

**LIME, MANURE AND INORGANIC FERTILIZER EFFECTS ON SOIL
CHEMICAL PROPERTIES, MAIZE YIELD AND PROFITABILITY IN
THARAKA-NITHI COUNTY, KENYA**

**KIMITI WINNIE WANJIRU
N50/CTY/PT/33497/2014**

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Environmental Science in the School of Environmental Studies of Kenyatta
University**

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university or any other award.

Signature.....

Date.....

Kimiti Winnie Wanjiru

N50/CTY/PT/33497/2014

SUPERVISORS

We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

Signature.....

Date.....

Dr. Monicah Mucheru-Muna

Department of Environmental Science

School of Environmental Studies

Kenyatta University

Signature.....

Date.....

Dr. Jayne Njeri Mugwe

Department of Agricultural Science and Technology

School of Agriculture and Enterprise Development

Kenyatta University

DEDICATION

This thesis is a dedication to my dear parents, Mr. Benard Kimiti and Mrs. Cecilia Nyokabi, for their unending support, encouragement, and value towards my education.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEZ	Agro-Ecological Zones
Al	Aluminium
ANOVA	Analysis of Variance
BCR	Benefit-Cost Ratio
Ca	Calcium
CaCo ₃	Calcium Carbonate
Cmol	Cent mole
DAP	Diammonium Phosphate
H	Hydrogen
ISFM	Integrated Soil Fertility Management
K	Potassium
LR	Long Rains
LSD	Least Significant Difference
Mg	Magnesium
N	Nitrogen
Na	Sodium
NBR	Net Benefit Return
P	Phosphorus
pH	Power Hydrogen ions
RCBD	Randomized Complete Block Design
SAS	Statistical Application System
SR	Short Rains
SSA	Sub-Saharan Africa

TSP	Triple Super Phosphate
UM	Upper Midland
WAP	Weeks after Planting

ABSTRACT

In Sub-Saharan Africa, acidic soils occupy 29% of the total area, while about 13% of the Kenyan total land area has acidic soils, widely distributed in croplands of the central regions. The high soil acidity coupled with soil nutrient depletion negatively affect performance and yields of maize in the region. This study was therefore carried out at Kirege in Tharaka Nithi County for two cropping seasons; short rains (SR) in 2016 and long rains (LR) in 2017 to determine the effects of manure, lime and inorganic fertilizer on (i) soil chemical properties (ii) maize yield and (iii) profitability. The treatments included manure (0, 5 and 10 t ha⁻¹), lime (0 and 2 t ha⁻¹), and P fertilizer (0, 30 and 60 kg P₂O₅ ha⁻¹). Maize (H516) was used as the test crop. The experiment was laid out in a randomized complete block design with eight treatments replicated ten times in farmer's fields. Key variables measured were soil chemical properties, plant growth parameters; height, chlorophyll content, grain yield and economic data. Data generated was subjected to analysis of variance and means using least significant differences of means (LSD at $p \leq 0.05$). The results showed that sole lime (2 t ha⁻¹) significantly ($p=0.0001$) increased soil pH by 17.7%. Reduction in soil exchangeable acidity was clearly seen in treatments lime and manure; Lime and fertilizer had the highest change of 27.8% and 30.6% in 2016 short rains and 2017 long rains respectively. Application of combined lime, manure and P fertilizer had the highest increase in soil available P (+22.5) and plant height (296.13 cm). The study observed high maize yield of 5 t ha⁻¹ with application of combined lime, manure and P fertilizer obtained at the end of the second season. Lime and fertilizer had the highest net benefit of 128.75 USD/ha in the 2017LR followed by sole fertilizer with 105.94 USD/ha. Treatments that had high grain yields did not have high net benefit. There is need to consider economic returns when selecting agricultural production technologies. Use of lime plus fertilizer could therefore, be recommended to smallholder farmers of Tharaka Nithi County, Kenya.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Globally, soil acidity is a key problem contributing towards reduced agricultural productivity (Van, 2007) hence threatening food security in Africa. About 4 billion hectares face the effects of acidity, representing a total area of approximately 30% of the land worldwide (Sumner and Noble, 2003). Most of these soils with high acidity are mainly found in Asia, North and South America, and Africa, attributed to extensive leaching and weathering (Kisinyo *et al.*, 2014). In Sub-Saharan Africa (SSA), acidic soils occupy 29% of the total area, which is associated with reduced fertility levels (Muindi *et al.*, 2016). Acidic soils in Kenya occupy approximately 13% of the agricultural area which is estimated to be 7.5 million hectares of land (Kanyanjua *et al.*, 2002). Over 5 million small-scale farmers in the central and western part of Kenya grow maize, legumes, tea, and coffee in over million ha covered by acidic soils (Gudu *et al.*, 2007).

Soil acidity is the most significant cause of low yield for many of crops (Mugai, 2004). It limits soil productivity, crop development and growth, as well as yield in highly weathered soils due to deficiency of essential crop nutrient elements (Akinrinade *et al.*, 2006). The most important being loss of essential crop nutrients through leaching (Ca Mg and K) with replacement by Al, H and Mn ions that contribute to acidification of soils (Okalebo *et al.*, 2009).

There is minimal and reduced crop productivity on such acidic soils, mostly where the application of acid-forming fertilizers like di-ammonium phosphate (DAP) are used continuously over the years (Nekesa, 2007). Low crop production as a result of multi-nutrient deficiencies has made it mandatory to use mineral fertilizer in order to increase crop yield. Nevertheless, mineral fertilizers are costly, inadequate and their continued use without liming may result to soil acidity problems (OgUIke *et al.*, 2006).

The soil acidity problem can be resolved by application of lime (Kanyanjua *et al.*, 2002) an important practice because of reducing exchangeable acidity and increasing pH. However, lime use by farmers in Kenya is minimal. Only 10% of the farmers in Embu and Siaya; and 5% of farmers in Nyeri and Eldoret use lime (Muindi *et al.*, 2016). Low use of lime is perhaps due to lack of awareness on the benefits of liming, unavailability in the market and high liming materials costs (Kanyanjua *et al.*, 2002; Okalebo *et al.*, 2009).

It is necessary to adopt integrated soil fertility management (ISFM), that involves combined use of organic and inorganic fertilizers, with the use of lime that can be beneficial to improve soil fertility, soil organic matter maintenance and high crop yield by farmers as reported in field trials (Okalebo *et al.*, 2009). Farmers mostly compare costs and returns associated with an appropriate integrated soil fertility management (ISFM), and if the returns outweigh the costs, they will opt to use it. Thus, profitability is the key factor that most smallholder farmers have to consider when making production decisions (Mucheru-Muna *et al.*, 2014) on use of lime, organic and inorganic fertilizers.

