium Silicate
CCE	Calcium Carbonate Equivalent
CEC	Cation Exchange Capacity
Cl	Chloride
Co	Cobalt
CO_2	Carbon dioxide
Cu	Copper
DAP	Diammonium Phosphate
ECC	Effective Calcium Carbonate
ECEC	Effective Cation Exchange Capacity
EU	European Union
FAO	Food and Agriculture Organisation
Fe	Iron
GA	Gatsby Africa
GDP	Gross Domestic Product
GPS	Global Positioning System
H	Hydrogen
H_2O	Water
HCO	Bicarbonate
HLCL	Homa Lime Company limited
IFAD	International Fund for Agricultural Development
IFDC	International Fertilizer Development Center
ISFM	Integrated Soil Fertility Management
K	Potassium
KALR	Kenya Agricultural and Livestock Research Act, 2013
KALRO	Kenya Agricultural and Livestock Research Organisation
KCEP-CRAL	Kenya Cereal Enhancement Programme Climate Resilient and Agricultural Livelihoods Window
KeBS	Kenya Bureau of Standards
KES	Kenya Shillings
KMT	Kenya Markets Trust
KNBS	Kenya National Bureau of Statistics
KSHC	Kenya Soil Health Consortium
LR	Lime Requirement
LSCM	Lean Supply Chain Management
MAP	Mono-Ammonium Phosphate
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MoALF&C	Ministry of Agriculture, Livestock, Fisheries and Co-operatives
MT	Metric tonnes
N	Nitrogen
Na	Sodium
NAP	National Agriculture Policy

NASEP	National Agricultural Sector Extension Policy
NASM	National Agricultural Soil Management Policy 2020
NEP	National Environmental Policy
NFMP	National Forestry Management Policy
NGOs	Non-Governmental Organisations
NIP	National Irrigation Policy
NLRP	National Land Reclamation Policy
NLUP	National Land Use Policy
NO_2	Nitrogen Oxide
NP	Nitrogen and Phosphate
NPK	Nitrogen, Phosphorus and Potassium
NV	Neutralising Value
O	Oxygen
OH	Hydroxide
P	Phosphorus
PDA	Potash Development Association
pH	Measure of acidity or alkalinity
PR	Phosphate Rock
4R	Nutrient stewardship- Right rate, right source, right placement right timing
RAS	Required Aluminium Saturation
S	Sulphur
SDGs	Sustainable Development Goals
SO_2	Sulphur dioxide
spp	Species
SSP	Single Super Phosphate
SWOT	Strengths Weakness Opportunities and Threats
$t\ ha^{-1}$	tonnes per hectare
TSP	Triple Super Phosphate
USD	US Dollars
Zn	Zinc

Executive Summary

Soil acidity develops from a combination of natural and anthropogenic processes. Its effects can be evaluated through its impact on soil's physical, chemical, and biological activities that ultimately affect nutrient availability and uptake by plants. Soil testing and data interpretation are integral parts of soil acidity management. Soil testing provides information on the acidity status of soils that can be used for making lime application recommendations. Soil acidity has adverse impacts that threaten Kenya's food security and limit agribusiness potential. Acidic soils hamper crop production and are a major cause of crop yield reduction, resulting in reduced agricultural incomes. Currently, 13% (7.5 million hectares) of Kenya's soils are acidic, which translates to approximately 63% of Kenya's arable land. Soil acidity is concentrated in the Central, Western, and Rift Valley regions – the main food baskets of Kenya. In addition, soil acidity is also found in some parts of Eastern and Coastal regions.

Several strategies have been documented for managing acid soils in Kenya. These include addition of liming materials, use of organic materials, judicious choice and application of fertilizers combining lime with organic materials and inorganic fertilizers (Integrated Soil Fertility Management or ISFM) and growing acid tolerant crop species. However, these options for managing soil acidity are not currently accessible to most farmers.

Liming of acid soils is the most common and effective amelioration strategy for improving crop production. It enhances the soil's physical, chemical, and biological characteristics. The reduction of soil acidity indirectly mobilizes plant nutrients immobilizes toxic aluminium (Al) and manganese (Mn) and improves soil structure. As the term is used in agriculture, liming is the addition of any calcium (Ca) and/or magnesium (Mg) containing compounds that can reduce soil acidity. A range of liming materials, which vary in their ability to neutralize soil acidity, is available. The most used liming materials are carbonates of Ca or Ca and Mg, including ground limestone, dolomitic ground limestone, and ground chalk.

The amount of liming material required to achieve a target pH that is favourable for crop production is defined as lime requirement. Many methods are used in different countries to determine lime requirements. Regardless of the method used to determine lime requirement, it is advisable to avoid excessive lime applications because it can significantly depress yields. The efficiency of lime use can be improved by applying the 4R principle that is used in improving fertilizer use i.e., right source, right rate, right placement, and right timing. Although the agronomic benefits of liming are well known, the practice is not yet common in Kenya. As of 2023 adoption of lime by farmers was very low ranging between 1% and 8%.

Considerable research on lime use has been conducted in Kenya. However, the range of crops studied is not wide and most focus is on maize, which is the staple food. These studies show that yield response to liming vary from 0 to > 400%. The increase in yields depends on initial soil pH, the crop, soil characteristics, and the lime rate. It is therefore vital to have soils tested for soil pH and exchangeable acidity before liming is recommended. Lime must, however, be applied with other nutrients, particularly macronutrient NP and NPK fertilizer which are usually the most limiting on most smallholder farms.

Kenya does not have a fully developed supply chain for agricultural lime (ag-lime). The value chain of ag-lime and policy considerations have not been extensively evaluated, shared and exploited. The ag-lime business in Kenya is still in early development stages. Aspects of ag-lime market dynamics such as market overview, market drivers, supply chain analysis and market challenges/constraints need to be studied. Comprehensive policy, legal and regulatory frameworks that lead to increased use of ag-lime need to be developed to encourage local manufacturing, distribution, and utilisation.

Although soil acidity has been identified as a major constraint to crop production by the Government of Kenya and other stakeholders in agriculture, there are no comprehensive plans to correct it. To address acidity, the use of lime is encouraged. However, inefficiencies and challenges arise due to several reasons. A key recommendation is the creation of a national action plan to rehabilitate acidic soils. Various stakeholders should coordinate efforts (national and county governments, development partners, private sector, and other players) to increase awareness and support for soil acidity and liming.

In conclusion, strategic research is needed to develop and promote liming in addition to integrated crop, soil, water, soil fertility management practices for acidic soils. Manuals for simple field tests, laboratory procedures, and lime requirement recommendations based on the soil test results need to be developed for different crops and varieties. Further, lime response studies need to be conducted to determine economical and optimum rates of liming soils in Kenya. In order to improve lime and liming materials' adoption, the government should increase its budgetary allocation to support agricultural research, development and knowledge dissemination that addresses soil acidity.

There is also a need for a national economic assessment of the benefits of liming agricultural soils in Kenya. The government should put together new regulations as part of a comprehensive policy framework for regulating lime use and application, with an appropriate legal framework that aligns with the current global liming trends. A lime business model for management of acidic soils in Kenya is urgently required. A first step is a detailed action plan, which is a step-by-step approach to develop the lime value chain. This will serve as a basis for donors, the national and county governments to fund activities that develop the value chain.

1.0 INTRODUCTION

The agriculture sector plays a vital role in Kenya's rural economy, contributing 26% of the Gross Domestic Product (GDP) directly, and 27% of GDP indirectly through linkages with other sectors. Over 40% of the total population and more than 70% of Kenya's rural population derive their employment from agriculture, with the sector accounting for 65% of Kenya's export earnings. It provides a source of livelihood (employment, income, and food security needs) for more than 80% of the Kenyan population while contributing to improved nutrition by producing safe, diverse, and nutrient-dense foods (KNBS, 2021). The sector also drives the non-agricultural economy, such as manufacturing through the provision of inputs and market for non-agricultural operations such as building and construction, transportation, tourism, education, and other social services.

Although agricultural production is recognised as the basis of economic growth, poverty reduction and food insecurity mitigation within the country, cereals production has stagnated over the past two decades (Birch, 2018). According to KALRO (2017), declining crop yields, particularly for staples that guarantee food and nutrition security such as maize, beans, millet, and potatoes, poses a food security threat to smallholder farmers across the country. Similarly, decline in yields of cash crops such as coffee, flowers and vegetables has resulted in a decrease in earnings and agribusiness income. The decline in agricultural production has been attributed to a myriad of factors ranging from a poor agronomic knowledge base, policy implementation, pests and diseases, nutrient mining, poor purchasing power, climate change, land degradation, soil salinization and acidification, among others (Muraya and Ruigu, 2017; Hijbeek *et al.,* 2021).

Approximately 13% of Kenya's soils are acidic (Kanyanjua *et al.*, 2002), which translates to approximately 63% of Kenya's arable land. Soil pH is related to the composition of ions on soil colloidal fraction exchange sites. In acidic soils, hydrogen (H^+) and aluminium (Al^{3+}) ions dominate the soil exchange sites while in non-acidic soils, basic cations calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) dominate. Soil pH is acidic when (H^+) ions predominate over (OH^-) ions in the soil solution (Weil and Brady, 2017; Sanchez, 2019), and at pH <5.5, yields of many crops are adversely affected. Acid soils are dominant in key agricultural zones which contribute more than 60% of the country's economy through cash crop and dairy production. Numerous biological and chemical factors in the soil are responsible for acid soil infertility, including aluminium toxicity, calcium and magnesium deficiencies, and low populations of symbiotic nitrogen-fixing bacteria. Acid soil infertility is also associated, to a lesser extent, with manganese toxicity and molybdenum insufficiency. Soil acidity often occurs together with phosphorus deficiency (Sanchez, 2019).

Although soil acidity is determined using various methods, soil pH, which is a measure of the hydrogen (H^+) ion concentration in the soil solution, expressed as the negative logarithm of H^+ concentration in soil solution, is commonly used to give a general idea of prevailing acidity (Table 1.1)

Table 1.1: Grading levels of soil acidity

Degree of acidity	pH range
Extremely acidic	<4.5
Strongly acidic	4.5-5.0
Moderately acidic	5.0-6.0
Slightly acidic	6.0-6.5
Near neutral	6.5-7.0
Alkaline	>7.0

Source: Mehlich *et al.* (1964)

The significance of soil pH lies in its ability to influence various soil processes that control crop growth. Soil pH is important because it:

1. affects nutrient availability in soil,
2. has a direct effect on nutrient uptake by roots,
3. affects the solubility of toxic substances such as aluminium and manganese, and
4. affects soil microbial biodiversity and their activities.

The range of soil pH where nutrient availability is best balanced for many crops is between 6.0 and 7.0 (Rengel, 2003; Havlin *et al.*, 2014; Sanchez, 2019). The factors that trigger soil acidification and their effects on soil fertility, plant nutrition, growth and yields are elaborated in Chapters 2 and 3.

The pH value of most agricultural soils in Kenya ranges from 5.0 to 7.0. Most areas that receive more than 2000 mm of rainfall annually are, however, dominated by soils with pH values between 4 and 6. These acid soils are distributed widely in the cropland regions of Central, Eastern, Rift Valley and Western Kenya (Esilaba *et al.*, 2023; Mbakaya, 2015). They cover over one million hectares under maize, legumes, tea, and coffee, cultivated by over five million smallholder farmers (Kanyanjua *et al.,* 2002). The distribution of acid soils in Kenya is shown in Figure 1.1. Kenya's coastal region also has some hotspots in Kwale, Kilifi and Taita Taveta Counties.

According to World Reference Base and the Food and Agriculture Organization (FAO) classification systems (FAO, 2015), most of the acid soils in Kenya are Nitisols, Acrisols, Ferralsols and Andisols. These soils are generally deep, well-drained with good structure, and dominant in high potential areas with high rainfall. If acidity is mitigated, these soils offer a high yield potential for crop production (Opala *et al.*, 2010).

Several strategies such as liming application of organic materials and planting of acid tolerant crop varieties have been used to manage soil acidity in Kenya with varying degrees of success (Chapter 5). Lime application (Chapter 6), however remains the most common and most effective strategy for improving crop production in acid soils globally. Despite the critical role lime plays in soil acidity management, its adoption and effective usage by farmers has remained low in Kenya. The low adoption and usage can be attributed to a myriad of factors such as limited knowledge base, high lime prices, lime bulkiness, lime quality, lack of streamlined liming policies and guidelines and poor returns on capital for small scale farmers.

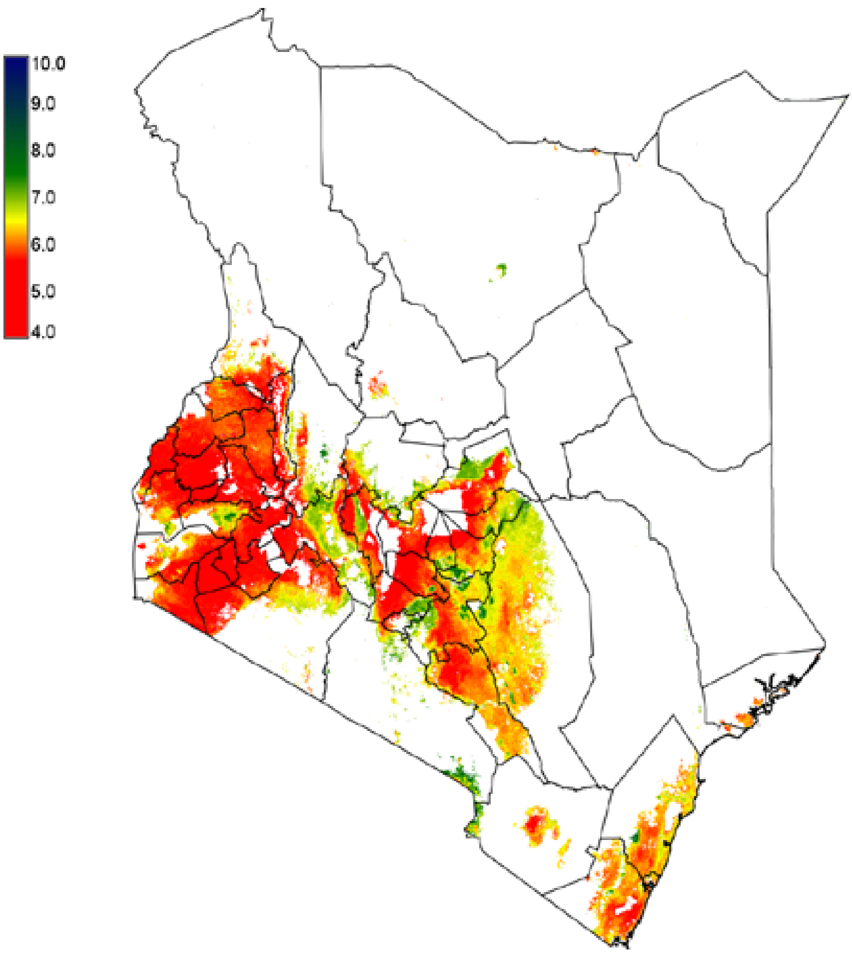

Figure 1.1: Distribution of acid soils in Kenya. Source (Africa SoilGrids, 2015)

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2.0 CAUSES OF SOIL ACIDITY

Soil acidity develops from a combination of natural and anthropogenic processes. Primary soil acidity involves the processes of soil formation and shorter-term biogeochemical processes. Secondary soil acidity is the consequence of agronomic practices (Sanchez, 2019). These processes are described as follows:

2.1 Parent material

Differences in the chemical composition of parent materials can render soils to be acidic or basic. Rocks containing high concentrations of quartz or silica relative to their concentrations of basic materials are classified as acid rocks, for example, granite and rhyolite. When acid rocks decompose during the weathering processes, acid soils are formed (Agegnehu *et al.,* 2021; Goulding, 2016; Weil and Brady, 2017). Soils that develop from such rocks are more acidic than those from basic rocks such as limestone.