1.2 Problem Statement and Justification

Soil acidity results in low crop yield (Muindi *et al.*, 2016) because of poor soil fertility. The smallholder farmers in Tharaka-Nithi County rely on maize as their staple food. The farmers have small holdings with an average of 1.2 ha, which is subjected to intensive continuous cultivation hence lack of adequate soil nutrients replenishment (Mugwe *et al.*, 2009). The productivity is declining and is estimated at 0.5-1.5 t ha⁻¹ annually (Mugwe *et al.*, 2009). Lime use has been recommended as a way of addressing soil acidity problems. However, in the Kenyan Central highlands, there is limited use of lime and awareness on its effectiveness among smallholder farmers (Muindi *et al.*, 2016). Moreover, organic and inorganic fertilizer use has been recommended to address soil acidity and nutrient depletion (Mucheru-Muna *et al.*, 2014). However, inorganic fertilizer use in the area is constrained by high costs that the smallholder farmer cannot afford and there is limited use of locally available manure. These technologies that combine lime, organic and inorganic fertilizers are better options in increasing fertilizer use efficiency, balance the supply of nutrients and other agro-ecological benefits (Mucheru-Muna *et al.*, 2014). On the other hand, adoption of any technology depends on financial benefits, particularly when additional labour is applied as farmers take up certain technology when assured of benefits in investments. It is therefore, important to account for economic gains to the introduction of new soil techniques. There is need to understand the effect of applying lime, manure, solely or combined with inorganic fertilizer on soil chemical properties, maize yields, and profitability on-farm conditions.

1.3 Research Questions

The study sought to address the following questions:

- i. How does agricultural lime, manure, and inorganic fertilizer affect soil chemical properties in Tharaka-Nithi County?
- ii. How does agricultural lime, manure and inorganic fertilizer influence maize yield in Tharaka-Nithi County?
- iii. How does the use of agricultural lime, manure, and inorganic fertilizer influence maize profitability in smallholder farmers in Tharaka-Nithi County?

1.4 Research Objectives

The general purpose of the study was to promote soil productivity in acidic soils thus improving food security. The study sought to address the following specific objectives:

- i. To determine the effect of agricultural lime, manure, and inorganic fertilizer on soil chemical properties in Tharaka-Nithi County.
- ii. To evaluate the effect of agricultural lime, manure and inorganic fertilizer on maize growth and yield in Tharaka-Nithi County.
- iii. To assess the profitability of agricultural lime, manure and inorganic fertilizer in production of maize in Tharaka-Nithi County.

1.5 Research Hypotheses

The study was guided by the following hypotheses:

- i. Integrated use of agricultural lime, manure, and inorganic fertilizers significantly improve soil chemical properties.

- ii. Application of agricultural lime, manure, and inorganic fertilizers significantly improve maize yield.
- iii. Integrated use of agricultural lime, manure, and inorganic fertilizers significantly increase the profits in maize production among smallholder farmers.

1.6 Significance of the Study

The findings from this study will contribute to scientific knowledge on how lime, manure and fertilizer affect soil properties, maize yield and profitability in the central highlands of Kenya. This would be helpful to smallholder farmers who have small sizes of land and have difficulties in managing acidic soils. Such information will also enable the extension service providers to advise farmers on the most appropriate integrated soil fertility management to increase yield.

1.7 Conceptual Framework

Leaching of elements such as (Ca, Mg, and K) is known to affect the soil acidity (Kisinyo *et al.*, 2012). Also, acidity is affected by, the continuous cropping and application of N fertilizers that contain ammonia and atmospheric pollution that result to acidic rain thus accelerating acidification in the soil (Mullen *et al.*, 2006). Degraded soils and poor management of farmers lead to widespread soil infertility that lowers crop productivity and economic returns. Adoption of soil management practices involving the use of lime and inorganic fertilizer increase extractable P and soil pH (Kisinyo *et al.*, 2012). Organic manure can be used to restore soil fertility by increasing soil organic matter, supplying plant nutrients and improving the soil properties. The combination of manure and fertilizers significantly increases soil

chemical properties (Antil and Singh, 2007) thus increasing crop yields, hence influencing the use of Integrated Soil fertility management, improve nutrition and increase investment returns in the society (Figure 1.1).

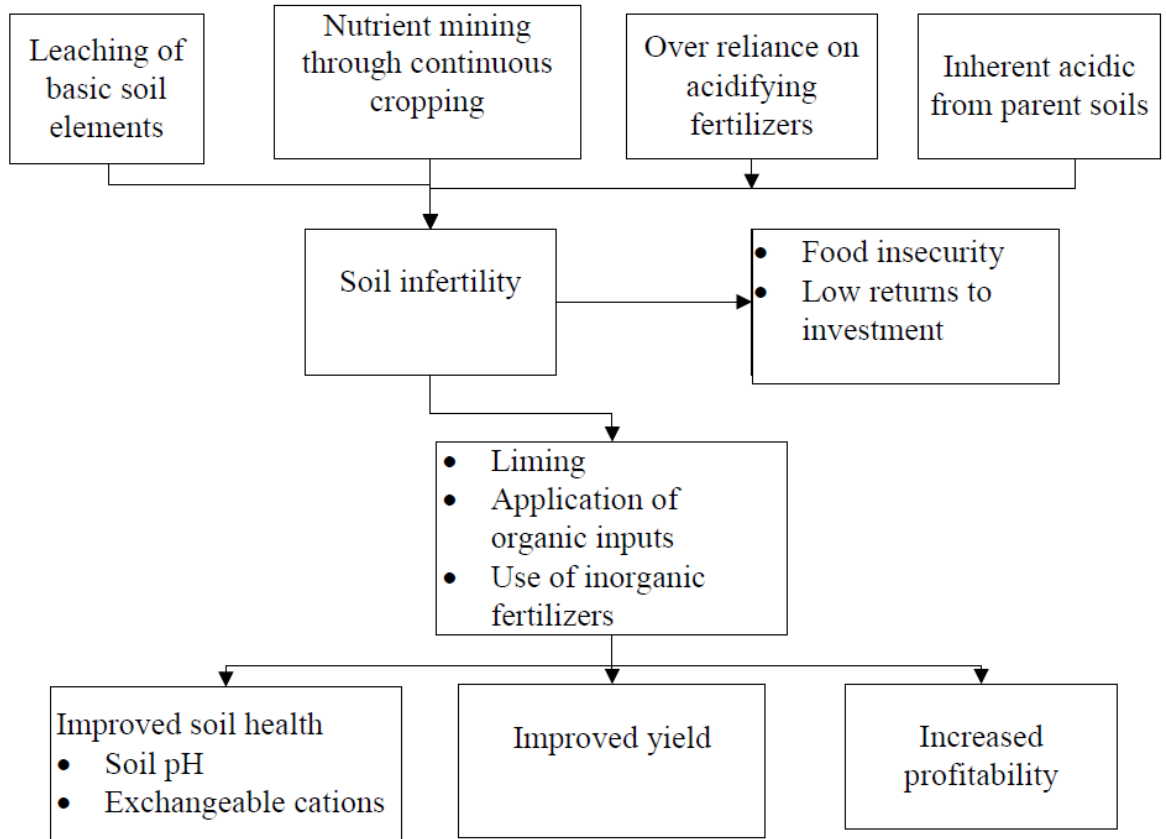


Figure 1.1: Conceptual framework of the study

1.8 Definition of terms

Integrated soil fertility management (ISFM): is an approach that have viable agricultural practices options that are sufficient for sustainable production in agriculture that is adapted to local conditions to utilize efficiency water use and supply of nutrients as well as improved agricultural productivity.