2.2 Leaching of bases by heavy rainfall

Soil may become acidic through leaching of the basic soil cations from them (Agegnehu *et al.,* 2021; Rengel, 2003; Weil and Brady, 2017). When these soluble bases are lost, acidic cations such as hydrogen (H^+) and aluminium (Al^{3+}) replace them on the colloidal exchange complex, causing the soil to become increasingly acidic. Leaching is more pronounced in areas with high rainfall; hence, there is a positive correlation between rainfall and soil acidity. Rain is most effective in causing soil acidity if a lot of water moves through the soil rapidly. Sandy soils are the first to become acidic because of their low buffer capacity due to their low clay and organic matter content.

2.3 Organic matter decay

Humus (soil organic matter) contains reactive substances such as carboxylic and phenolic groups, which behave as weak acids (Bolan and Hedley, 2003). When these groups detach from the matter, they release ions which are responsible for causing acidity. Depending on the nature of the plants growing in a particular soil, different amounts of diverse organic acids are generated from the litter. For example, litter from acacia trees tend to produce more organic acids when decomposed than the leaf fall from deciduous woodlands (Kahi, 2004). Decaying organic matter also produces carbon dioxide, which reacts with water to form weak carbonic acid. The conversion of organic nitrogen (N) to mineral nitrogen through nitrification (mineralization of nitrogen) can also increase soil acidity.

2.4 Uptake of nutrients by plants and removal

As plants absorb basic cations such as calcium, magnesium, and potassium, hydrogen ions are released into the soil at the root surface. Leguminous plants are particularly acidifying because they take up more cations than anions compared to non-leguminous plants (Williams, 1980; Bolan *et al.*, 1991). Legumes also take up little nitrate from the soil because microbial nitrogen fixation within their nodule satisfies most of their nitrogen needs. In non-leguminous plants, nitrate uptake partially balances basic cation (e.g., Ca^{2+}, Mg^{2+} and K^+ ions) uptake, so less hydrogen is exchanged from the root to obtain these nutrients. When the crops are harvested from the field or burnt and washed away via surface run-off, these basic cations, responsible for counteracting the acidity developed by other processes, are lost. The net effect is increased acidity. This acidification process is accelerated when plant residues are harvested (such as for animal fodder) rather than returned to the field (Goulding, 2016; Scheffer *et al.*, 2001; Tully *et al.*, 2015).

2.5 Continuous application of acidifying fertilizers

Fertilizer application is one of the major contributors to soil acidification in agricultural ecosystems as shown in Table 2.1.

2.5.1 Ammonium-containing fertilizers

Application of acid-forming ammonium fertilizers such as ammonium sulphate (AS), di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and ammonium nitrate increases soil acidity (Agegnehu *et al.,* 2021; Goulding., 2016; Hue, 1992; Guo *et al.*, 2010). During the nitrification process, the ammonium ions (NH_4^+) from the fertilizers are converted to nitrate ions (NO_3^-) and hydrogen (H^+) ions, which increase acidity (Equation 2.1):

$2NH_4^+ + 4O_2 \rightarrow 2NO_3^- + 4H^+ + 2H_2O$	Equation 2.1

Table 2.1: Acidifying effects of common fertilizers in Kenya.

Fertilizers	Chemical formula	Acidity equivalent*	Acidity produced (kmol H^+ha^{-1})
Ammonium sulphate (AS)	$(NH_4)_2SO_4$	110	2.60
Diammonium phosphate (DAP)	$(NH_4)_2HPO_4$	74	2.06
Urea	$(CO)_2NH_2$	79	0.86
Single superphosphate (SSP)	$Ca(H_2PO_4)_2CaSO_42H_2O$	8	0.48
Triple superphosphate (TSP)	$Ca(H_2PO_4)_2$	15	0.50
Elemental sulphur	S	310	1.55

Source: Bolan and Hedley (2003).

* Acid equivalent is the amount of calcium carbonate (Kg $CaCO_3$) required to neutralise acid residues caused by acid fertilizers in the soil.

2.5.2 Urea

Upon application on soil, urea $(CO)_2NH_2$ is acted on by the enzyme urease, which catalyses the conversion of urea to ammonium (NH_4^+) and bicarbonate (HCO_3^-). The ammonium will react in the same way as ammonium-containing fertilizers (Equation 2.1) to cause acidity.

2.5.3 Fertilizers containing elemental sulphur

Elemental sulphur is typically applied as a soil amendment remedy if a soil has a pH higher than desired and pH reduction is necessary. Sulphur is oxidized in well-aerated soils to produce sulphuric acid, as shown in Equation 2.2.

$2S + 2H_2O + 3O_2 \rightarrow 4H^+ + 2SO_4^{2-}$	Equation 2.2

Different microorganisms mediate sulphur oxidation, such as heterotrophic bacteria and fungi.

2.5.4 Fertilizers containing the H2(PO4)- ion

Soils with pH values greater than six will generate some acidity when fertilizers containing the $H_2(PO_4)^-$ ion are applied. This is demonstrated as per Equation 2.3.

$H_2(PO_4)^- \leftrightarrows H^+ + H(PO_4)^{2-}$	Equation 2.3

These fertilizers include single superphosphate (SSP), triple superphosphate (TSP), and monoammonium phosphate (MAP). This reaction increases as pH increases and is at almost 100% of applied phosphorous (P) at pH values greater than 8.0. However, the reaction does not occur in soils with a pH value less than 6.0.

2.6 Soil erosion

Gradients are common in acidic soils, with higher pH, organic matter, and available nutrient concentrations at the soil surface, which decline rapidly with depth. Plant life causes this gradient by accumulating basic cations, nutrients, and organic residue and depositing them at the soil surface. When this soil surface is subjected to erosion, the soil loses its most nutrient-rich, higher pH strata (Weil and Brady, 2017).

2.7 Acid sulphate soils

Acid sulphate soils are naturally occurring soils, sediments, or organic substrates (e.g., peat) formed under water-logged conditions. These soils contain iron sulphide minerals (predominantly as the mineral pyrite) or their oxidation products. In an undisturbed state, acid sulphate soils in the water table are benign. However, if the grounds are drained, excavated, or exposed to air by lowering the water table, the sulphide reacts with oxygen to release hydrogen ions (Equation 2.4), contributing to soil acidification (Dong *et al.*, 2018). Such soils are rare but can be found in swampy areas such as Yala Swamp in Siaya County (Kanyanjua *et al.*, 2002).

$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 4H^+ + 2SO_4^{2-}$	Equation 2.4

Pyrite + oxygen + water → Iron sulphate + hydrogen ions + sulphate ions

2.8 Acid rain

When gases such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and carbon dioxide (CO_2) are emitted into the atmosphere from internal combustion engines, industrial emissions and agricultural activities, they react with water to form acid rain. These gases are transformed in the atmosphere into sulphuric, nitric and carbonic acids, respectively. The quantities of these acids brought to the earth in acid precipitation globally are enormous. But the amount falling on a given hectare in a year is of limited importance in less industrialized countries like Kenya, and will not induce short-term pH changes (Goulding, 2016; Li *et al.*, 2019; Weil and Brady, 2017).

2.9 Plant root and microbial respiration

The release of carbon dioxide to the soil atmosphere by respiration of plant roots and microorganisms as they decompose organic matter results in the formation of carbonic acids with acidulating effects (Rengel, 2003; Weil and Brady, 2017) (Equation 2.5).

$H_2O + CO_2 \rightarrow H^+ + HCO_3^-$	Equation 2.5

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3.0 EFFECTS OF SOIL ACIDITY ON CROP PRODUCTION

Acid soil infertility is a complex interaction of several growth-limiting factors (Rengel, 2003). Plant growth and yield in acid soils may be restricted by deficiencies of major nutrients such as Ca, Mg, P and Mo and toxicities of aluminum (Al) and manganese (Mn) and hydrogen (H) ions which adversely affect plant physiological processes (Foy, 1984; Marschner, 2012). This chapter discusses the effects of soil acidity on crop growth.

3.1 Element toxicities

a) Hydrogen ion toxicity

At pH levels below 4.0–4.5, the H^+ ions themselves are of sufficient high concentration to be toxic to some plants (Weil and Brady, 2017). Hydrogen ion toxicity is primarily manifested as inhibition of root elongation and root death. The pH at which H^+ toxicity occurs differs between plant species (Islam *et al.,* 1980). The physiological and molecular mechanisms of H^+ toxicity are not yet fully understood, but there are principally three mechanisms: (i) disruption of cell wall integrity, (ii) interference with the maintenance of the cytosolic pH, and (iii) inhibition of the uptake of cations (Marschner, 2012).

b) Aluminum toxicity

In many acid soils in the tropics, Al, which is not an essential plant nutrient, presents the main constraint to plant growth (Rengel, 2003). As pH decreases below 5.5, solubility of Al^{3+} increases to such an extent that they become toxic to many plants. Below pH 5, much of the cation exchange capacity (CEC) may be occupied by Al and when the saturation reaches 60%, Al^{3+} increases to toxic levels in the soil solution. Al saturation is often used to predict Al toxicity, and its reduction is a target for liming soils (Kamprath, 1970). For most plant species, effects of excess Al are on root growth. Roots affected by Al toxicity are swollen, stunted and crooked and there are few fine roots (Figure 3.1). A high level of Al in soils therefore prevents plants from utilizing soil water and nutrients effectively, resulting in poor crop growth and yields.

The seedlings on the left are aluminium tolerant with no symptoms of toxicity, while those on the right are aluminium sensitive and show symptoms of aluminium toxicity

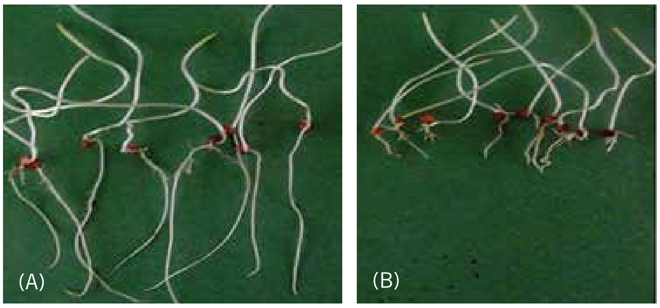

Figure 3.1: Effects of aluminium stress on root growth and morphology of selected sorghum accession. Picture on the left (A) is free from Al stress while the one on the right (B) is suffering from Al stress (Source: Too, 2011).

c) Manganese toxicity

Unlike aluminium, manganese is an essential plant nutrient but its presence in excess can cause toxicity to plants (Kochian *et al.,* 2004). Solubility and availability of soil Mn increase steeply with decreasing pH, especially below 5.5 and this Mn may subsequently be taken up in excessive amounts by plants (Kogelmann and Sharpe, 2006). Manganese levels in the plant usually correlate with toxicity symptoms, with toxicity beginning at levels from 200 mg kg^{-1} in sensitive plants to over 5000 mg kg^{-1} in tolerant plants (Weil and Brady, 2017). Symptoms of Mn toxicity as well as the concentration of Mn that causes toxicity therefore vary widely among plant species and varieties within species (El-Jaoual and Cox, 1998). Necrotic brown spots, usually on older leaves, and chlorotic leaves are reliable indicators of the severity of Mn toxicity in plants (Wissemeier and Horst, 1991). However, many acid soils in the tropics are highly weathered, and their total Mn concentration is often low because of enhanced mobilization and leaching. Thus, in these soils there is less risk of Mn toxicity than of Al toxicity (Marschner, 2012).

d) Iron Toxicity

Iron toxicity is a disorder associated with large concentrations of reduced iron (Fe^{2+}) in the soil solution. Iron can become toxic to plants in the oxidized form at very low pH levels (usually less than 4.0) (Weil and Brady, 2017). Anaerobic conditions combined with acid pH can cause toxicity of iron in the reduced Fe (II) form, which is far more soluble than the oxidized form. Such iron toxicity can be a problem in acid rice paddies Sahrawat (2005). The typical visual symptom associated with iron toxicity is the "bronzing" of the rice leaves. The bronzing symptoms start in fully developed older source leaves, with the occurrence of tiny brown spots that spread from the leaf tip to the base (Becker and Asch, 2005).

3.2 Availability of essential nutrients to plants

Plant nutrient availability is strongly influenced by the soil pH. In strongly acid soils the availability of the macronutrients (Ca, Mg, K, P, N, and S) as well as the two micronutrients, Mo and B, is curtailed (Weil and Brady, 2017). In acid soils, basic cations (Ca, Mg and K) have been leached and therefore their deficiencies are common (Sanchez, 2019). In contrast, availability of the micronutrient cations (Fe, Mn, Zn, Cu, and Co) generally increases as soil pH decreases, even to the extent of toxicity (Weil and Brady, 2017). That said, deficiencies of these minerals, particularly Zn, Cu and Co, can and do occur in acid soil environments.

The effects pH on P and B are primarily indirect, since the availability of these nutrients depends on formation of less soluble compounds with Al, Fe and Ca, which is affected by pH (Bartlett and Picarelli, 1973). As a result, P and B availability decrease at both very low and very high pH, with maximum availability in the range of pH 5.5 to 7.0. (Weil and Brady. 2017). Under low soil pH (< 5.5) available P may be reduced by reactions Fe and Al sesquioxides in acid soils (P fixation), while in alkaline soils, it is precipitated by Ca therefore causing P deficiencies (Havlin *et al.,* 2016). Availability of Mo is low in acidic soils but increases at slightly to moderately alkaline pH (Kaiser, *et al.* 2005).

According to Truog (1946), optimal nutrient availability for most plant nutrients occurs around pH 6.5 (Figure 3.2). It should, however, not be interpreted as an assurance of nutrient availability or lack at any specific pH. Rather, it only indicates the effect of pH, which is one of many factors affecting plant nutrient availability. Other factors that may promote the presence of an abundant supply include soil texture, organic matter, as well as plant nutrient removal (Brady and Weil, 2017). Moreover, certain crops having a low requirement may be fully satisfied with a low supply.

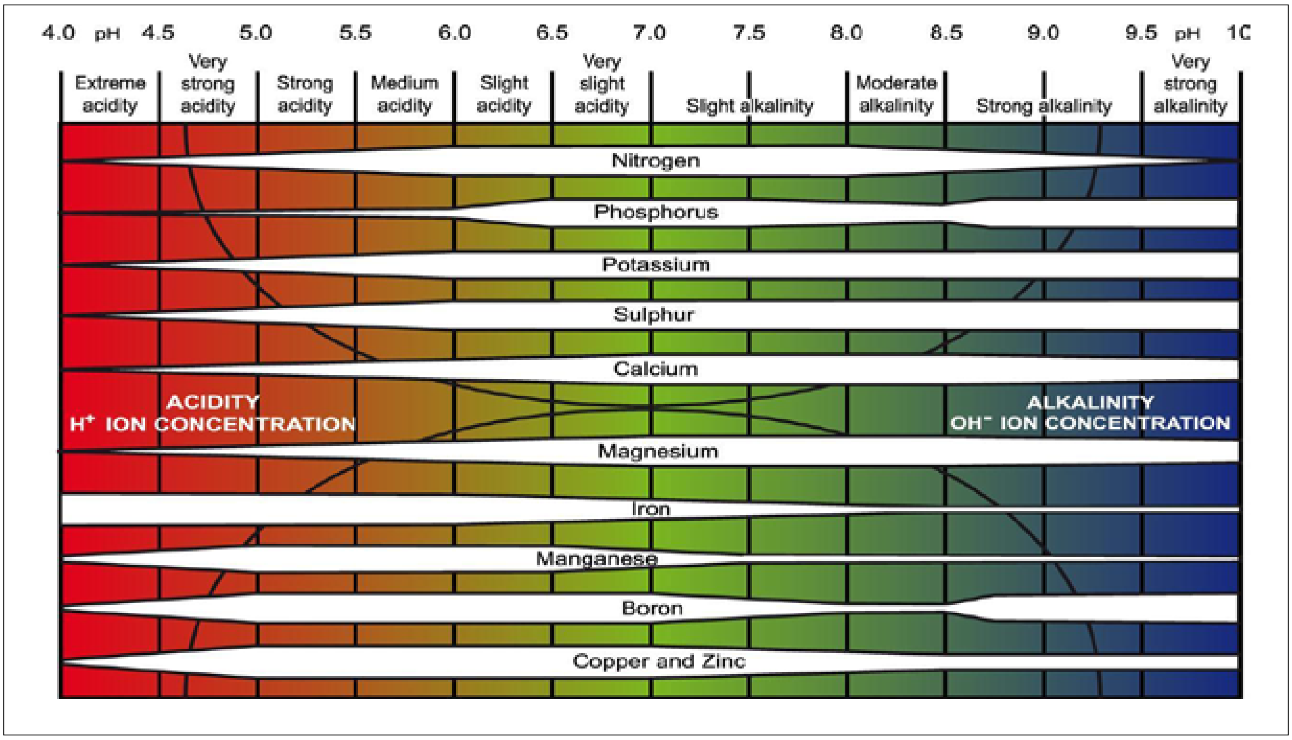

Figure 3.2: Soil reaction (pH) influence on availability of plant nutrients. Soil Science Society of America Proceedings 11, 305-308

The wider the white band, the more favourable are the conditions for the availability of that nutrient. Source: Potash Development Association (PDA). Redrawn for PDA from Truog, (1946).

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4.0 SOIL SAMPLING, TESTING, AND INTERPRETATION

4.1 Introduction

Soil testing is an important first step in soil fertility and acidity management. Effective soil testing offers information on the fertility and acidity condition of soils within a field, which can be used to make recommendations for fertilizer, organic matter, and lime application.

A reliable soil test involves (1) soil sample collection, (2) laboratory analysis, (3) interpretation of results and (4) fertilizer or management recommendations. This chapter will outline basic agronomic soil sampling, common soil acidity determination methods, and simplified interpretation of analysis results.

4.2 Soil Sampling

The first step in soil analysis is soil sample collection. Proper soil sample collection relies on organization, consistency, and simplicity. Adoption of a simple and orderly sample collection, and handling procedure minimizes human errors such as mislabelling or misplacing soil samples. Collection of representative samples ensures quality and reliability of analytical results.

As soils can be highly variable, even over short distances, it is often insufficient to collect soil at just one location. Instead, it is preferable to collect composite samples. A Composite samples is a mixture of individual samples, or sub-samples, generally collected from multiple locations and mixed to form a single sample. By combining multiple sub-samples into a single composite sample, we minimize the effects of soil variability by averaging the soil properties over larger areas. Before sampling a field for lime recommendations, it is important to evaluate the field's soil characteristics, productivity, topography, drainage, texture, and past management. Where these features are uniform throughout the field, a composite sample can be taken to represent the entire field. In cases where a farm field is not uniform, areas with uniform soil characteristics are identified and a representative composite sample for each area is taken.

Depth of sampling is critical because tillage and nutrient mobility in the soil can influence nutrient levels in different soil zones. Sampling depth depends on crop, cultural practices, tillage depth, and nutrients to be analysed. Plant roots, biological activity and nutrients are usually concentrated in the topsoil (0-20 cm); hence, most soil samples are collected within this layer. For tree crops and other deep-rooted crops, samples from the subsoil (20-50 cm) should be collected.

4.2.1 Sample collection procedure

The following materials and tools are required for collecting soil samples:

- A soil auger or probe
- A clean plastic bucket
- A trowel
- Permanent markers
- Sample bags
- Notebook
- Equipment to record Global Positioning System (GPS) readings. If a GPS device is not available, apps for smart phones can perform this function.

Figure 4.1 illustrates the steps in a sampling procedure. Before arriving at the field, determine the number and approximate location of soil samples. Divide your farm according to variability and then sketch and label each field. The distance between locations where you collect sub-samples will vary depending on your sampling method, the larger the area of land you are sampling, the more distance you need between sampling locations. Sampling locations should be well distributed in the uniform area. If employing a zone-based or grid-based soil sampling program, it is often worthwhile to select the location of soil samples before arriving in the field for sampling.

Once the appropriate sampling materials have been assembled, travel to the first sampling location. Record the location with a GPS device or GPS application on your smartphone. This is useful for tracking where samples have been collected, and further allows the analysis data to contribute to a soils database.

At the sampling location, remove any crop residue and organic matter from the soil surface. Insert the soil auger vertically to the desired depth, then remove and transfer the soil core from the auger into a bucket.

Continue this process of sample collection at new locations until you have collected enough samples. Typically, a composite sample should comprise between 10 and 20 sub-samples. The more sub-samples you add into a composite, the more reliable a sample becomes. In small-

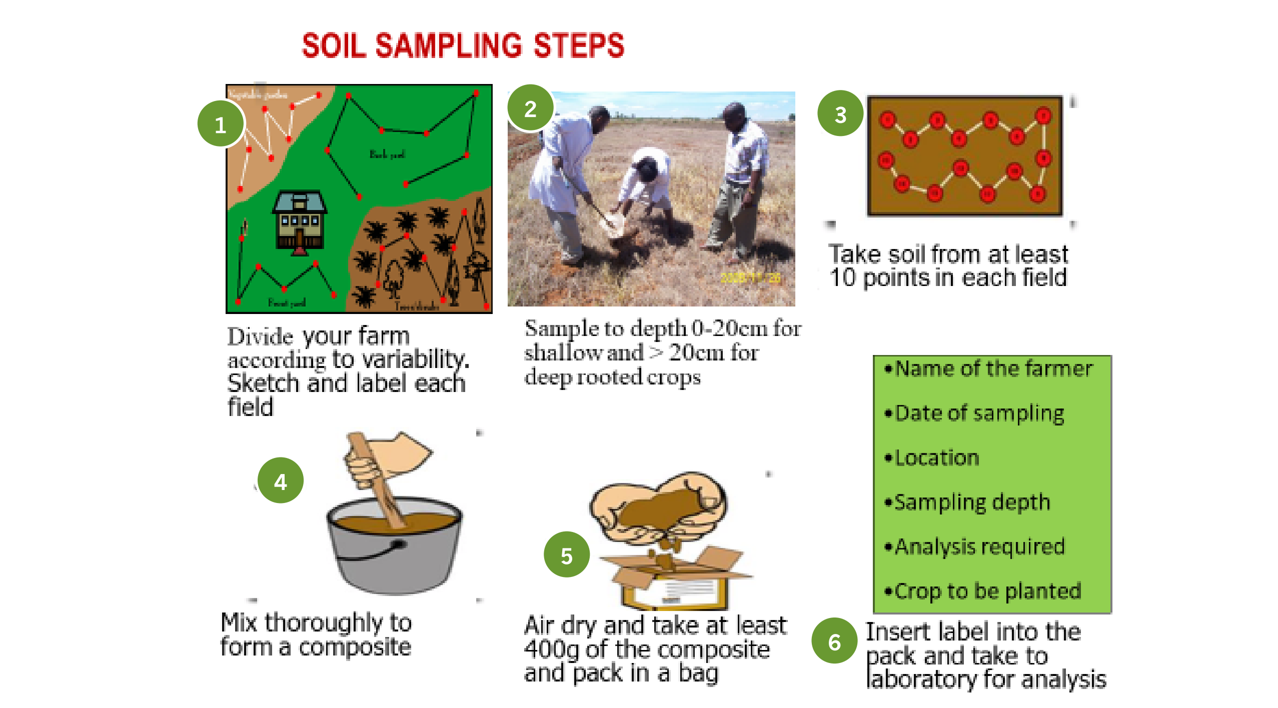

Figure 4.1: Steps for a sampling procedure (Source: Mbakaya, 2015)

holder farms, a minimum of nine core samples for about 0.5-hectare fields have been found adequate to detect differences in nutrient status of soils in Eastern, Central, and Western Kenya. Mix the sub-samples well, breaking any large aggregates so that the sub-samples can be well-homogenized.

For efficient sampling, one soil sample should not represent more than 2 hectares regardless of apparent field uniformity. This is because non-uniformity is usually difficult to assess over broad areas of landscape. Large fields can be divided into two or three smaller sampling sections.

4.2.2 Sample handling

Using a permanent marker, label the bag with a unique name or the same details as the label inserted in the sample bag. Names should contain identifiers to the field and sample number. The labelling information may include site information e.g., location description, past cropping and management history, and proposed crops, along with a list of requested tests. Alternatively, this information can be collected on a separate sheet, with both the sheet and the soil sample having a unique data number or label.

Store samples properly to prevent contamination. If the soil is excessively wet, it should be air-dried by spreading a thin layer on a flat surface. A piece of paper should be spread on top to protect the surface from getting dirty. Samples may be oven-dried, but only at temperatures less than 40°C, because excessive heat can alter laboratory results. Once well dried, the soils can be packed and sent to the laboratory for analysis. Moist samples may be sent directly to the laboratory provided they are sent within a week. If the samples are not sent directly to the laboratory, they should be stored in a refrigerator or freezer if nitrate or ammonium is to be analysed.

4.3 Methods of soil acidity determination

4.3.1 Measurement of soil pH

Several methods are used in laboratories to measure soil pH (Carter, 2016; Davenport *et al.*, 2001; Soil Survey Staff, 2009; Ssali and Nuwamanya, 1981). These procedures are qualitative in nature and involve measuring the soil pH potentiometrically in soil-liquid suspensions using an electronic pH meter. A qualitative method can be used to determine when a pH correction is required but cannot be used to determine the lime requirement per acre or hectare.

Soil pH determination using water is the predominant method of measuring soil pH for active acidity in research and commercial soil testing laboratories. In this method, a suspension of one-part soil by weight to two and a half-part distilled water by volume is measured using a pH meter. However, different solid to liquid ratio of 1:1 or 1:2.5 are used in pH determination for different purposes. The results of pH measured by this method are reported as pH (H_2O) Mehlich A., 1976; Okalebo *et al.*, 2002). Other methods for measuring pH include using a calcium chloride (pH $CaCl_2$) or potassium chloride (pH KCl) solutions (Okalebo *et al.*, 2002). The concentration of the solution should be specified if these methods are employed.

4.4 Soil pH levels for specific crops

Different crops require different levels of soil pH to thrive. Some crops do well in acidic soils while others in alkaline soils (Uchida and Hue, 2000). The acidity range of tolerance is defined as follows.

a. Highly acid tolerant – pH less than 5.3
b. Medium acid tolerant - pH between 5.3 and 6.0
c. Not acid tolerant – pH greater than 6.0

However, these ranges do not apply to crop varieties that have been bred to well-adapt to more acidic soils (see section 5.6).

The soil pH is an important consideration in selection of the crops that will be grown. Table 4.1 presents preferred pH ranges for several crops.

Table 4.1: Preferred soil pH ranges for selected crops

Crop	Optimal pH	Crop	Optimal pH
Maize	5.8-6.2	Wheat	6.3- 6.5
Beans	6.0-7.0	Peanuts	5.0-6.0
Barley	6.3- 6.5	Soybeans	6.6- 7.0
Avocado	6.0-7.0	Peas	5.6-6.6
Beet	5.6-6.6	Peppers	6.0-8.0
Broccoli	6.0-7.0	Potato	5.8-6.5
Cabbage	5.6-6.6	Pumpkins	5.0-7.0
Carrot	5.0-6.0	Spinach	5.0-7.0
Chili pepper	5.0-6.0	Squash	6.0-7.0
Cucumber	5.0-6.0	Strawberries	6.0-7.0
Eggplant	5.0-6.0	Sunflowers	6.0-7.0
Garlic	5.0-6.0	Sweet potatoes	5.0-7.0
Leek	5.0-6.0	Tea	4.0 - 5.6
Lettuce	6.5-7.0	Tomatoes	5.5-7.0
Mushroom	7.0-8.0	Turnip	5.0-7.0
Yam	6.0-8.0	Grasses	5.3- 6.2
Coffee	5.5 -6.5		

Source: McCall (1976) and Maynard and Hochmuth (1997).

4.4.1 Exchangeable soil acidity determination

Exchangeable acidity refers to the measure of the hydrogen (H^+) and aluminium (Al^{3+}) ions retained or fixed on soil colloids (McCarty *et al.,* 2003). Determination of exchangeable acidity is useful in agronomy to establish aluminium phytotoxicity which is closely correlated with the rate of exchangeable aluminium. In acid soils (pH-water < 5.5), Al^{3+} and H^+ ions are usually absorbed on clay or humus surfaces in exchangeable forms. Extraction with 1M KCl is the most common method for exchangeable acidity determination. In the method, a soil sample of known quantity (e.g., 10 g) is leached with 1 M KCl and K^+ ions replace exchangeable cations, including the acid cations Al^{3+} and H^+ which lower the pH of the leachate. This leachate is then titrated with a base, NaOH, of a known concentration to neutrality, commonly using phenolphthalein as a pH colour indicator (Okalebo *et al.,* 2002). Exchangeable acidity in tropical soils can be used to calculate aluminium saturation, which is an indicator of an acid soil's potential to induce aluminium toxicity. Table 4.2 shows the critical aluminium saturation levels for different crops.

Table 4.2: Critical aluminium saturation levels and ranges for selected tropical crops

Common Name	Critical Al Saturation %
Mung beans	0
Soybeans	0 – 25
Sorghum	15
Maize	30
Sweet potato	30
Bambara nuts	40
Peanut	40
Upland rice	40 – 60
Cowpea	60
Cassava	75

Adopted from Anonymous, 1986.

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5.0 MANAGEMENT OF SOIL ACIDITY IN KENYA

Several strategies have been documented for managing acidic soils in Kenya and other sub-Saharan countries. They include i) addition of liming materials;; ii) use of organic materials; iii) judicious choice and application of fertilizers; iv) use of rock phosphates v) combining lime with organic materials and inorganic fertilizers; vi) growing acid tolerant crop species. These strategies are discussed herein.

5.1 Use of lime

Lime is the most effective means of correcting soil acidity (Kanyanjua *et al.,* 2002; Kisinyo *et al.*, 2014; Muindi *et al.*, 2015; The *et al.*, 2006). Limestones are mined from natural deposits and include calcitic limestone (calcium carbonate; $CaCO_3$) and dolomitic limestone (calcium magnesium carbonate; $CaMg(CO_3)_2$), which are carbonates containing various ratios of calcium and magnesium. Calcium oxide (burnt or quicklime; CaO) and calcium hydroxide (hydrated lime; $Ca(OH)_2$) are fast-reacting, white powdered liming materials made from limestone that are more costly. They are caustic when wet, and difficult to mix uniformly with soil, and thus used less frequently than limestone. Basic slag (calcium silicate; $CaSiO_3$) is a by-product of the steel industry, and often contains some amounts of magnesium and phosphorus (Smyth, 2011). Selection of liming material and when to apply them depends on their neutralizing value, fineness of the liming materials, and the effective calcium carbonate rating. Detailed information on the practice of liming is covered in Chapter six.