Lime: refers to calcium or calcium-magnesium containing compounds capable of reducing harmful effects of an acid soil by neutralizing soil acidity and raising the soil pH

Smallholder farmers: Farmer with small land parcels of 3 acres or less whose primary occupation is farming as a source of livelihood.

Soil acidity: refers to concentration of hydrogen cations in a solution

Soil Amendment: These are soil additives meant to improve soil quality during the trials period. They include lime, manure and P fertilizer.

Soil pH: refers to the negative logarithm (base 10) of the activity of hydrogen ions in a solution.

Soil quality: The soil capacity to function within natural or managed ecosystem boundaries with capacity to sustain plant and animal life; while enhancing water and air quality to support both human and animal health and habitation.

CHAPTER TWO

LITERATURE REVIEW

2.1 General overview

Soil acidity has been reported as the main limitation to crop growth in the tropical region (Busari *et al.*, 2008). The tropical land that was one time productive has been reported to be infertile due to consistent farming and erosion causing physical soil destruction, low organic matter and a decline in cation exchange capacity (CEC) as well as increased manganese (Mn) and aluminium (Al) toxicity (Kafle and Sharma, 2015). Other than Al and Mn toxicity, deficiencies of calcium, magnesium, and phosphorus in the soils are also considered as other significant constraints that limit plant growth on acidic soils (Liao *et al.*, 2006).

The agricultural sector is constrained by low available soil nitrogen and available phosphorus due to high soil acidity that results in low crop yield in both commercial and small-scale farms (Sanchez and Jama, 2002; Kisinyo, 2012). In Kenyan highlands, most of the improved maize germplasm and land used by farmers are responsive to the high exchangeable Al ($>2 \text{ cmol kg}^{-1}$) and high ($>20\%$) Al saturation commonly encountered in many acidic soils (Kifuko *et al.*, 2007).

2.2 Soil pH and acidity

The soil pH varies with amount of H^+ . The more the high H^+ in the soil solution, the higher the acidity while less H^+ influences the soil to be alkaline and when moderate the soil is said to be neutral. The pH less than 7 indicates the degree of soil acidity and greater than 7 indicates the increase in the soil alkalinity level (Tan, 2010). The soil

with pH less than 4.4 are considered exceedingly acidic, 4.5 to 5.5 strongly acidic, 5.5 to 6.0 are moderately pH, and 6.1 to 6.5 are considered slightly acidic (Kanyanjua *et al.*, 2002). Table 2.1 shows the classification of soils based on the soil pH.

Table 2.1: Classification of soils based on the soil pH

Degree of Acidity/Alkalinity	Soil pH Range
Extremely acidic	< 4.4
Very strongly acidic	4.5-5.0
Strongly acidic	5.1-5.5
Moderately acidic	5.6-6.0
Slightly acidic	6.1-6.5
Neutral	6.6-7.3
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9

Source: USDA (1999)

Soil pH is an important soil chemical property that indicates the quality of the soil. It is important to understand the soil pH to ensure proper soil management and optimal crop productivity. Tentatively, soil acidity is quantified on the basis of aluminium (Al^{3+}) and hydrogen (H^+) concentrations of soils (Fageria and Baligar, 2008). Soil acidity involves the amount of H^+ in the soil solution and occurs when there is a build up of acid-forming elements in the soil. Soil acidity is related to high aluminium (Al), hydrogen (H), manganese (Mn) and iron (Fe) toxicities in plant roots (Fageria *et al.*, 2008). Also is related to deficiencies of plant available including K, P, and (Ca) among others (Wood, 1993). Low soil pH has a high amount of Fe and Al oxides with corresponding deficiency of Phosphorus in the soil solution (Kanyanjua *et al.*, 2002) which negatively affect soil fertility and productivity (Muindi *et al.*, 2016). The decrease in the pH level of the soil is associated with a decline in the availability of plant nutrients such as phosphorus, potassium, and nitrogen. In highly acidic soils,

phosphorus is particularly sensitive and becomes a limiting nutrient to the soil (Harun *et al.*, 2005). Also decline in the soil pH stimulate presence of phytotoxicity substances, e.g. Mn and Al resulting in acidic soil infertility thus limiting crop production (Proietti *et al.*, 2015).

2.3 Causes of soil acidity

Soil acidity maybe as a result of the natural process caused by acidic parent materials, the decay of organic matter and leaching by rainfall (Havlin *et al.*, 2005) making soils to be inherently acidic especially in areas with high rainfall (McCauley *et al.*, 2009). The differences in parent material chemical composition, soils becomes more acidic within a prolonged period of time (Rowell, 2014). Thus, soils developed from limestone or calcareous rocks are less acidic than those developed from granite material. Organic matter decay produces H^+ that is responsible for acidity in the soil, though it forms a weak acid the effects in the soils accumulate over many years (Thapa, 2015). On the other hand, excessive rainfall causes soils to become acidic over a long time through continuous removal of basic cations in the soils (Reuss and Johnson, 2012).

The production of the acid in the soils, known as acidification, is a slow process though it can be accelerated by agricultural activities such as use of inappropriate nitrogenous fertilizer, leaching of nitrogen in lower plant root zone and growing of high yielding crops (Fageria and Baligar, 2008). Acidification through application of nitrogenous fertilisers varies with the type of fertilizer. Most acidifying fertilisers being diammonium phosphate and ammonium sulfate with less acidifying being

ammonium nitrate, urea and anhydrous ammonia (Khan *et al.*, 2018). The superphosphate fertiliser has no effect on soil pH, however, its application stimulates legumes that fix atmospheric nitrogen. This leads to increase in the amount of nitrate nitrogen hence leaching in the soil below plant root zone causing soil acidification. The high yielding crops such as wheat and maize tend to draw cations (lime-like elements) from the soil hence causing soil acidity to develop much faster than other crops (Nwite *et al.*, 2016). The soils become more acidic thus plants that are intolerant to the acidic conditions cannot thrive well hence result to productivity decline.

Attempt to adjust the soil acidity is important to neutralize the toxicities caused by solubility of aluminium and manganese in the soil and most importantly to replace the lost plant nutrients cations, particularly magnesium and calcium (Fageria and Baligar, 2008). Liming of the soil is the most easy and economical way to manage the adverse effect of toxic elements in the soil. Through liming, soil pH is raised hence causing aluminium and manganese to be held in insoluble form with other elements hence does not harm to plants (Fageria and Baligar, 2008). The toxic elements are problem in acidic soils since they are more soluble at low pH.