5.2 Use of organic materials

Organic materials ameliorate soil acidity through their effect in reducing aluminium toxicity in soils (Haynes and Mokolobate, 2001). Organic compounds react with aluminium to form sparingly soluble organo-aluminium compounds, thereby reducing aluminium toxicity. Reduction in aluminium levels can reduce phosphorus adsorption by soils and enhance phosphorus release, and also reduce aluminium toxicity. Both direct and indirect effects of organic materials on increasing soil available phosphorus have been documented. The direct effect has been observed where organic materials with high phosphorus levels such as Tithonia (*Tithonia diversifolia*) as well as pigeon pea have been used (Lungu, 1993). Another direct effect is the release of basic cations (calcium, magnesium and potassium) into the soil solution, during organic matter decomposition which increases soil pH (Ikerra *et al.*, 2006; Opala *et al.*, 2011). The indirect effects are through formation of organo-aluminium compounds which are less soluble, which leads to release of fixed phosphorus by aluminium. Increase in soil pH in tropical soils is, however, normally short term due to inadequate amounts of organic materials available for use by farmers to build soil organic matter capital.

5.3. Judicious choice and application of fertilizers

To alleviate soil acidity, some judicious methods have been proposed:

I. Selection of fertilizers that contribute little or no acidity to soils. Nitrate sources of N are non-acidifying but more expensive per unit N. Ammonium sources of nitrogen are by contrast acidifying. Triple superphosphate is less acidifying than mono ammonium or diammonium phosphate. Farmyard manure is less acidifying than leguminous sources of organic matter.

II. Wise application of organic and inorganic fertilizers to keep nitrates within the crop rooting zone. Plant uptake of nitrate anions reduces root exchange of hydrogen ions for basic cations. Avoid applying too much fertilizer at once, instead use split applications. Alternatively, use slow-release fertilizers.

5.4 Use of phosphate rock

Although phosphate rock (PR) is a phosphorus management strategy, its use on acid soils can mitigate harmful effects of acidity. Phosphate rocks are used for sustainable agriculture management (Kisinyo and Opala, 2020); as a source of phosphorus and lime materials. A few PR deposits exist in East Africa, such as Minjingu PR from northern Tanzania and Busumbu PR from eastern Uganda, with potential for use in the region. Busumbu is however, an igneous PR that is mainly iron phosphate and is not useful for direct application to the soil.

Calcium is a major component of PR in the form of apatite $[Ca_3(PO_4)_2]$. Apatite has potential to provide calcium nutrient under favourable conditions upon its dissolution.

Furthermore, many sources of PR contain free carbonates, such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), that can also provide calcium and magnesium in acidic soils to neutralize acidity. The dissolution of apatite in PR reduces the concentrations of hydrogen ions thus increasing soil pH, depending on PR reactivity (Narayanasamy and Biswa, 1998; Woomer *et al.*, 1997). If a PR contains a significant amount of free carbonates, it can further increase the soil pH. Although the increase in soil pH may reduce the aluminium saturation level, it can also reduce apatite dissolution at the same time. The optimum condition would call for a soil pH that is high enough to reduce the aluminium saturation level, but still low enough for apatite dissolution to release phosphorus (van Straaten, 2002; Chien, 1977; Kisinyo *et al.,* 2014). Most PRs are slow reacting, therefore increase in soil pH is gradual and depends on the amounts of free carbonates it contains. Changes in soil pH due to PR application is normally not significant compared to lime application, but the decrease in exchangeable aluminium can be significant where soil pH is less than 5.5 (Okalebo *et al.*, 2006; The *et al.*, 2006).

5. 5. Combined use of lime and organic materials

The combined use of lime with available organic materials such as farmyard manure has proven beneficial in acidic and infertile soils (Islam *et al.*, 2021). This approach is attractive to resource-poor farmers who cannot afford expensive inorganic fertilizers because it ameliorates soil acidity while simultaneously improving soil fertility (Gitari, 2013). Combined application of lime and organic materials increases soil pH, microbial activity, plant growth and grain yield compared to either of them singly applied.

5.6 Use of crops and varieties tolerant to acidic soils

Choosing a crop species that tolerates acidic soil conditions is another way of managing soil acidity. Agricultural crop species do not respond uniformly to acidic soil conditions and vary significantly on their genetic potential to tolerate soil acidity (Figure 5.1). Certain crops such as tomatoes are highly sensitive to acidic soil conditions, while others like cowpeas and sugarcane are highly tolerant (Kochian *et al.*, 2015).

Genetic variation for tolerance to soil acidity/aluminium toxicity has been reported among cultivars of sorghum, maize, groundnuts, soybean and beans in Kenya and in many other crops across the world (Ouma *et al.,* 2013). Most plant species use one of two mechanisms to tolerate aluminium toxicity. The first mechanism is to exclude toxic aluminium ions from entering the root tip cells through production of chemical exudates such as phenolic compounds, phosphatases, or organic acids which bind aluminium ions and render them non-toxic. The second mechanism allows entry of toxic aluminium ions into the cytosols of root tip cells but produces binding proteins which render them non-toxic, after which they are sequestered into cell vacuoles (Kochian *et al.,* 2015). Variation in root growth in a toxic aluminium environment occurs rapidly; hence, simple screening methods to identify and aluminium tolerant or sensitive plants have been developed. Once identified through conventional or marker-assisted selection, the tolerant genes can be transferred and/or pyramided to produce aluminium-tolerant cultivars through conventional breeding techniques and/or biotechnological methods (Kochian *et al.,* 2004). Acid-tolerant cultivars provide cheap and sustainable management of soil acidity and can improve yields.

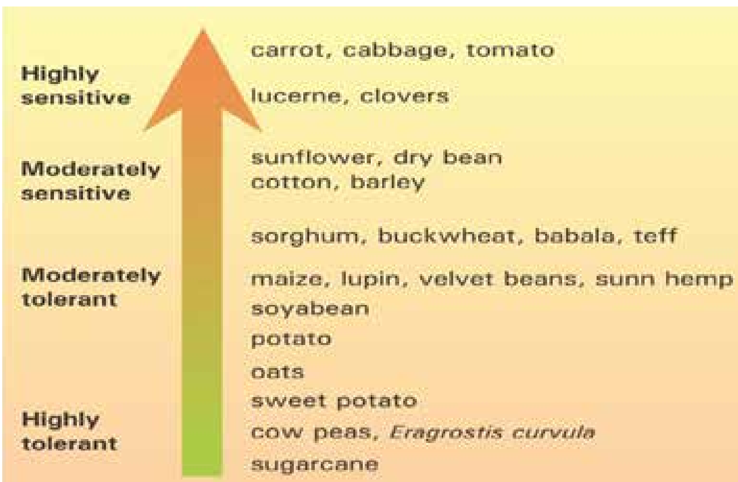

Figure 5.1: Relative tolerances of crop and vegetable species to soil acidity. Source: Neil and Mart (2013)

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6.0 LIMING ACIDIC AGRICULTURAL SOILS

Liming acidic soils for agricultural use is essential for good crop productivity. The significance of liming, commonly used liming materials in Kenya, and their soil reactions are discussed in this chapter.

6.1 Importance of liming acidic soils

Acidic soils pose several challenges to crop growth, as indicated in Chapter 3. Liming agricultural acidic soils is one of the most common and effective amelioration strategies for improving crop production in such soils. Liming, as the term is used in agriculture, is addition of any calcium and magnesium containing compound that can reduce acidity to the soil. The term 'agricultural lime' is usually applied to any form of liming materials that contain calcium or magnesium oxides, hydroxides or carbonates that can be used in neutralizing soil acidity.

Liming enhances the physical, chemical, and biological characteristics of soil through its direct effect on the amelioration of soil acidity and through its indirect effects on the mobilization of plant nutrients, immobilization of toxic heavy metals, and the improvement of soil structure. The benefits of liming are documented by several authors (Esilaba *et al.*, 2023; Hijbeek *et al.*, 2021; Kisinyo *et al.* 2014; Mbakaya, 2015) are summarized as follows:

1. Liming reduces aluminium toxicity which is a main constraint to crop production in acidic soils. Elevation in pH due to addition of lime results in the precipitation of exchangeable aluminium. Liming has also been reported to eliminate manganese toxicities.
2. Liming can alleviate calcium as well as magnesium deficiencies in soils if dolomitic limestone is applied. Calcium and magnesium are essential nutrients for plant growth, yet they are often deficient in highly weathered acidic soils.
3. The pH dependent cation exchange capacity increases with liming of acidic soils. The ability of the soil to hold more plant nutrients is improved and leaching of basic cations reduced.
4. Soil acidity restricts the activities of beneficial microorganisms, except fungi, which grow well over a wide range of soil pH values. Liming enhances the activities of beneficial microbes by providing optimum conditions for several biological activities including nitrogen fixation and mineralization of nitrogen, phosphorus and sulphur in soils. The enhanced mineralization of these nutrient ions is likely to cause an increase in their concentration in soil solution for plant uptake. Nitrogen fixing bacteria in leguminous plants require calcium, hence liming is likely to enhance nitrogen fixation in legumes through increased activity of nitrogen-fixing bacteria, especially *Rhizobium spp*.
5. Liming increases solubility of certain plant nutrients such as phosphorus improving their availability to plants. At low pH and on soils with high aluminium and iron compounds, phosphates are rendered less available through the process of fixation. Liming precipitates aluminium and iron compounds increasing phosphorus availability.
6. Liming influences micronutrient availability. Except for molybdenum, the availability of micronutrients increases with decrease in pH. This can be toxic to plants e.g., solubility of aluminium, iron and manganese increase with increasing acidity. Liming precipitates them and soil pH of 5.6 to 6 is usually most satisfactory from the standpoint of minimum toxicity and adequate availability of these elements. Molybdenum availability is improved by liming and deficiencies are rare at pH above 5.5.

6.2 Liming Materials

A range of liming materials, which vary in their quality and ability to neutralize soil acidity, are available and have been used. Frequently used liming materials are oxides, hydroxides and silicates of calcium, or calcium and magnesium, and include ground limestone, dolomitic ground limestone, chalk, ground chalk, burnt lime and hydrated lime. Some of the liming materials and their characteristics are presented in Table 6.1 Ground limestone is predominantly used in Kenya; dolomite is also available, with limited usage due to its higher cost.

Table 6.1: Commonly used liming materials.

SL No.	Material	Chemical formula	Neutralizing Value (CCE)*	Characteristics
i)	Quicklime	CaO	179.0	Fast reacting and difficult to handle
ii)	Hydrated lime	$Ca(OH)_2$	136.0	Fast reacting and difficult to handle
iii)	Dolomitic lime	$CaMg(CO_3)_2$ (Total Magnesium:17 % MgO)	109	Mostly insoluble in water. Contains 7.8 -12% Mg and 18 to 21% Ca.
iv)	Limestone	$CaCO_3$	100.0	Mostly insoluble in water. Contains 28.4 -32% Ca
v)	Slag	$CaSiO_3$	86.0	By-product of pig iron industry, also contains 1-7% P
vi	Shells	$CaCO_3$		
vii	Marl	$CaCO_3$	70-90	Soft unconsolidated deposits of CaCO3. Frequently mixed with earth and quite moist.

Source: GoK (2014).
**CCE, Calcium carbonate equivalent.*

6.3 Reactions of lime in soil

Several events occur when lime is added to acidic soil, with most of them occurring simultaneously. Regardless of the form in which calcium is added to the soil, in the presence of atmospheric carbon dioxide, it will be converted to calcium carbonate ($CaCO_3$) as outlined in Equations 6.1 and 6.2 (Rengel, 2003).

$CaO + CO_2 \rightarrow CaCO_3$	Equation 6.1

or

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$	Equation 6.2

In acidic soil, the calcium carbonate then reacts in the presence of water to produce Ca^{2+} and hydroxide (OH^-): as shown in equation 6.3.

$CaCO_3 + H_2O$ (in soil) $\rightarrow Ca^{2+} + 2OH^- + CO_2$ (gas)	Equation 6.3

Newly produced Ca^{2+} will exchange with Al^{3+} and H^+ on the surface of acid soils as shown in equation 6.4.

Ca^{2+} + Soil particle + $Al^{3+} + H^+ \rightarrow$ Soil particle + $Ca^{2+} + Al^{3+} + H^+$	Equation 6.4

The OH^- produced by lime will react with Al^{3+} to form solid $Al(OH)_3$, or it will react with H^+ to form H_2O as shown in equations 6.5 and 6.6.

$3OH^- + Al^{3+} \rightarrow Al(OH)_3$ (solid)	Equation 6.5

$OH^- + H^+ \rightarrow H_2O$	Equation 6.6

Thus, liming eliminates toxic Al^{3+} and H^+ through reactions with OH^- to neutralize them (Kanyanjua *et al.*, 2002; Kisinyo *et al.*, 2014.

6.4 Determination of soil lime requirement

Lime requirement is defined as the amount of liming material that should be applied to a particular soil to achieve a target pH that is favourable for crop production. Many methods for determination of lime requirement are used in different countries. A summary of some of these methods is outlined below:

6.4.1 Buffer pH method

Buffer pH methods are based on the use of a buffer solution, whose pH changes when treated with acid. The Shoemaker, McLean, and Pratt (SMP) (Shoemaker *et al.*,1961) method that was validated in Kenya by Ssali and Nuwamanya (1981) and Nuwamanya (1984), is the most preferred and practical buffer pH method used in many laboratories for lime requirement determination. In this method, a buffer is added to the soil, and after a short period of agitation, the pH of the buffered solution is measured. The buffer pH is then translated into a lime recommendation for a chosen target pH using a table or equations (Shoemaker *et al.*, 1961). The method was developed for any target pH between 6.0 and 6.8.

6.4.2 Desired aluminium saturation method

In conditions where aluminium toxicity exists, lime requirements can also be calculated using empirical equations proposed in literature. A commonly used example is the Cochrane *et al.* (1980) equation used for liming acid mineral soils to determine the amount of $CaCO_3$ or its equivalent that must be applied to a soil to neutralize the exchangeable acidity. Taking the concentration of exchangeable calcium and magnesium in the soil into account (Equation 6.7):

LR ($CaCO_3$ equiv. t ha^{-1}) = 1.5 [Al - RAS (Al + Ca + Mg)/100]	Equation 6.7

Where:

LR = lime requirement expressed in tons $CaCO_3$ per hectare

RAS = required (or desired) aluminium saturation (%)

Al = extractable Al (exchangeable + soluble Al) cmol/kg soil

Al + Ca + Mg is an approximation for the effective CEC (ECEC), expressed in cmol ($^+$) per kg of soil.

Where Al = cmol kg^{-1} soil, Ca = cmol kg^{-1} soil, Mg = cmol kg^{-1} soil, RAS = required % Al saturation of the ECEC. ECEC = ∑ (Al, Ca, Mg, K, Na) in cmol C kg^{-1}.

To use equation 6.7 properly, a soil test for exchangeable aluminium, calcium, magnesium, potassium, and hydrogen in a 1M KCl extract is essential.