2.4 Effects of lime, manure and NPK fertilizer on soil chemical properties

There are several means that can be adopted to enable crop production in acidic soils. These include; liming, application of manure and mineral fertilizer (Onwonga *et al.*, 2010) that may result to improvement of soil physical and chemical properties. Soil pH, exchangeable bases (K, Mg, Ca, Na) and exchangeable acidity (Al, H) and Na) are the soil chemical properties that affects nutrients availability to crop and thus have

possibility to decrease or increase crop yields (Masulili *et al.*, 2010). Amendments of soil through application of lime, fertilizer or manure sole or combined may lead to improvement of soil conditions thus forming favourable conditions that enhances crop development, growth and yield (Fageria *et al.*, 2010).

2.4.1 Effect of lime on soil chemical properties

Liming lowers acidity of soils and improves soil fertility of acid soils (Caires *et al.*, 2008; Brown *et al.*, 2008). Lime is comprised of carbonates, oxides or hydroxides which can be added in form of calcium carbonate, calcium oxide, calcium hydroxide and granulated lime (Mayfield *et al.*, 2004). When CaCO_3 is added to a moist soil, the following reactions occur:

I. Soil moisture dissolves lime to produce calcium ions (Ca^{2+}) and hydroxide (OH^-): **$\text{CaCO}_3 + \text{H}_2\text{O}$ in soil $\rightarrow \text{Ca}^{2+} + 2\text{OH}^- + \text{CO}_2$ gas** Equation [1]

II. Al^{3+} and H^+ exchanges with the newly Ca^{2+} produced on acid soils surface:

OH^- produced by Lime reacts with Al^{3+} to form solid $\text{Al}(\text{OH})_3$, or H^+ react with OH^- to form H_2O :

$\text{OH}^- + \text{H}^+ \rightarrow \text{H}_2\text{O}$ Equation [2]

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

Thus, liming through the reactions with OH^- eradicates toxic H^+ and Al^{3+} . The soil pH will then be raised by the excess OH^- from lime. This is the most recognizable liming effect (Brown *et al.*, 2008). Other advantage of liming is the addition of Ca^{2+} supply in the soil and Mg^{2+} incase dolomite [$\text{Ca, Mg}(\text{CO}_3)_2$] is used. Philip and Martin, (2003) mentioned that lime supplies Ca^{2+} and Mg^{2+} , which are important nutrients for the

plants. Magnesium is fundamental to formation of plant chlorophyll and aids in phosphorus uptake while calcium is importantly essential for numerous structural roles in the cell membrane and cell wall formation. Ca^{2+} is also a counter-cation for organic and inorganic anions in the vacuole. The cytosolic Ca^{2+} concentration ($[\text{Ca}^{2+}]_{\text{cyt}}$) helps in response coordination to various developmental signals or even on environmental challenges, as an obligate intracellular messenger (Philip and Martin, 2003). Calcium and Magnesium are often underprovided in vastly weathered acidic soils (Uchida and Hue, 2000).

Liming increases P availability, soil pH, and reduces aluminium concentration in acidic soils (Fageria and Stone, 2004) and improves plant growth as a result of increased soil pH and reduced phytotoxic levels of Al (Fageria and Baligar, 2008). There is a natural deficiency in available and total P in acidic soils due to immobilized portions of applied P as a result of precipitation of P in an insoluble Al phosphate to Al oxide (Nurlaeny *et al.*, 1996). Liming results into a release of P for uptake by plant an effect referred to as “P spring effect” of lime (Bolan and Hedley, 2003). Fageria and Baligar (2004) reported improved efficiency of P, and micronutrients in upland rice genotypes through use of lime in acidic soils. The study showed that efficiency of these nutrients was higher under soil pH of 6.4 than in pH 4.5. At low pH, liming the soil precipitates Al and Fe as $\text{Al}(\text{OH})_3$ and $\text{Fe}(\text{OH})_3$ hence increase plant P availability (Brown *et al.*, 2008). The precipitation of Al^{3+} and H^+ by the lime causes an increase in pH and plant nutrients availability in the soil (Onwonga *et al.*, 2008). Similar findings of reduced possibility of Al^{3+} , Mn^{2+} , Fe^{3+} as well as Cu^{2+} and Zn^{2+} toxicity are reported (Douglas and Linginfelter, 1995; Bolan *et al.*, 2003). Over liming brings

a new set of effect as it causes deficiency and cation imbalances (Robert and Burgholzer, 1998). In other cases, over liming soils to pH 6.8-7.0 reduces P availability in the soil due to the precipitation of Ca or Mg phosphates (Isherwood, 2003).

Appropriate rate of lime application brings several biological and chemical changes in the soils, that are important in crop yield improvement on acid soils (Fageria and Beligar, 2008). Kaitibie *et al.* (2002) noted that liming is a long-term method widely used for amelioration of soil acidity, and its performance is well documented (Scott *et al.*, 2001).

2.4.2 Effect of manure on soil chemical properties

The continued rise in fertilizer prices, has led to great drive to either substitute or supplement mineral fertilizers with cheaper and renewable sources of soil nutrients like organic manures (Sanginga and Woomer, 2009). Ability of manure to improve soil chemical and physical properties is known, and in terms of the soil supplying nutrients in a form that is readily available to plants (Tejada *et al.*, 2006).

Manure is considered as an ameliorating material that is relative cheap and is used for acidic soils management (Haynes and Mokolobate, 2001). Calcium and magnesium in the manure tends to reduce the pH due to capacity by forming complexes with Al and Fe in acidic soils hence manure has been found to increase the soil's ability to hold and also resist the natural tendency of soils to become acidic (Harun *et al.*, 2015). Addition of farmyard, composts, green manures and manure to the acid soils has been

reported to reduce Al toxicity (Wong and Swift, 2003; Tejada *et al.*, 2006; Tang *et al.*, 2007). Hailin (1998) found that soil pH was higher by 0.5 units to a depth of 30 cm under soils with manure than in soils without manure. Increase in soil pH has been attributed to phenolic, humic-like material present in manure that cause proton exchange between the soil and manure (Tang *et al.*, 2007). Another mechanism proposed to reduce soil acidity by manure is the adsorption of humic material and/or organic acids (from decomposition) onto hydrous surfaces of Al and Fe oxides through the exchange with subsequent discharge of OH⁻ (Hue *et al.*, 1986).

Manure can be utilized as a source of fertilizer for enhancement of yield in the central highlands of Kenya (Mucheru-Muna *et al.*, 2007; Mugwe *et al.*, 2007; Mugwe *et al.*, 2009; Mucheru-Muna *et al.*, 2014). Use of organic amendments in form of livestock manures and crop residues has been reported to increase availability of P through stimulating microorganisms that solubilize soil P and improve soil moisture conditions (Fankem *et al.*, 2008). Other benefits of manure varies from soil structure maintenance and carbon sequestration (Palm *et al.*, 2000; Craswell and Lefroy, 2001; Merckx *et al.*, 2001). Microbial activity is needed for manures to decompose in order to release nutrients, this is slow but has positive results.

2.4.3 Effect of mineral fertilizers on soil chemical properties

The inorganic fertilizers use is essential in alleviating nutrient constraints as an Integrated Soil Fertility Management (ISFM) practices for improved soil productivity (Sanginga and Woomer, 2009). High concentration of nutrients in mineral fertilizers supply the readily available nutrients that are readily available for uptake by plant

(McCauley *et al.*, 2009). Farmers are aware that lack of application of inorganic fertilizers reduces crop productivity due rapid decline in soil nutrient levels (Blackwell *et al.*, 2009).

The annual loss of soil nutrients in Kenya is at an average of 3 kg P, 42 kg N and 29 kg K per ha (Smaling, 1997). Application of inorganic fertilizer is one way that address this situation as it increases nutrient availability in the soil solution hence enhancing their availability for easy supply to the soil for plant uptake (Mugwe *et al.*, 2007). The issue of mineral fertilizer application is controlled by the elevated cost that the less privileged farmers cannot afford (Eakin, 2000). Generally, mineral fertilizer is necessary, as they are used to supplement the natural soil nutrient supply, compensate for the lost nutrients by removal of plant products, gaseous loss or through leaching to satisfy the demand of crops with high yield and economically viable yields (Mucheru-Muna *et al.*, 2014). Application of P fertilizer was reported to have a significant positive effects on available P and soil pH in acid soil of Western Kenya (Kisinyo *et al.*, 2012).

2.5 Effects of manure, lime and phosphorus fertilizer on yield

Use of inorganic and organic fertilizers has been reported to be a solution to increase crop yields through restoring and maintaining soil fertility (Danga *et al.*, 2010; Sharief *et al.*, 2010). A study in India by Maheshbabu *et al.* (2008) indicated that mineral fertilizer and FYM combination significantly increased soybean growth parameters and grain yield. Similarly, Anetor and Akinrinde (2006) in a study with soybeans in Nigeria reported that combination of organic fertilizer and lime significantly affected

the number of pod weight and number. Nekesa *et al.* (2011) in western Kenya also found that combination of lime and fertilizer (DAP and TSP) led to significant increases in soybean yield.

Liming is an essential method of increasing yields of crops grown on acid soils. The best practice is one that combines lime, organic manure and inorganic fertilizers (Mukuralinda, 2007). This has been observed to be the most appropriate technique of addressing the problem of soil acidity and enhancing soil fertility in Rwanda (Ruganzu, 2009). Significant yield increases have been observed in areas where the organic and inorganic nutrient sources have been applied together with lime, particularly in the research stations (Nabahungu, 2003).

In other studies, high maize grain yield was obtained when mineral fertilizer and manure were applied together (Mugendi *et al.*, 1999; Mucheru-Muna *et al.*, 2007). Jagadeeswaran *et al.* (2005) and Tittonell *et al.* (2007) reported that the organic fertilizers most accessible to farmers have low nutrient concentrations with inadequate potential to improve crop yields when applied as the sole source of nutrients. However, a combination of both inorganic and organic fertilizer may significantly show to be more effective than the sole application (Vanlauwe *et al.*, 2001).

Additionally, inorganic fertilizers have readily availability nutrient though pricey and leacheable from the soil surface (McCauley *et al.*, 2009). Application of combined inorganic and organic fertilizers is an effective solution to maintain and restore soil fertility and boost crop yields (Sharief *et al.*, 2010; Danga *et al.*, 2010). Obiri-Nyarko

(2012), reported reduced soil acidity menace through combination of organic manure and lime.

2.6 Yield and profitability on combined use of lime, manure, and inorganic fertilizer

Profitability is the major incentive to adopt organic and inorganic fertilizer and a key factor that determine their patterns use (Ragasa and Chapoto, 2017). The adoption and sustainable effect of organic and inorganic inputs depend on the degree to which their use is profitable. According to Snapp *et al.* (2003) fertilizer application increased crop yield of farmers had extra yield by 105% and profit of 21–42% compared to non-adopters in Malawi.

Continuous rise in fertilizer prices has the great force to either complement the mineral fertilizer with locally and cheaper sources of nutrients e.g. use of organic manure that is considered to be a cheaper and beneficial source of plant nutrients that enhances soil fertility management (Sanginga and Woomer, 2009). Bhatta and Doppler (2016) reported that profitability aspects have showed high potential in manure and inorganic fertilizer to give higher returns in contrast to conventional farmers' practices. Adiel (2004) reported value cost return of 3.3 for manure plus mineral fertilizer, 3.2 for sole mineral fertilizers and 2.4 for farmers' practice of no inputs. According to Mucheru-Muna *et al.* (2014), treatments applied with organic matter caused high yields in maize, in comparison to the treatments with fertilizer only, indicating the importance of organics in improvement of yields. However, fertilizer and lime application gave

the highest economic returns as compared with the sole or separate application (Manpreet and Dixit, 2017).

2.7 Gaps identified in literature

Based on the previous studies, lime has the potential to ameliorate soil acidity problems but cannot be used as a fertilizer since it is not affordable to most farmers. However, organic inputs which are locally available to the smallholder farmers have also a similar potential of reducing soil acidity conditions. Some studies have focused on usage of inorganic and organic fertilizers on soil properties and yields but failed to focus on combining these agricultural inputs with lime (Mugwe *et al.*, 2007; Sharief *et al.*, 2010; Kafle and Sharma, 2015). However, economic analysis of these technologies to the smallholder farmers is scanty. Therefore, economic analysis integration gives a clearer understanding in assessment of ISFM technologies from farmers perspectives and therefore, has an impact in widespread adoption and viability of these technologies. Therefore, this study, was designed to assess the effects of lime, manure and fertilizer on soil chemical properties, maize grain yield as well as profitability to the smallholder farmers.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

The study was carried out in Kirege, Meru South sub-county in Tharaka-Nithi County, Kenya (Figure 3.1). The area is located in the Upper Midland Zones two and three (UM2–UM3) Agro-ecological zones (AEZ), (Jaetzold *et al.*, 2007), and lies at an altitude of approximately 1,500 m above sea level and receives an annual rainfall of 1,200 -1,400 mm(Jaetzold *et al.*, 2007). The rainfall is bimodal, falling in two seasons with the long rains (LR) lasting from March to May and short rains (SR) from October to December. The mean temperature is 20⁰C per annum. The soils are Humic Nitisols which are well weathered and deep with moderate to high inherent fertility (Jaetzold *et al.*, 2007).