6.4.3 Lime requirement as a function of texture and organic matter

Lime requirement rate is affected by soil acidity and several other properties, including soil texture and the amount of organic matter, among others (Sims, 1996). In this case, lime requirement is determined based on aluminium, calcium, and magnesium contents of the soil using equation 6.8:

LR (Mg ha^{-1}) = (2 × Al) + [2– (Ca + Mg)],	Equation 6.8

Where Al, Ca, and Mg are in cmol c kg^{-1} soil extracted in 1M KCl.

Where soil texture for example is also considered for lime requirement, equation 6.8 is written as Equation 6.9:

LR (Mg ha^{-1}) = (Y × Al) + [X–(Ca + Mg)],	Equation 6.9

Where: **Y** is the soil texture and value **1** is used for sandy textured soils (clay content <15%), value **2** for medium textured soils (clay content 15–35%), and value **3** for heavy textured soils (clay content >35%). X is determined based on the crop. For example, 2.0 is for most crops, 1.0 for eucalyptus, and 3.0 for coffee.

6.4.4 Incubation method

Long-term incubations of a wet soil with various levels of lime and derivation of a calibration curve of pH against lime are used for research studies to determine lime requirements and to calibrate other lime requirement methods. But these are impractical for use by routine testing laboratories because they take too long (several months) to obtain results (Hirpo *et al.* 2020).

6.4.5 Crop response

The most accurate method for determining lime rate is actual testing of crop responses to applied lime rates (Sims, 1996). Crop response curves to lime levels should be determined for each crop species under different agro-ecological regions to make liming recommendations effective and economical. The method is, however, costly and takes a long time.

Regardless of the method used to determine lime requirement in tropical soils, it is advisable to avoid excessive lime application. Usually this happens when such soils are limed to neutrality. Tropical soils should only be limed to neutralize exchangeable aluminium, which generally brings soil pH to values in the 5.5 to 6.0 range. Over-liming leads to soil structure deterioration, reduced phosphorus (P), boron (B), zinc (Zn) and manganese (Mn) availability, and lower yields.

6.5 Factors affecting lime requirements

The quantity of lime required to produce maximum economic yields of crops grown in acidic soils is determined by several factors. These include:

6.5.1 Soil pH

Soil pH is the most common acidity index used in soil testing programs to assess whether liming is required. Soil pH alone cannot be used to determine how much lime to apply (the lime requirement). The higher the desired or target soil pH for a particular soil, the higher the lime requirement and vice versa.

6.5.2 uffer capacity of the soil

Buffer capacity of the soil is influenced by type and amount of clay, and organic matter content. The more highly buffered the soil is, the higher the liming requirement. Thus, soils with more clay and organic matter require more lime.

6.5.3 Quality of liming material

The quality of liming materials is determined by two factors. One factor is the ability to neutralize acid (purity), called the calcium carbonate equivalent (CCE) or neutralizing value which is defined as the acid-neutralizing capacity of the material by weight in relation to $CaCO_3$. As CCE increases, the material purity increases and the acid neutralizing ability increases. If the neutralizing value is lower than $CaCO_3$, a higher quantity of liming material is required and vice versa, i.e., the lower the CCE value, the more lime you will need to neutralize the soil's acidity. Table 6.1 discussed under introduction above shows various liming materials and their CCE values (neutralizing values).

The second factor is the degree of fineness of lime. Finer limestone particles react faster due to increased surface area. Fineness is measured by the proportion of processed agricultural lime which passes through a sieve with an opening of a particular size. A 60-mesh sieve, which is the standard for comparisons of lime fineness and efficiency rating of 100%, is assigned. The fineness range for most liming materials is 60% to 100%.

The Effective Calcium Carbonate Equivalent (ECCE) or Relative Neutralizing Value combines the two indexes (CCE and fineness) into one single value for the purpose of adjusting lime requirements under field conditions. ECCE is calculated as in equation 6.10 (Iowa Department of Agriculture and Land Stewardship. 2008):

$$\text{ECCE (\%)} = (\text{CCE (\%)} \times \text{fineness})/100. \quad \text{Equation 6.10}$$

The lower the ECCE, the higher the rate of lime application should be to obtain the same effect in terms of soil acidity control.

6.5.4 Crop species and genotypes within species

Because crops differ in their sensitivity to soil acidity (Tables 4.1 and 4.2, Chapter 4), recommendations for liming differ with the crop. Crops that are generally acid-tolerant such as cassava, cow pea, groundnut, pigeon pea, potato (*Solanum tuberosum*), rice, and rye will require less lime compared to sensitive crops such as some cultivars of sorghum, soybeans, cotton, alfalfa, and wheat.

6.5.5 Economic considerations

Experimental results on lime application suggest that liming is generally profitable particularly when used in moderate amounts including micro-dosing, in conjunction with other improved agricultural practices (use of inorganic and organic fertilizers, high yielding seed or crop varieties, and associated better agronomic practices) (Hijbeek *et al.,* 2021; Opala, 2017; Kisinyo, 2016; Mbakaya, 2015; Muindi *et al.,* 2015). However, it should be noted that, lime application may last several years, therefore, it may not be profitable in the short term but beneficial in the long-term.

6.6 Liming in Kenya

6.6.1 Liming recommendations in Kenya

Unlike with fertilizers, where recommendations have been made for specific crops countrywide (e.g., FURP, 1987), many factors determine lime requirements (Section 6.5) and therefore blanket recommendations are not advised. Soil analysis should always be carried out to facilitate application of optimum quantities of lime. Several studies on lime use in Kenya have been conducted and give an idea of what the lime recommendations for certain regions are likely to be for the studied crops. The range of crops studied is, however, limited. Most focus has been on maize, which is the staple food. Studies have concentrated mainly in parts of central, western and the rift valley, where most of the acidic soils are found. Table 6.2 summarizes some of the studies on lime in Kenya.

From Table 6.2 broadcasting and incorporation of lime into the soil at 2-4 t ha^{-1} will give optimum pH correction for most crops. Nutrient limitations still need to be corrected with fertilizers. When micro-dosing lime is used, lower rates of lime are applied.

Table 6.2: Summary of the studies on lime rates for different crops in Kenya.

Crop	Region/site	Lime rate used	Source
Maize	Uasin Gishu	2 t ha^{-1}	Chebet *et al.* (2018)
Maize	Maseno, Kisumu	2 t ha^{-1}	Opala (2017)
Maize	Mumias	2 t ha^{-1}	Opala *et al.* (2018)
Maize	Githunguri, Kiambu	4.5 t ha^{-1} (strongly acid soil pH < 5.5)	Muindi *et al.* (2015)
Wheat	Uasin Gishu	2 t ha^{-}	Osundwa *et al.* (2013)
French beans	Uasin Gishu	2 t ha^{-1}	Barasa *et al.* (2013)
Maize bean intercrops	Mabanga, Bungoma	2 t ha^{-1}	Okalebo *et al.* (2009)
Sugarcane	Mumias , Kakamega	3 t ha^{-1}	Mutonyi *et al.* (2014)
Sugarcane	Kibos, Kisumu	2 t ha^{-1}	Omolo *et al.* (2016)
Tea	Kericho	2 t ha^{-1} (applied during replanting in old tea fields)	Wanyoko (1999)

6.7 Improving efficiency of lime

The 4 Rs stewardship principle (i.e., right source, right rate, right method, and right timing of application) used in improving fertilizer use efficiency can also be applied to liming. The frequency (right time) and depth (right placement) of lime are important practices in improving its effectiveness. These factors are briefly discussed below.

6.7.1 Methods of lime application

Lime placement is important in determining reactivity and movement into the sub-soil. The options include surface application, topsoil incorporation, and subsoil amelioration. Uniform broadcasting of lime and thorough incorporation into the soil as deeply as possible by a plough or disc harrow for arable crops is mostly recommended. Lime is not very soluble and when left on the soil surface may, depending on a soil's buffer capacity and amount of pH-dependent charge, react only with the surface layer (1-2 cm) of soil and will not release calcium to move down the profile. Presently available machinery can mix lime to a depth of 20–30 cm. A depth greater than 30 cm requires more power and would prove costly to apply.

For permanent grasslands where the soil is not disturbed, there are a few options other than surface application. In orchards with adult trees, the application of limestone at the surface, without incorporation, will gradually neutralize the acidity below the surface due to the movement of the particles through the profile, if moisture and drainage conditions are suitable. Therefore, surface liming, even though possible, requires time to produce beneficial effects. Use of ultra-fine lime products which are mobile in the soil is another alternative.

6.7.2 Timing of lime application

Lime should be applied well in advance of the expected planting period, to allow it to react with soil colloids and bring about significant changes in soil chemical properties. With sufficient moisture, significant chemical changes can take place 4–6 weeks after applying liming materials. In a no-till system, lime should be applied on the surface several months before sowing crops or pastures to allow time for the lime to react in the soil. Crops with more sensitivity to low pH, such as forage legumes, should have pH corrected well in advance of seeding. Soil moisture is critical for the reaction of limestone with soil acidity; thus, rainfall patterns can also be used as a guide for application timing.

Wind affects lime distribution due to its finely ground nature. Lime will drift over considerable distances even in moderate winds. Spreading in calm conditions is advisable.

6.7.3 Liming frequency

Liming frequency is determined by intensity of cropping, the crop species planted, and levels of calcium, magnesium, aluminium, and pH in a soil after each harvest. The effect of lime is long lasting but not permanent. After several crops, calcium and magnesium move downward and beyond the reach of roots. These elements are taken up by crops and may be lost through soil erosion. Acid-forming fertilizers and decomposing organic matter lower the soil pH and release more aluminium to the soil solution and cation exchange sites on soil particles. When pH values fall below optimum levels for a given crop species, liming should be repeated. Soil samples should be taken periodically to determine changes in soil chemical properties and to decide liming frequency. The residual effect of coarse lime material is greater than with fine lime material because large lime particles react slowly with soil acidity and tend to remain in the soil longer. Liming may generally be done between three to five years depending on:

i) *Cropping intensity and nitrogen fertilization*, especially with ammonium containing fertilizers. Intensive cropping and nitrogen fertilization necessitates more frequent liming.

ii) *Amount of lime previously applied* (residual effects of previous lime). For example, Kisinyo *et. al*. (2014) found that an application of lime at 4 t ha^{-1} required another application after five cropping seasons, while an application of lime at 2 t ha^{-1} required another application after three cropping seasons.

iii) *Buffer capacity of the soil* is influenced by type and amount of clay, and organic matter content. The more highly buffered the soil is, the less frequent is the liming application because massive doses of lime have a residual effect.

iv) *Fineness and solubility of the liming material*. The finer the material, the more soluble it is, and the more frequently liming is required. Coarse materials have a slow-release nature reducing their frequency of application unless lime is eroded.

6. 8 Improving usability, environmental and economic attributes of lime

Lime presents an array of benefits (Section 6.1) and is essentially environmentally friendly when used correctly, i.e., using the 4R stewardship principles. Nonetheless, its application is labour intensive because large amounts are usually required. This increases the cost of production and application.

Lime in Kenya is predominantly available in powder form, which is dusty, and makes it unpleasant and difficult to apply as it is blown away by wind. The airborne lime dust can also drift to other areas where it may not be required and could be a nuisance to neighbours. If excessively inhaled over a prolonged period, the dust can constitute a long-term health hazard. These challenges can be addressed by using granulated lime and micro dosing.

6.8.1 Granulated or pelletized lime

Some companies in Kenya promote the use of granulated lime. Granulation is the conversion of finely ground lime into granules similar in size to fertilizer granules. This process helps overcome many difficulties in handling and spreading powdered lime, making it easy for mechanized application. The effectiveness of the granulated lime is similar to that of ground limestone (Opala *et al.,* 2018; Kirui, 2018). The cost of pelletizing the lime makes it considerably more expensive than ground limestone, so some see it as a maintenance material applied in smaller amounts than bulk lime. With this approach, when the soil pH is considerably below the optimum, ground limestone would be applied, followed by an annual application of pelletized lime to acquire the desired soil pH.

Some granulated lime products are ground to ultra-fine particle sizes (<75 microns) prior to granulation. Such products are expensive but very fast-reacting and so fine as to be mobile in the soil, capable of moving with rainwater, and can even be dissolved and used in drip irrigation without clogging drip emitters. Ultra-fine granulated products, because of their fast action, can be applied at low doses and have an immediate effect on crops. However, they need to be re-applied more often.

6.8.2 Micro-dosing

There is potential to reduce lime requirements and increase yield through micro-dosing lime, a- technique which involves the precise point application of small, affordable quantities (<1 t ha^{-1}). It has been tested in western Kenya with good results. For example, using the micro-dosing technique, Kisinyo *et. al.* (2015) used 0.77 t ha^{-1} of lime on maize and obtained yields comparable to those of 1.5 t ha^{-1} spread on the surface of lime in western Kenya. This shows that when using the micro-dosing technique, the quantity required to attain a similar yield is halved compared to the broadcast method. However, maintenance applications may be more frequent.

6.9 Adoption of lime application in Kenya

Although the agronomic benefits of liming are well known, the practice is rare in Kenya. Adoption of liming by farmers is low at between 1% and 8% depending on the region (KMT, 2021; KMT, 2019; Muindi *et al.*, 2016; www.oneacrefund.org). Various factors hinder the use of lime in Kenya. These include:

1. Limited knowledge and awareness of the benefits of lime.
2. Inconsistency in farmers' knowledge. There needs to be more harmony in the messages given to farmers by different stakeholders about lime.
3. Inappropriate lime application rates. Due to limited knowledge of liming, some farmers mix lime and fertilizer during planting, leading to poor crop responses.
4. Large quantities of lime are required for application per unit area, with farmers needing more lime purchasing capacity.
5. Availability and access: Few agro-dealers stock lime as it is a bulky commodity. Existing lime markets are limited or non-existent in many areas with soil acidity problems.
6. High costs are associated with transporting bulk amounts of lime required per unit area.
7. Limited availability of granulated lime in the Kenyan market. The powder form is difficult to apply by hand, especially for smallholder farmers, which is easily blown away by wind and can cause irritation to the skin, eyes, and lungs.
8. Lack of accessible and affordable soil testing services. Consequently, inappropriate lime rates are applied. This leads to poor crop responses that discourage farmers from using lime.

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7.0 CROP RESPONSES TO LIMING ACID SOILS IN KENYA

7.1 Introduction

Several studies have shown that on infertile soils, which dominate most of the smallholder farms in Kenya, crops did not respond to application of lime alone (Opala *et al.* 2018; Opala, 2017; Kisinyo *et al.* 2014). Lime must be applied with other nutrients, particularly macronutrient NP and NPK fertilizer which are usually the most limiting on most smallholder farms. Table 7.1 summarises selected crop responses in various sites in Kenya.

Sites that were responsive were low in soil pH and high in exchangeable acidity or aluminium saturation. Non-responsive sites had generally high pH (> 5.5), or other limitations such as low rainfall. The range of responses was from 0-525% and this varied amongst crops, within varieties and between soils. Figure 7.1 shows maize response to lime and other nutrients.

In conclusion, empirical liming studies conducted over the past two decades have provided some lime requirement and crop response information for Kenya. However, details for other crops and soils still need to be studied. Further research on liming impacts on other aspects of crop response such as quality and interaction with other inputs, is also needed.

Table 7.1: Summary of selected crop responses to liming at various sites in Kenya.