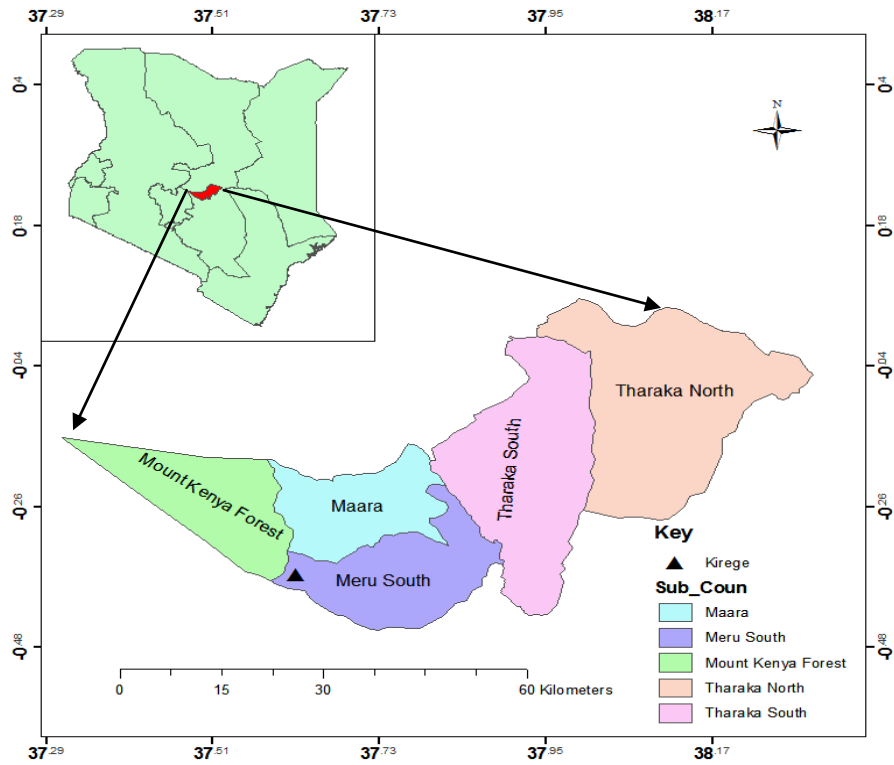


Figure 3.1: A map of the study area showing location of trial sites

The initial soil status analyzed before the commencement of the experiments showed that the soil was very acidic. The soil pH before application of treatments was averaged at 4.64 which is very acidic (Table 3.1). The available soil P was low. The exchangeable cations (K, Na and Ca) were adequate (0.42%, 0.27% and 3.25%, respectively) while Mg was deficient (0.52%).

Table 3.1: Initial soil chemical characteristics at 0-20 cm before planting (September 2016) at Kirege.

Soil Chemical Properties	Baseline Value
Soil pH	4.64
Exchangeable acidity (cmol kg ⁻¹)	0.39
Total organic carbon (%)	1.80
Total nitrogen (%)	0.17
Phosphorus (ppm)	11.56
Potassium (cmol kg ⁻¹)	0.42
Calcium (cmol kg ⁻¹)	3.25
Magnesium (cmol kg ⁻¹)	0.92
Manganese (cmol kg ⁻¹)	0.52
Copper ppm	5.81
Iron ppm	31.27
Zinc (ppm)	7.20
Sodium (cmol kg ⁻¹)	0.27

The manure used was analyzed for pH, total N, available P and exchangeable cations (Ca, Mg, K, Al³⁺ and H⁺) following the procedures as outlined by Okalebo *et al.* (2009). Table 3.2 shows the characteristics of manure used in the experiment.

Table 3.2: Average nutrient composition (%) of Manure applied in the soil during the Experimental period at Kirege, Tharaka- Nithi County, Kenya

Manure Properties	Value
Total Nitrogen (%)	2.10
Phosphorus (ppm)	0.16
Potassium (cmol kg ⁻¹)	0.64
Calcium (cmol kg ⁻¹)	0.70
Magnesium (cmol kg ⁻¹)	0.33
Manganese (cmol kg ⁻¹)	228
Copper (ppm)	38.7
Iron (ppm)	141
Zinc (ppm)	32.5

3.2 Experimental Design

The experiment was laid out in a randomized complete block design (RCBD) with eight treatments replicated in ten farms. The farmers' fields were selected based on soil pH, size of the land, terrain and tree cover. The experiments were conducted during the short rains season lasting from October to December 2016 and long rains season from March to May 2017. The plots were 4.5 m by 4 m and were demarcated after ploughing maintaining a guard row of 1 m from one plot to another. Maize hybrid H516 was used as the test crop. The treatments comprised application of agricultural lime (calcium carbonate), manure and mineral fertilizer (Table 3.3).

Table 3.3: Treatments at Kirege site on ten farms during the 2016SR and 2017LR

Treatment	Input application rates		
	Lime	Manure	Inorganic (NPK)
Control		No Inputs	
Lime	2 t ha ⁻¹	-	-
Manure	-	10 t ha ⁻¹	
Inorganic Fertilizer	-	-	60 Kg ha ⁻¹
Lime + manure	2 t ha ⁻¹	10 t ha ⁻¹	-
Manure + inorganic fertilizer	-	5 t ha ⁻¹	30 Kg ha ⁻¹
Lime + inorganic fertilizer	2 t ha ⁻¹	-	60 Kg ha ⁻¹
Lime + inorganic fertilizer + manure	2 t ha ⁻¹	5 t ha ⁻¹	60 Kg ha ⁻¹

During land preparation, lime and goat manure were broadcasted and incorporated into the soil thoroughly using a hoe four weeks before planting. The inter-row and intra-row spacing was 75 cm and 50 cm, respectively. Three seeds were sown per hole and then thinning done two weeks after germination leaving two plants per hole. During planting NPK (23:23:0) fertilizer was applied at the recommended rate (60 kg N ha⁻¹). These fertilizers were then mixed with soil thoroughly to avoid direct contact with the seeds. The first weeding was done four weeks after planting and then second one at two weeks after the first weeding. Bulldock pesticide spray was used which was done two months after planting to prevent pests and diseases.

3.3 Soil Sampling

Soil samples were obtained from all plots using an Edelman auger at a depth of 0-20 cm. The initial sampling was done before setting up the experiment (July 2016). Sampling was also done after the harvest of the first season (Short rains period-January 2017) and then after the end of the experiment (Long rains period-July 2017). The samples were taken randomly at five different points using the zigzag method (Santos *et al.*, 2017) and then mixed thoroughly to a composite sample. The composite

samples were labelled, packed and taken to laboratory for chemical analyses during all the sampling intervals.

3.3.1 Laboratory Analysis

The samples collected were analyzed for soil pH, available P, base saturation (Ca^{2+} , Mg^{2+} , K^+ and Na^+) soil organic C and total N.

3.3.1.1 Soil pH

The soil pH was measured in a ratio of 1:2 soil:water ratio (Ryan *et al.*, 2011) where the ratio was attained by mixing 20 ml of distilled water with 10g of soil in a 100 ml beaker, followed by measuring the pH after 30 minutes of shaking and waiting for it to settle using a pH meter.

3.3.1.2 Exchangeable bases (K, Na, Ca and Mg) and extractable P

Exchangeable bases and soil extractable P were extracted using Mehlich 1 method (Mehlich, 1953). Approximately 5 g of air-dried soil, ground and passed through 2 mm sieve was weighed then extracted using 25 ml of mixed 0.025M H_2SO_4 and 0.1M HCl solution., using an automatic shaker, the suspension was shaken for 1 hour then put in a centrifuge and filtered using filter paper.