Crop Responses	Author(s)
Lime (CaO) at 1.5t ha^{-1} increased wheat (Njoro BW2) grain yield by 51% at Chepkoilel (Soil pH: 4.92), Uasin Gishu County, but at Kipsangui (Soil pH: 5.32), in the same County the best response (131%) was obtained with a lime rate of 2 t ha^{-1}. For KS Mwamba variety, the yield increased by 89% in Chepkoilel and by 138% in Kipsangui with lime application at 2 t ha^{-1}.	Osundwa *et al.* (2013)
At Sega in Siaya County, application of 2 t ha^{-1} and 4 t $ha^{-1}$of lime gave an average maize yield increase of 2.5% and 11.2% respectively (mean of 7 seasons). The site had pH 4.9, Al saturation 29% .	Kisinyo *et al.* (2014)
At Butere and Mumias in Kakamega County, application of 2 t ha^{-1} of lime (CaO) gave maize yield increases of 30.2% and 27.0% respectively, while at Kakamega North in the same County there was no response to liming. However, when granulated lime ($CaCO_3$) was used, the response more than doubled in Butere (74.4%) but there was no response in Kakamega North and Mumias. Butere had pH 5.21, exchangeable acidity 0.4 cmol/kg. Kakamega North had pH 5.48, exchangeable acidity 0.3 cmol/kg. Mumias had pH 5.01, exchangeable acidity 0.3 cmol/kg.	Opala *et al.* (2018)
At Soy in Uasin Gishu County application of 2 t ha^{-1} of lime (CaCO3) gave maize yield increase of 525% and 22.7% in 2017 and 2018 respectively. At the same site, wheat yield increased by 22.7% and 20.0% in the same years. Soy (maize site) had a soil pH of 4.0, exchangeable acidity of 1.8 cmol/kg. Soy (wheat site) had a soil pH of 5.5 and exchangeable acidity of 0.5 cmol/kg	Gikonyo *et al.* (2020)
At Kuinet (soil pH: 5.0) in Uasin Gishu County an application of 2 t ha^{-1} of lime ($CaCO_3$) increased French beans (fresh pods) variety Amy by 12.5% but variety Samantha did not respond to lime in the first season of application (2007). In the second season, residual response variety Samantha increased by 47.8% but Amy did not respond.	Barasa *et al.* (2013)
At Agriculture Training Centre in Embu County, (soil pH 5.06), application of 2 t ha^{-1} of lime (CaO) gave soybean yield increase of 42% above the un-limed plots.	Serafim *et al.* (2013)
At Kibos site in Kisumu County, liming (CaO) at 2t ha^{-1} had no significant effect on sugarcane yields in a soybean intercrop, mainly due to a high soil pH (top-soil 6.19 and sub-soil 5.93).	Omolo *et al.* (2016)
In Mumias sugar zone (4 sites with mean pH 5.1), in Kakamega County, application of 3 t ha^{-1} of lime (CaO) gave mean sugarcane yield increase of 8% above the un-limed plots.	Mutonyi *et al.* (2014)

Note: Major nutrients were not limiting

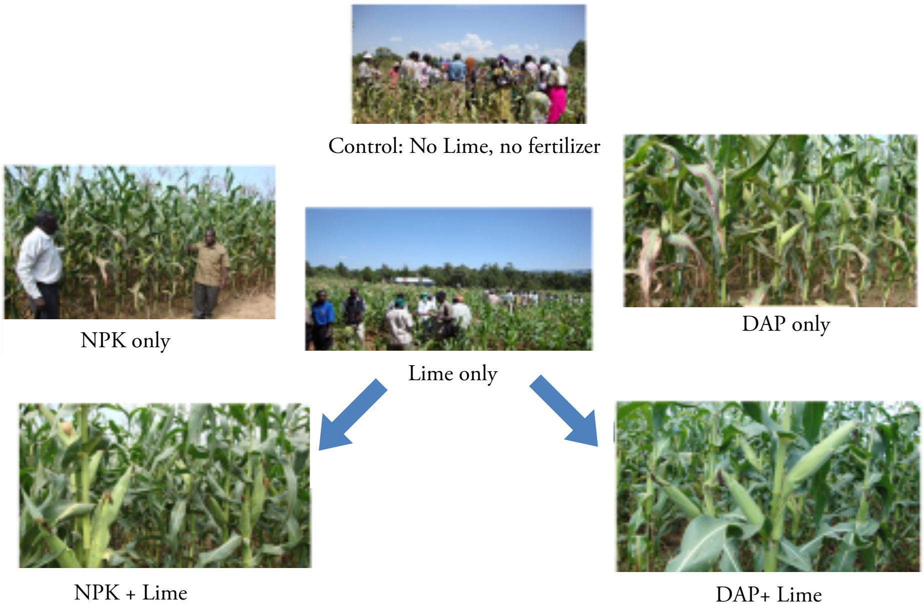

Figure 7.1: Performance of maize crop grown under various fertilizers and lime amendments in Siaya County, Kenya (Source: Mbakaya, 2015).

1. It is evident from various studies reviewed that liming increases crop yields by up to 500%. However, inappropriate lime application depresses yields.
2. Most liming studies did not consider the soil's exchangeable acidity and lime buffering capacity in addition to the soil pH.
3. The increase in yields depended on the initial soil pH, the crop, soil characteristics and the rate applied.
4. The higher the rate of applied lime, the longer its effectiveness, but over-liming should be avoided.
5. It is vital to have soils tested for soil pH, exchangeable acidity, and lime recommendations based on soil characteristics and the target crop.
6. Research findings on essential crops such as Irish potatoes, coffee, tea and common beans responses to liming are limited.

There is a need for further lime rate response trials on many other crops and soils.

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8.0 LIME SUPPLY CHAIN ANALYSIS AND POLICY CONSIDERATIONS

8.1 Introduction

Kenya is yet to develop its agricultural lime supply chain. The potential supply value chain of agricultural lime (aglime) and policy considerations are yet to be extensively evaluated, shared, and exploited. The demand and supply of aglime in Kenya are important elements in designing interventions geared towards upgrading its value chain. With sufficient demand for aglime products or services, it will be easier to have a valid supply value chain/delivery business model. In addition, with a favourable policy environment, upgrading the aglime supply chain can be effectively done. The aglime business in Kenya is still in the early development stages and calls for a better understanding of aglime market dynamics, including market overview, market drivers, supply chain analysis and market challenges and constraints.

8. 2 Aglime materials/products in the Kenyan market

8.2.1 Aglime materials/products in the market

Liming of agricultural land has been practiced for millennia (Peters *et al.,* 1996). The main types of aglime in the Kenyan market are calcitic lime, composed of calcium carbonate ($CaCO_3$) and dolomitic lime ($CaCO_3$ with magnesium carbonate, $MgCO_3$). The liming efficacy of any material is expressed as calcium carbonate equivalents (CCE). Table 6.1 (Chapter 6) shows the CCE of common liming materials. There are several aglime products on the Kenyan market (Table 8.1)

Most jurisdictions have guidelines which require liming materials to be labelled. Lime packaging commonly includes the following information:

- Neutralizing Value
- Calcium and magnesium percentages
- The form of calcium and magnesium (carbonate, oxide or hydroxide)
- Fineness

The challenges in the Kenya aglime market segment are the discrepancy between the labelling guidelines and the ability of farmers to interpret the labelling requirements. The other issue is the cost of and difficulties in transportation, hindering accessibility of aglime to smallholder farmers, which needs to be applied in large quantities for effective results on farms (KMT, 2021; One Acre Fund, 2016).

Table 8.1: List of liming products available in Kenya

Product form	Product name	Examples of distributors
Calcium carbonate	Calcium fertilizer	Homa Lime Company limited
	Agricultural lime	Mavuno Fertilizer Limited
	Agricultural lime	Ocean Agriculture
	Agricultural lime	Amiran (K) Limited
	CalciGrow	Chiromo fertilizer ltd
	Mel calcitic lime	Mineral Enterprises Limited
A mixture of three forms of calcium (hydroxide, oxide and carbonate).	Super calcium fertilizer	Homa Lime Company limited

Product form	Product name	Examples of distributors
Granulated micronized granulated calcitic lime	CalciGrow granules	Chiromo fertilizer ltd
	Calciprill	Omya EA Ltd.
	Calcipower	Amiran (K) Limited
	Fealime	MEA Limited
	Calcisuper	Elgon Kenya
Dolomitic lime powdered	Dolmax	Mavuno Fertilizer Limited
	Dolmax	Amiran (K) Limited
	Dolmax	Ocean Agriculture
	Mel dolomitic lime	Mineral Enterprises Limited
Granulated micronized dolomitic lime	Magprill	Amiran (K) Limited
	Magprill	Lachlan (K) Limited
Hydrate Lime	Neelkanth	Neelkanth Lime Limited
	Maxi Calcium Fertilizer	Homalime
Concentrated water dispersible liquid fertilizer containing 35% calcium.	Ezyflow lime	Flamingo Horticulture Dudutech
Concentrated fully water dispersible liquid fertilizer containing 30% calcium and 5% magnesium.	Ezyflow dolomite	Flamingo Horticulture Dudutech
Soil amendment material used to correct soil alkalinity by reducing the pH value of soil.	Agricultural gypsum	Amiran (K) Limited
Soil conditioner composed of liquid organic fertilizer used to increase the pH value of soil.	Dolmax	Amiran (K) Limited
Gypsum – contains calcium and sulphur	Gypsum	Ocean Agriculture
	Gypsum regular grade	Mavuno Fertilizer Limited
A liquid suspension of gypsum containing 16% calcium and 13% sulphur, applied to reduce salinity and improve soil structure by reducing sodium build-up and increasing calcium levels in the soil. Gypsum will increase calcium in acidic soils and reduce exchangeable aluminium in the surface soil layer.	Ezyflow gypsum	Flamingo Horticulture Dudutech

8.2.2 Aglime market segments in Kenya

There are two categories of aglime market based on type ; powdered lime and granulated lime. These products are further differentiated as quick lime, hydrated lime, liquid lime, and granulated lime. Micronized granulated lime breaks down rapidly and offers faster results than powdered lime. Powdered lime requires a special mechanical spreader, unlike granulated lime, which is more easily applied. There are multiple potential benefits to aglime in the country, and the market size and share of aglime products have been growing over the years.

8.2.3 Market drivers of agricultural limestone

Although numerous large cement-producing companies in the country have the potential to provide agricultural lime as limestone or as a by-product from industrial lime production, the existing producers of agricultural lime are relatively small. One of these smaller producers is Homa Lime Co. Ltd (HLCL), which has partnered with Gatsby Africa (GA) and Alliance for a Green Revolution in Africa (AGRA) to distribute lime to farmers mainly in Kakamega, Bungoma, Uasin Gishu, Trans Nzoia and a few other counties in the region (Kenya Markets Trust, 2019).

HLCL produces approximately 30,000 tonnes of lime annually and has a range of limestone products, including Boresha calcium fertilizer for agricultural purposes and other products for building and road construction, water treatment and the leather industry. Since 2015, HLCL has expanded its aglime distribution channels from a single wholesaler to 17 lime distributors and stockists spread across four counties. In the process, its sales more than doubled from 3,600 tonnes in 2013 to 9,200 tonnes in 2018 (Kenya Markets Trust, 2019).

Currently, 10 firms produce and/or sell calcitic and dolomitic lime. Athi River Mining Limited has the potential to supply lime in much larger quantities. Apart from being the largest supplier of cement in East Africa, the company has commercial interests in quick lime, hydrated lime, and fertilizers (sold under the brand name Mavuno). Most granulated aglime is imported into the country. However, this is changing with recent investments in local lime granulation by Chiromo Fertilizers, Elgon Kenya Ltd, MEA Ltd, and Amiran Kenya Ltd.

The lime manufacturers/importers supply lime to their distributors, who sell to stockists, and they, in turn, serve farmers at the local level. However, distributors also retail their products. According to farmer responses, maize, sugarcane, and coffee are the major crops to which lime is applied in Kenya.

The aglime industry is characterized by its low unit value. Aglime is a material of low price at the point of production. However, due to the bulky nature of the product, transportation costs substantially increase the price at the point of delivery. Production of aglime should take place near its marketable area and points of use to lower its costs. Thus, high-demand areas would be ideal locations for these industries.

8.2.4 Aglime supply value chain analysis

The agricultural lime supply chain is the flow of lime as a product along the different stages, from production to end-level supply, by which a producer or company adds value to the product. Supply chain analysis evaluates every stage of a supply chain, from when the business acquires raw materials to the delivery of final products to the customers.

A *supply chain* is defined as the connected activities related to the creation of a product or service through the delivery of the product to the customer. It includes upstream suppliers and downstream activities such as wholesalers and distribution warehouses. Different stakeholders or actors are involved in the supply or value chain, including producers or farmers, collectors, transporters, processors, dealers, wholesale/retail traders, importers/exporters, and consumers. Other key actors are extension/researchers and regulators. They perform necessary and special functions. The actors get varying profit margins along the supply chain. Each of these segments needs to be efficient in performing marketing functions.

A wide range of information about the industrial policies, governmental regulations, leading market players and their major strategies constitute a central reference point regarding the prospects offered by the lime market and the investment opportunities that will reap profits in the near future when properly planned and regulated. The aglime value chain analysis involves the following aspects:

1. Supply chain analysis and structural descriptions including processing
2. Value chain analysis and structural descriptions
3. Stakeholder level analysis
4. Operation level analysis
5. Value additions at different levels of the supply chain, from crop planting area to crop yield
6. Profit margin analysis
7. Flow and match analysis from producers to middlemen to end-consumers (farmers)
8. Competitive environment at the country, region, and global levels

Lime has a long history of use in agriculture. Aglime is usually in the form of ground or crushed limestone. Aglime is recognized by its being considered as a fertilizer, a soil conditioner, and a soil amendment agent, correcting soil acidity for improved productivity. There is a significant disparity between the need for and actual use of aglime, even though there are proven benefits associated with its application. The returns on investment in aglime are high if used at its recommended rates.

The supply of aglime has been affected by low profit margins for aglime producers, seasonality in demand for aglime, difficulties in its storage by producers, and additional requirement of crushing operation into very fine aglime that attracts additional operating costs. Hence, companies such as Homa Lime have resorted to the application of a Lean Supply Chain Management (LSCM) – the management of a set of activities linked directly by downstream and upstream flows of products, services, information, and finances that work together to reduce cost in production and reduce waste incurred during production, by efficiently and effectively coming up with products that meet the needs of customers (Womack & Jones, 2007). LSCM necessitates that supply chains minimize the cost of operation at all production levels. The LSCM practices are significant to organizational performance because it improves the relationship between suppliers and the organization, which results in the delivery of the best value to the customer at an affordable cost. It bridges the gap between the customer relationship manager and the supply chain manager. LSCM leads to the delivery of the best value, thus creating a good reputation for the firm in terms of overall value creation (Daudi & Zailani, 2011). By adopting LSCM, Homa Lime Company improved their organizational performance, resulting in flexible product processes, proper resource utilization, and customer satisfaction. Figure 8.1 presents the different actors in the lime business model for acidic soil management.

8.2.5 Aglime value chain actors

The aglime sub-sector has several actors from farmers on the demand side to agro-dealers, stockists, distributors and aglime manufacturers or importers on the supply side. They perform different but closely related and synergistic functions.The five categories of value chain actors (including the enablers and regulators) and their functions are summarized on Table 8.2.

8.2.6 Aglime production process

The production includes site clearing, extraction of limestone from the ground, crushing and milling. The process is summarized in Table 8.3.