A spectrophotometer was used to determine extractable P (430 nm wavelength) after addition of 1ml of ammonium vanadate and ammonium molybdate mixture to 5 ml of the extraction for development of color, after resting it for 1 hour. Flame photometry was used to determine sodium (Na), calcium (Ca) and potassium (K) were determined. Absorption spectrophotometry (540 nm wavelength) was used to determine magnesium (Mg).

3.3.1.3 Total organic carbon

Soil organic C was determined using the Walkley-Black method calorimetrically by H₂SO₄ dichromate oxidation (Van Lagen, 1996). Approximately soil weighing 1.00 g was weighed into a erlenmeyer flask (500 ml), 10 ml of 1N potassium dichromate solution and 20 ml sulfuric acid was added and mixed by gentle rotation for one minute, with care avoiding throwing soil to the flask sides. The mixture was then let to stand for 30 minutes. Deionized water was used to dilute to 200 ml then phosphoric acid (10 ml), 0.2 g ammonium fluoride, and then 10 drops of diphenylamine indicator was added. Ferrous ammonium sulfate solutions (0.5 N) was titrated till the change of color from dull green to turbid blue. Addition of drop by drop of titrating solution until the end point was reached when the color shifted to a brilliant green. Preparation of a blank solution was made and titrated in the same manner.

3.3.1.4 Total nitrogen: Kjeldahl method

The total N was determined using Kjeldahl oxidation method (Ryan *et al.*, 2011) through digestion with a concentrated sulphuric acid and a mixed catalyst that has potassium sulphate (K₂SO₄), copper sulphate hydrated (CuSO₄) and selenium. Distillation was used to determine Total N, titration followed with diluted standardized 0.007144 N H₂SO₄.

3.3.2 Determination of yield component

All plant data collected from crop emergence to harvest were treated as growth parameters. Growth parameters determined were; chlorophyll content, plant height, stover and grain yield. Grain yield was estimated by adjusting moisture content to 12.5%.

3.3.2.1 Determination of Chlorophyll content

At the 4th, 8th and 12th week from planting time, chlorophyll content was determined using a SPAD meter. The meter (SPAD-502) measures the amount of chlorophyll present in the leaf.

3.3.2.2 Determination of plant height

Maize plant height was measured as an indicator of maize growth during the 4th, 8th and 12th week after planting. Eight plants were randomly selected per plot and tape measure was used to measure the height of the plants. The plants were measured in centimeters from the soil surface of the plant to the longest tip of the leaf.

3.3.3 Profitability

The profitability analysis in the study considered the cost of farm inputs; seeds, fertilizer, pesticides purchased, operations costs and returns from the stover and maize sales (Table 3.4). For each activity, time was taken and recorded using a stop watch where labour was valued at a local wage of Kshs. 200 (USD 2) per day (eight hours).

Table 3.4: Parameters used in the profitability analysis of the selected ISFM technologies

Parameter	Cost (USD)
Price of maize seed (kg ⁻¹)	1.90
Price of TSP fertilizer ((P kg ⁻¹)	0.78
Price of NPK fertilizer (kg ⁻¹)	0.60
Price of CAN fertilizer (kg ⁻¹)	0.50
Labour cost (day ⁻¹)	2.00
Price of maize grains (kg ⁻¹)	0.30
Price of maize stover (t ⁻¹)	30.00

Exchange rate Ksh 100 = 1 USD (official exchange rate at the end of the trial period (July 2017))

On the other hand, the returns during the study period were based on prevailing market price for maize grain (Table 3.4). In the area, the farmers use maize stover as cattle feed and therefore it was valued at a market price thus considered as an additional benefit. Costs of farm inputs (TSP, NPK, Lime, CAN, seeds and insecticides) were based on retail prices as per agro-vet stockists in Embu.

$$\text{Net benefits} = \{Gross\ benefits - Total\ costs\}$$

$$\text{Benefit - Cost Ratio} = \frac{Total\ discounted\ benefits}{Total\ discounted\ costs}$$

$$\text{Return to labour} = \frac{\{(Gross\ benefits - Cost\ of\ inputs)\}}{Cost\ of\ labour}$$

3.4 Rainfall measurement

Daily rainfall measurements were taken by an automatic rain gauge (0.2 mm resolution) installed at Kirege Primary School. Measures were taken to ensure that it was in a level position and clear of overhead structures and free from vibration on the stand it was mounted. HOBO ware Pro Version 3.2.2 was used to read out the data logger that was launched in rain gauge. The data recorded was exported to an excel sheet for further analysis including the tipping count, air temperature and time of tip at an interval of 15 minutes along the two study period. To ensure the continuous proper functioning of the rain gauge, regular check-ups were maintained that involved replacement of the old exhausted batteries to ensure accurate and constant recording throughout the study period.

3.5 Data Analysis

The soil chemical properties, maize yield, benefit-cost ratio and net benefits for the experimental period were subjected to analysis of variance (ANOVA) using SAS 9.3 (SAS Institute Inc., 2003). The means were separated using the Least significant differences (LSD) at $p \leq 0.05$. Pair-wise comparison of the initial and final soil properties parameters were subjected to *t-test*.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Rainfall

The distribution of rainfall during the study period varied between the seasons. Cumulatively, 2017LR received higher rainfall amounts than 2016SR. The total rainfall recorded in 2016SR and 2017LR was 455 mm and 967 mm, respectively (Figure 4.1). There was soil moisture deficit for most of the growing season during 2016 SR, with more than 80% of the rain being received in the first month followed by a prolonged dry season. This adversely affected crop yields.

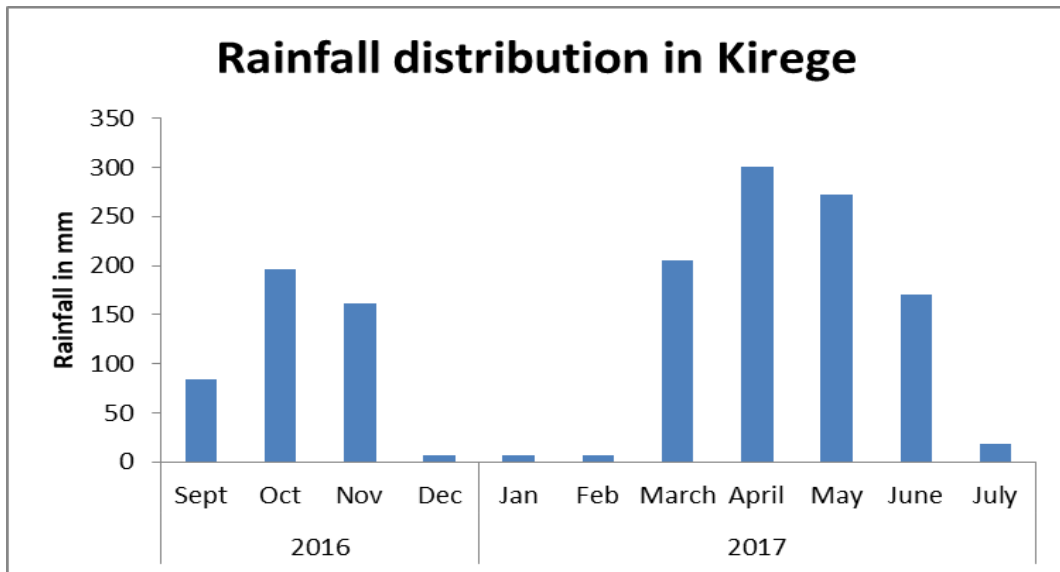


Figure 4.1: Rainfall distribution during 2016 short rains (October to December 2016) and 2017 long rains (March to May 2017) at Kirege, Tharaka Nithi County, Kenya