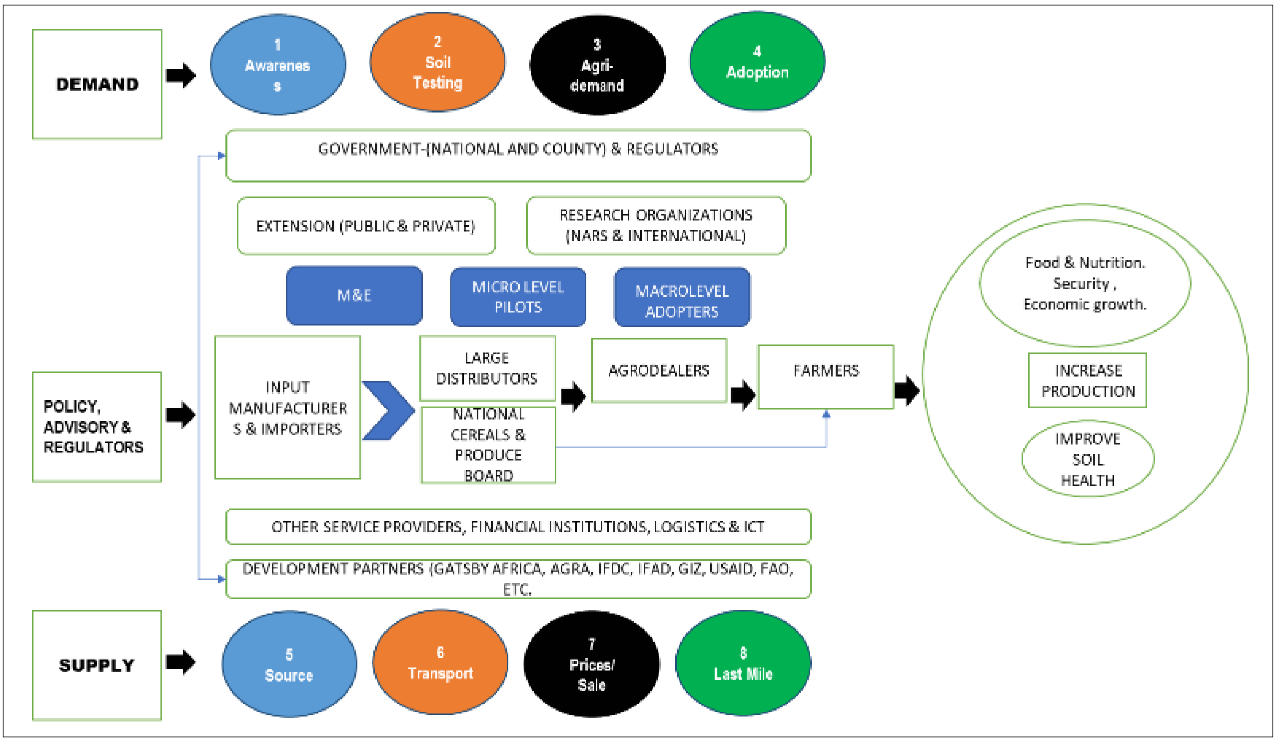

Figure 8.1: Lime Business Model for Acidic Soil Management

Table 8.2: Aglime actors along the value chain

Policy makers and Regulators	Manufacturer	Distributor	Agro-dealer	Farmers
National and County governments agencies and regulatory bodies (work on policy regulation and advisory).	Large companies (public and private) that manufacture and/or import agricultural inputs including seeds, fertilizer, agro-chemicals etc. They usually have a network of distributors in various countries through which they supply their products.	Large or mid-sized registered companies are usually based in capital cities of various countries. They procure agricultural inputs from suppliers and distribute to agro-dealers based on orders received. In a few cases, the distributor can also be an agro-dealer.	Retail shops, located in urban and rural areas, procure inputs from different distributors, and sell them directly to farmers. Agro-dealers also purchase products (usually fake items) from unregistered traders.	Farmers directly purchase items from the nearest agro-dealer.

Table 8.3: Aglime production process

Process	Operations
Site clearance	• Site clearance, including removal of vegetation, soil, and overburden
Extraction	• Drilling and blasting of rock 'benches' in a quarry
	• Breaking of large rocks using pneumatic drills
	• Removal of rock to a processing plant
Crushing	• Primary crushing (using a jaw or gyratory crusher)
	• Screening of crushed material to remove the fines, which usually contain soil and fine-grained material (potential aglime)
	• Secondary and tertiary crushing using cone or jaw crushers
	• Screening of crushed rock to produce sized material for aggregate or feed to lime or cement plants
Milling	• Milling of crushed material using a mill (hammer, ball and/or impact mill) to produce mineral filler and/or aglime
	• Micronise and granulate
	• Bagging into bulk bags (<1 tonne) or small bags (50 to 100 kg) and labelling

8.2.7 Economics of lime supply and on-farm utilization

Maximization of return on aglime investments dictates a need to conduct a data-driven evaluation and targeting from three key sources: the farmers, private sector, and governments (national and county). These analyses should combine agronomy, economics, social science, and business modelling in an integrated approach. In Kenya, the most available type of lime is in powder form. By the beginning of 2022, at least 13 companies were involved with manufacturing, importing, and distributing lime and lime products, with two companies being dominant in the market.

The current annual demand for lime for agricultural production is estimated to be less than 50,000 metric tonnes (MT). However, based on the assessment of acidic soils and the volume of crops produced, the demand should be at approximately 187,000 MT. Increased efforts in awareness creation on soil acidity and liming at the farmer level are projected to increase demand to 319,000 MT and 532,000MT in the next five and 10 years, respectively, translating to KES 1.3 billion value in annual sales. Kenya would enjoy savings of about USD 2.07 million per annum in importation fees in foreign exchange by shifting from powder-form lime to local production of granulated lime. This would also lead to a drop in the price of granulated lime from the current KES 2,800 per 50kg bag to as low as KES 650 (Kenya Markets Trust, 2021). The additional benefits, including employment creation in extraction, transportation, processing, packaging, and distribution of the granulated lime produce, would help ease the pressure on the youth job market.

8.2.8 Profitability of on-farm application of lime

Although the government has encouraged the acquisition, production, distribution, and adoption of agricultural soil amendment inputs (fertilizers) by smallholder farmers over the years, aglime use for reducing soil acidity is very low in Kenya.

At the farm level, the economical rate at which farmers apply lime depends on net farm returns relative to the lime application. Several factors should be considered to evaluate the costs and benefits of lime application at the household level. These include expected yield increases, prices per unit of lime, transportation and application method, stages, and the expected number of years of enhanced productivity. All these factors affect net farm returns of lime use. A rough calculation of net farm returns to lime application based on experimental results suggests that lime application is generally profitable, particularly when used in moderate amounts ranging from 2.0 to 2.2 t ha^{-1} in conjunction with other improved agricultural practices (use of inorganic and organic fertilizers, high yielding varieties and associated better agronomic practices) (Hijbeek, 2021; Opala, 2017; Kisinyo, 2016; Mbakaya, 2015; Muindi *et al.,* 2015).

Various studies have evaluated the economic benefits of liming acidified soils on crop production and the environment. One such study in western Kenya observed that considering a five-year period, investing the available resources in fertilizer gave better economic returns and positive profit than using lime alone (Hijbeek *et al.*, 2021). The meta-analysis observed an increasing return on investment of liming when associated with increased fertilizer application. The study also calculated the payback period on investing in lime over five years as two years. Based on 54 treatment pairs - with an average lime application of 2.0 t ha^{-1} - maize yields increased by 57% in the first year after application. The type of nitrogen or phosphorus fertilizer used and the amount of nitrogen or phosphorus applied did not significantly influence the yield effect of liming. However, nitrogen rate was significantly confounded with the liming rate and P rate was significantly (positively) confounded with N rate. Based on 64 observations from 16 experimental sites, an average lime application of 2.77 t ha^{-1} increased soil pH from 5.00 to 5.57 in the first year after application. This increase in soil pH depended on the amount of lime applied and was significantly and positively correlated to the soil pH at the start of the experiment. The addition of fertilizer had a negative effect on the soil pH. With no lime application after the first year, soil pH decreased on average with 0.13 pH units per year in the following two to five years. The study concluded that liming of acidic soils for maize production consistently results in increased yields. This affirms the importance of liming acidic soils for specific crop requirements, basing fertilizer and lime application rates on soil testing.

A study by Kisinyo (2016) determined the individual and combined effects of lime and phosphorus application on maize productivity and economic benefits on an acidic soil of Uasin Gishu County, Kenya. The work was conducted over a period of four years. Treatments were phosphorus fertilizer (0, 26 and 52 kg P ha^{-1})) and lime (0 and 6 tons/ha), with all being applied at once. All treatments, except control, received 75 kg N ha^{-1}. The mean grain yield increments due to 26 kg P, 52 kg P and 6 tons lime/ha were 35%, 61% and 29%, respectively. In the second, third and fourth years, 75 kg N+52 kg P ha^{-1} produced economically viable returns with net financial benefits of (NFBs) of USD 942, 1802 and 2,540, ha^{-1} respectively. Application of 52 kg P/ha together with 75 kg N and 6 tons of lime/ha produced economically viable returns with NFB of USD 2,732 ha^{-1} during the fourth year.

Kisinyo *et al.* (2015) conducted a study on a nutrient deficient acid soil on a smallholder farmer field in Busia County between 2008 and 2009. Lime was applied once during the long rain in the year 2008, while phosphorus and nitrogen fertilizers were applied each cropping season. The majority (57-75%) of the production costs were due to inorganic inputs. Only combined application of 50% of both the recommended nitrogen (N) and phosphorus (P) fertilizers produced economically viable returns throughout the cropping period. Combining 50% and 25% of the recommended phosphorus and lime, respectively, and 50% and 25% of the recommended nitrogen and lime, respectively, produced economically viable returns only during the second and third cropping seasons. However, a combination of 50% of both the recommended phosphorus and lime produced economically viable returns during the third cropping season only.

8.2.9 Analysis of Lime Demand and Supply Relationships

There is a significant disparity between the need for and actual use of agricultural lime. Though lime efficiency has been proven through various empirical studies (Osundwa *et al.,* 2013; Muindi *et al.,* 2016) and on farmer fields (Nekesa *et al.,* 2011), the demand in Kenya remains low. The returns on investment from liming are high, especially on significantly acidic soils, if applied at recommended rates (Kisinyo, 2016). Moreover, micro-dosing of liming inputs further increases economic viability as it results in higher cereal yields at lower application rates (Kisinyo *et al.,* 2015). Most agricultural liming materials are of low price at the point of production; however, transportation costs substantially increase the price at the farmer level.

8.2.10 Challenges in Agricultural Lime Use and Marketing in Kenya

Even though there are several sources and types of liming materials in Kenya, most of it is available in ground lime or powder form. This form is bulky, difficult to apply and dusty, resulting in limited use at the farm level, especially by smallholder farmers. This low uptake is also attributed to limited knowledge of lime usage, its effectiveness, availability, and high transport costs that result from its bulkiness (One Acre Fund, 2016).

An evaluation of a pilot project conducted by KMT (2019) highlighted the challenges of using lime in Kenya, which included limited farmer knowledge, awareness and access to lime, insufficient information on the available products, and weak collaboration between the value chain actors including manufacturers, distributors, and stockists. Low demand results in low incentives to manufacture and market agricultural lime, causing the agricultural lime sector in Kenya to stagnate.

While lime itself is relatively inexpensive per ton, the high volumes required and cost of transportation makes it a relatively expensive input to smallholder farmers. Further, the quantities of lime required to change the soil pH significantly are large and, at times, practically impossible for smallholder farmers to access. According to a report by One Acre Fund (2015), frequent lime recommendations are often in tonnes per hectare, several times greater than other inputs (i.e., seeds and fertilizers), which are required only in a few kilograms per hectare. Research conducted by the Kenya Soil Health Consortium (KSHC) and AGRA on maize grain yields and cost-benefit analysis comparing lime and soil health inputs in Western Kenya indicate that the best and highest profit was obtained from liming at four tons per hectare for many fields. This assertion is, however, not conclusive given that appropriate lime rates depend on initial soil pH, the desired pH according to the crop, soil clay content, and soil organic matter concentration. Another challenge relates to lime application, with farmers noting that powdered lime is dusty, difficult to apply, a health hazard, and labour intensive, further increasing costs.

A KMT (2019) evaluation highlighted some of the key challenges towards the expansion of the lime market and use of lime by farmers, as follows:

a) Many farmers still expect government and donor agencies to help them acquire lime. Some farmers, due to limited knowledge on liming, mixed lime and fertilizer during planting. A coordinated national policy on lime manufacturing, distribution, subsidization, and use is also lacking.

b) Although a KeBS standard exists (KS 2526:2014), most products in the market do not adhere to it. Lack of enforcement of the standards has resulted in numerous agricultural lime products being marketed without clear labelling – specifically without information on the product purity (calcium carbonate equivalent) and the particle size of the liming material, which can inform farmers regarding the speed of reactivity. This absence makes it difficult for buyers to make informed choices between the different liming materials.

c) Agricultural lime is not classified as an agricultural input, subjecting liming products to a 16% value added tax. This increases product price and makes lime products, especially the value-added granular lime, less affordable.

d) Considering the available types of lime in the market (granulated, hydrated, powder, chalk, liquid, and others), knowledge is incomplete regarding the best application time, best application approach, and the reapplication rate for these various products.

e) Low demand for lime is associated with low awareness among the farmers and challenges in the distribution channel used. It was found that only 59.5% of farmers were aware of agricultural lime. Information on lime was spread through word-of-mouth by fellow farmers and agricultural extension officers. However, lime use was still low. Despite the indicated awareness level and 29.3% having access to lime, only 20.2% of the respondents reported having ever used agricultural lime. Notably, 20.2% is a cumulative historical figure; the current lime usage is estimated at about 7%. This means that a majority (79.8%) have never used lime.

f) Finally, among the small holder farmers, there is a knowledge gap on soil health, nutrition, and use of lime. This is due to the lack of satisfactory advisory services on necessary interventions from the relevant service providers.

8.3 Policies, laws and regulations governing aglime

Considering the increasingly high acidity in parts of the country (65% of Kenya's arable land), there is a need for a comprehensive policy that not only leads to increased use of aglime but provides guidelines for its local manufacturing or importation, distribution, and use. One of the essential enabling factors for aglime industry development is the existence of supportive policies, which are currently unavailable. The effect of policies could be direct or indirect. Thus, there is a need for a review of key and relevant policies which directly or indirectly affect the development of the aglime sector in Kenya. These policies could include specific incentive structures to develop the production and distribution of agricultural inputs (including agricultural lime), policies and strategies designed to abate the effects of acidic soils on agricultural production and productivity, rules and regulations on product standards, and quality control mechanisms. Further, policies on rural financial services and property (use) rights on land and gender concerns also need to be reviewed in relation to their role in enabling farmers to invest in aglime for acidic soil management. Agricultural marketing and pricing policies affecting farmers' ability to pay back loans on aglime investment, agricultural extension and advisory services, policies supporting the development of agricultural mechanization services for aglime application, and soil testing services for precise agronomic recommendations, all need be reviewed and/or developed. These incentivize business opportunities around lime. National investment plans, which present the resources required for different scenarios, and national communication and advocacy strategies around soil health management, should also be reviewed.

The legal framework governing soil conditioners and aglime and liming products is covered across several government documents. The Constitution of Kenya of 2010 (GoK, 2010) is the overarching law governing natural resources in Kenya. Chapter 5 of the Constitution deals with land use and land tenure and in it are various articles that are relevant to soil fertility. Article 60 requires that all land (private, public and community) be held, used, and managed in a manner that is equitable, efficient, productive, and sustainable, and in accordance with a set of principles including security of land rights, sustainable and productive management of land resources, sound conservation and protection of ecologically sensitive areas, and the elimination of gender discrimination in law, customs and practices related to land and property in land. Kenya's Vision 2030, which is Kenya's development blueprint or strategy (GoK, 2009), recognizes the importance of soil fertility in enhancing agricultural productivity for driving economic growth.

The National Land Use Policy (NLUP) of 2017 (GoK, 2017) aims to guide Kenya towards sustainable and equitable land use. It stipulates the principle of conservation and management of land-based natural resources. However, it does not address agricultural soil management, soil fertility and salinization *per se*.

The National Agriculture Policy (NAP) of 2019 (GoK, 2019) provides a framework for sustainable development of the agricultural sector based on the requirements of the Constitution, Vision 2030, and Sustainable Development Goals (SDGs) (SDG, 2015). Some of the policy statements in the NAP have a direct bearing on soil management and propose the promotion of organic farming. However, it needs to address soil management matters exhaustively and in sufficient depth.

The National Irrigation Policy (NIP) of 2017 (GoK, 2017) recognizes that soil resources can be a significant limitation to expanding irrigated agriculture in Kenya. Some irrigation schemes in the country have been abandoned due to build-up in soil salinity and sodicity. However, NIP does not recommend incorporating holistic agricultural water management (AWM), including soil fertility management and appropriate agronomic practices.

The National Environmental Policy (NEP) of 2013 (GoK, 2013) sets out important provisions relating to the management of ecosystems, ecosystem services and sustainable use of natural resources. It advocates for the following on soils: development and implementation of a National Soil Conservation Policy, promotion of ecological and organic farming practices to maintain soil fertility, promotion of good soil management practices, and empowerment of the communities in soil conservation. This policy has strategies that have a direct bearing on soil management, particularly soil restoration and conservation.

The Draft National Land Reclamation Policy (NLRP) of 2013 (GoK, 2013) focuses on protection, management and restoration of degraded lands and threats to land resources. It integrates reclamation, rehabilitation, restoration, and remedial practices. Despite being an important policy regarding agricultural soil management, it does not address issues of soil salinity, soil biodiversity and fertilizers.

The National Agricultural Sector Extension Policy (NASEP) of 2012 (GoK, 2012) sets guidelines for agricultural extension, promotion and diffusion of technologies for land management. However, NASEP does not address the issue of research for technology development and other support services for agricultural soil management.

The National Forest Management Policy (NFMP) of 2014 (GoK, 2014) provides a framework for improved forest governance, resource allocation, partnerships and collaboration with state and non-state actors to enable the sector to contribute to meeting the country's growth and poverty alleviation goals within a sustainable environment. The contribution of the sector to soil and water conservation and in creating conducive conditions for soil fertility restoration has been recognized in this policy.

The Agricultural Sector Transformation and Growth Strategy (ASTGS) 2019-2029 (GoK, 2018) aims at transforming Kenya's agricultural sector into a regional powerhouse. It is anchored in the belief that food security requires a vibrant, commercial, modern and equitable agricultural sector that sustainably supports economic development. ASTGS builds on lessons learned from prior strategies and takes an evidence-based approach focusing on the counties. This approach is the foundation for addressing the challenges that constrain agricultural output, productivity, natural resource management and the effects of climate and environmental change. However, this strategy does not explicitly address soil fertility improvement through liming.

The KALR Act of 2013 (GoK, 2013) created a new institution, the Kenya Agricultural and Livestock Research Organization (KALRO) by merging four state corporations, the former Kenya Agricultural Research Institute (KARI), the former Tea Research Foundation of Kenya (TRF), the former Coffee Research Foundation of Kenya (CRF), and the former Sugar Research Foundation of Kenya (KESREF). This Act, with its revision in 2015, mandates KALRO 'to develop and promote sustainable land management (SLM) technologies and methodologies for the agricultural sector'. KALRO has recommendations on aglime application requirements for soil acid management.

The Fertilizers and Animal Foodstuffs (Amendment) Act 2015 (Cap 345) (GoK, 2014) establishes the Fertilizer and Animal Foodstuffs Board of Kenya. However, the amended Act is not explicit on fertilizer or lime quality standards and regulations to guide laboratory testing of fertilizers and soils. It excludes regulation of organic fertilizers, bio-fertilizers and soil conditioners, such as lime. The Act has more provisions for animal foodstuffs than fertilizer, and does not adequately address all matters of soil management.

There are many institutions involved in soil and water management, each with their specific act that give them their mandates. However, none of these acts address agricultural soil management adequately. Cap 345 has inadequacies regarding quality standards, definition of fertilizers, and environmental protection, amongst other issues. There is a need to develop a comprehensive legal and regulatory framework that adequately addresses all issues pertaining to agricultural soil management.

The National Agricultural Soil Management Policy (NASMP) of 2020 (MoALF&C, 2020) proposes a wide range of measures and actions responding to key agricultural soil issues and challenges. It provides a framework for an integrated approach to sustainable management of agricultural soils in the country. The policy highlights the challenges facing our soils and proposes various policy measures to address them. Nonetheless, there are only two chapters (2 and 5) where the word "lime" is mentioned in passing. Chapter 2, which reviews the status of sustainable agricultural soil management in Kenya, highlights key soil management issues and challenges. The policy addresses the issues of governance through the status of existing policies, regulations and strategies related to the management of agricultural soils. Chapter 5 deals with the status and challenges in fertilizer development and investments in Kenya. NASMP recommends strong institutional and governance measures to support the achievement of the desired objectives. Thus, although there are many institutions involved in soil and water management each with their specific acts that give them their mandates, none of these acts adequately address agricultural soil management through liming. There is need to create an institutional framework for effective management and enforcement of all issues pertaining to agricultural soil management and in particular liming of acidic soils.

From the foregoing, there are several policy considerations for implementing a profitable aglime supply value chain system. These may include, but are not limited to:

- Quality of agricultural liming products – lack of clear quality guidelines and standards for agricultural lime
- Bridging the information gap – on soil health, use and application of agricultural lime
- Lime awareness and demand acceleration –a nationwide lime awareness platform is needed
- Enabling Environment – Given the benefits of lime, the national and county governments and other stakeholders need to develop and finalize draft policies and incentives to support increased awareness, use, production and distribution of agricultural lime
- Liming Equipment – Support local machinery and equipment fabricators through trainings, exposures and provision of required infrastructure
- Crop Response trials – Need for funding of research organizations by national and county governments or donors to undertake crop response trials

However, there are some key challenges in the aglime industry that include:

a) Inadequate capacity for aglime quality assurance and analysis including modern laboratories, equipment, personnel and infrastructure

b) High logistical costs related to handling, storage and application of aglime

c) Inadequate technical knowledge among the value chain players (farmers, agro-dealers, manufacturers and extension service providers among others).

8.4. SWOT analysis on aglime value chain actors

The SWOT analysis on aglime actors is shown in Table 8.4

Table 8.4: SWOT Analysis of Actors in the Agricultural Lime Supply Value Chain

Actor	Strengths	Weaknesses	Opportunities	Threats
Local manu-facturers	• Existing resource base and capacity for extraction • Linkage with experts in soil health field (Government agencies/extension, private sector, NGOs) who work with farmers	• Limited marketing skills • Some have limited manufacturing capacity	• Increased awareness of soil acidity and liming and link to crop production • Existing and upcoming programs by government and other agencies e.g., subsidy program etc. • Enabling environment as lime has been included as one of the inputs in the government's E-voucher subsidy program.	• Competition from importers of granulated lime
Importers	• Existing networks/ linkages, infrastructure and permits for handling fertilizers • Access to financing solutions • Supplier network from fertilizer linkages already existing	• Demand driven, based on profits • currently have low volumes and fluctuating global prices	• Able to negotiate flexible buying arrangements with sellers due to linkages • Increase in programs creating awareness of liming of acid soils for increased food production • Enabling environment as lime has been included as one of the inputs in the government's E-voucher subsidy program	• High prices of imported lime compared to locally produced • Establishment of manufacturers of granulated lime at lower cost
Distributors	• Existing retailer networks • Relationships with importers/ manufacturers of lime • Capacity to deal with bulk products	• They are traders and hence dependent on having sufficient demand before stocking	• Increase in programs creating awareness of liming of acid soils for increased food production	• Poor relationship between Public and private actors as always targeted by proponents of shortened value chain
Agro-dealers	• Existing networks/ linkages with wholesalers/ distributors of fertilizer • Established infrastructure and licenses/permits • Close interactions/ relationships with farmers, hence ready market	• They are traders and stock based on demand • Minimal information and knowledge on liming… • Some have limited management, technical competence and stock holding capacity	• Access to credit • Increase in programs creating awareness of liming of acid soils for increased food production • Increased access to soil analysis services by farmers	• Limited demand due to low awareness among farmers of importance of lime • Government subsidy programs that result in dependency syndrome amongst farmers • Lime is bulky hence requires sufficient space • High levels of competition enhancing less competitive models

Actor	Strengths	Weaknesses	Opportunities	Threats
Extension agent	• Linkages to researchers and other practitioners who have information on soil acidity and liming • Network and good will with the farmers	• Lack of facilitation	• Government subsidy programs • Projects that provide facilitation	• Limited soil analysis within the operating region
Farmer or producer	• Access to agro dealers	• Limited knowledge on liming and soil acidity • Dependence on subsidies • Limited use of soil testing activities	• Local availability of lime products • Availability of programs and projects on soil acidity and liming • Increased availability of information on soil testing, soil acidity and liming • Group formation hence social capital	• Lack of legislation to safeguard quality of product and packaging could result in misinformation, mispackaging etc.
Soil testing services	• Existing laboratories with capacity for testing for soil acidity	• Varying cost of soil testing	• Accredited national laboratories for capacity building	• Existing laboratories with capacity for testing for soil acidity
National and county governments	• Laws and policies guidelines exist for lime operants	• Poor implementation of the laws and policies	• Review of policies negatively affecting aglime	• Noncompliance to laws and policies by aglime Actor
Financial institutions	• Financial lending Institutions available	• High interest rates		• Risk of making economic loses

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9.0 RECOMMENDATIONS AND WAY FORWARD

Soil acidity is one of the major constraints to crop productivity in Kenya, as more than 63% of the country's arable soils are acidic. Managing soil acidity is critical to increasing soil fertility and the supply of plant nutrients. Although the Government of Kenya and other stakeholders in agriculture have identified this as a major challenge, there are no comprehensive plans to correct it, despite empirical evidence showing that the use of lime is beneficial. The following key issues ought to be addressed for the sector to move forward.

9.1 National agenda on rehabilitating acidic soils

There needs to be higher investment by both the public and private sectors in awareness creation, with investment in nationwide platforms and funding opportunities in Kenya. The level of public awareness is currently low but could be higher, on the issue of soil acidity and the importance of liming, compared to the use of fertilizers. In addition, both national and county governments do not have set guidelines on liming.

The national and county governments should create an enabling environment for the development and growth of the lime sub-sector. Supportive lime sector strategies, policies, and regulations require to be developed to accelerate awareness of soil acidity and its effects on productivity. It is also essential to develop soil testing and analysis infrastructure to enhance soil health.

9.2 Farmer awareness and support

There is limited farmer knowledge, awareness and access to lime, insufficient information on the available products, and weak collaboration between the value chain actors including manufacturers, distributors, and stockists. The value chain stakeholders (national and county governments, development partners, the private sector, and other players) should coordinate efforts to increase soil acidity and liming awareness.

Public and private sector extension services that facilitate farmer awareness should be enhanced. In addition, there is a need to develop extension manuals for field officers who are directly involved in training farmers on appropriate lime utilization. Simplified liming information packs should similarly be developed for farmers to get the full benefit of liming. Private companies may also be encouraged to develop manuals specific to their products. Information on the 4Rs stewardship (source, rate, timing, placement methods) is needed for increased crop yield and lime adoption.

There is a need for financing and offering credit facilities to farmers for lime procurement, distribution, and use.

9.3 Management practices for acidic soils

Several acid soil management strategies have been documented for managing acid soils in Kenya and other countries in sub-Saharan Africa. They include i) addition of liming materials; ii) use of rock phosphates; iii) use of organic materials; iv) judicious choice and application of fertilizers; vi) combining lime with organic materials and inorganic fertilizers; vii) growing acid tolerant crop species and varieties.

To adequately address soil acidity, there is a need for judicious soil health and environmental quality management. All soil nutrients need to be balanced to avoid antagonism and enhance plant uptake and optimize yields. Integrated Soil Fertility Management (ISFM) is among the best options for soil fertility management in acidic soils. ISFM is the use of farming practices that involve the combined use of inorganic and organic inputs, improved seed and other planting materials, combined with the knowledge on how to adapt these practices to local conditions to maximize the plant nutrient use efficiency while improving crop yields. All inputs need to be managed following sound farming principles.

9.4 Develop manuals for laboratory and field methods for lime requirement determination.

Soil testing for acidity levels in various parts of the country, conducted by different laboratories, and has revealed variable results and recommendations from the same soil sample, attributable to the different laboratory methodologies, equipment, and human capacity. This points to the need for more capacity in determining lime requirements and recommendations. Harmonization and standardization of soil test methodologies across the accredited laboratories are required to ensure quality and reliable data on soil acidity determination and lime recommendations.

Manuals for simple field tests, lime recommendation procedures, and more precise laboratory procedures and lime recommendations based on the soil test results and acidity tolerance of different crops/varieties need to be developed. Soil laboratories that perform the tests and offer interpretation for lime recommendations need to be capacity built through training in some quality assurance programs to ensure data credibility and farmer confidence.

9.5 Research and development

Strategic research is needed to develop and promote liming in addition to integrated crop, soil, water, soil fertility management practices for acidic soils. Inadequate availability of required materials and research addressing soil acidity has hindered access to and adoption of lime and liming materials. An increase in budgetary allocation is imperative to supporting agricultural research and development that addresses soil acidity and information dissemination for enhanced agricultural productivity.

9.6 Liming material for agricultural acid soils

A variety of liming materials are available in Kenya. Liming materials with small particle sizes offer the greatest reactivity per quantity applied. This has offered an opportunity for lime granulation, where ultra-fine particles formed into granules and delivered onto or into the soil using standard fertilizer application methods or equipment.

The effectiveness of liming materials is assessed using the Neutralizing value (NV), which should be indicated on the package. Correct labelling is useful in calculating and comparing different liming materials and establishing the best value lime available for farmers.

9.7 Lime supply chain and policy

There is a need to develop an efficient and sustainable lime delivery system that balances cost-effectiveness with widespread farmer adoption and job creation .An ex-ante assessment of the economic benefits of liming is central to developing a national-level lime policy. Therefore, there is need for cost/benefit analysis on a national scale. This analysis should not only assist in identifying the overall economic benefits, but where liming investments should be targeted to achieve maximum benefits, and the farmer typology to target.

A fully developed government policy that addresses the needs of an efficient and sustainable acidic soils reclamation strategy and complimentary services is required. Most existing legal frameworks – policies, laws, regulations, and standards – that attempt to regularize agricultural inputs remain in draft form, and these need to be fast-tracked to their conclusion.

Gatsby Africa
P.O Box 41472-00100
Merchant Square, Riverside Drive
Nairobi, Kenya
www.gatsbyafrica.org.uk

Kenya Agricultural and Livestock
Research Organization
Kaptagat Rd, Loresho
P.O Box 57811-00200
Nairobi, Kenya
www.kalro.org

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