A meteorological drought was experienced during 2016SR after 45 days, three weeks after planting. The rainfall received was lower than the water required during critical stages of maize production, this signifies a critical limiting factor for maize production

(Omoyo *et al.*, 2015). On the other hand, sufficient and well-distributed rainfall was received in 2017LR. In the 30-day and 45-day periods, rainfall amounts of 300 and 500 mm received, are in line with crop water requirements (FAO, 2001). They indicate rainfall required to prevent water shortage during the reproductive phase (Omoyo *et al.*, 2015). The well-distributed rainfall across the season is often more important than total rainfall, as soil moisture is retained at a desired level for crop growth (Fischer, 2015).

4.2 Effects of lime, manure and phosphorus fertilizer on soil chemical properties

4.2.1 Soil pH and exchangeable acidity

Soil pH values were not significantly different in 2016SR but were observed to be significantly different ($p = 0.0228$) at the end of the experimental period in the 2017LR season (Table 4.1). In both seasons, pH increased significantly in all treatments apart from the control treatment where it decreased. In 2016SR season, lime + manure treatment recorded the highest change in soil pH (+13.02%) while sole lime, recorded the highest change (+17.07%) in the 2017LR season (Table 4.1). This was followed by lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure in both seasons with +12.72% and +15.30%, respectively (Table 4.1). The sole fertilizer application consistently recorded the lowest percentage increase in the 2016SR and 2017LR seasons with a corresponding increase of 5.31% and 5.10%, respectively though not significantly different in the 2017LR season ($p = 0.0515$).

Table 4.1: Changes in soil pH (0-20 cm depth) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatments	Baseline (Sept 2016)	2016SR	% Change	<i>t</i> -test, <i>p</i>	2017LR	% Change	<i>t</i> -test, <i>p</i>
Lime + ½ fertilizer + ½ manure	4.64 ^a	5.23 ^a	12.72	0.0107	5.35 ^a	15.30	0.0015
Lime + fertilizer	4.63 ^a	5.01 ^a	8.21	0.002	5.26 ^a	13.61	0.0004
Fertilizer	4.71 ^a	4.96 ^a	5.31	0.0469	4.95 ^{ab}	5.10	0.0515
½ Manure + ½ fertilizer	4.61 ^a	5.07 ^a	9.98	0.0026	5.13 ^a	11.28	0.0025
Lime + manure	4.61 ^a	5.21 ^a	13.02	0.0004	5.30 ^a	14.97	<.0001
Manure	4.71 ^a	4.98 ^a	5.73	0.003	5.20 ^a	10.40	0.0001
Lime	4.51 ^a	4.99 ^a	10.64	0.009	5.28 ^a	17.07	<.0001
Control	4.70 ^a	4.71 ^a	0.21	0.9207	4.64 ^b	-1.28	0.6158
P-value	0.9887	0.5504			0.0228		
LSD	0.446	0.490			0.421		

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

The treatments with lime plus manure, sole or combined recorded a significant increase in soil pH (Table 4.1). The increase could be attributed to reduction of H⁺ ions concentration in exchangeable sites and in soil solution due to lime and manure application (Kisinyo *et al.*, 2012; Khoi *et al.*, 2010; Kanyanjua *et al.*, 2002). Wong and Swift (2003) reported that organic manures application to acidic soils led to significant increases in soil pH, decrease in Al saturation, leading to improvement of soil properties for plant growth. Haynes and Mokolobate (2001) reported that manure has capacity to consume H⁺ hence the ability to neutralize soil acidity. Kheyrodin and Antoun (2012) and Awodun *et al.* (2007), reported that addition of manure to acidic soils improved soil fertility through addition of nutrients, organic matter and also leads to increase in soil pH and decrease in phytotoxic soluble/exchangeable Al concentrations. Chen *et al.* (2015) reported increase in pH in acidic soil due to manure

application. However, Shrestha (2015), noted that the quality of manure determines its efficiency in increasing soil pH. This may explain why manure had a slower rate in soil pH increase in comparison to lime. Nyambati *et al.* (2003) and Mugwe *et al.* (2009) noted that frequent application of organic manure over the season could improve the pH of moderate acid infertility.

Liming in this study increased the soil pH. This corroborates with the findings of The *et al.* (2001) who reported similar findings with application of 2 t ha⁻¹ of lime. Anetor and Akinrinde (2006) in a study using lime and P fertilizers reported significant improvement in soil pH and attributed this to the effect of lime. Sole or combined application of manure and lime as reported by Repsiene and Skuodiene (2010) significantly increased pH, Ca and Mg and reduced Al concentration. Similarly, Ademba *et al.* (2010) in a study with 250 kg ha⁻¹ of lime, 60 kg P₂O₅ ha⁻¹ and sole 10 t ha⁻¹ of manure reported an increase in pH, Mg, Ca, K, and total P.

Overall, soil exchangeable acidity declined in all the treatments in both seasons except for the control that showed an increase (Table 4.2). In both seasons, the exchangeable acidity did not reduce significantly ($p=0.2669$, $p=0.1647$). The Lime and fertilizer treatment had the highest reduction in exchangeable acidity by 27.8% in 2016 short rain season and 30.6% in 2017 long rain season. The control treatment had a 5.4% increase in exchangeable acidity from the baseline. Sole application of P fertilizer reduced soil exchangeable acidity slightly in the 2017 long rain season (Table 4.2).

Table 4.2: Changes in soil exchangeable acidity (0-20 cm depth) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatments	Exchangeable Acidity (cmol kg ⁻¹ soil)						
	Baseline (Sept 2016)	2016SR	% Change	t-test, p	2017LR	% Change	t-test, p
Lime + ½ fertilizer + ½ manure	0.41 ^a	0.38 ^a	-7.3	0.2789	0.32 ^{ab}	-22.0	0.0294
Lime + fertilizer	0.36 ^a	0.26 ^a	-27.8	<.0001	0.25 ^b	-30.6	<.0001
Fertilizer	0.39 ^a	0.36 ^a	-7.7	0.3938	0.38 ^{ab}	-2.6	0.3434
½ Manure + ½ fertilizer	0.37 ^a	0.27 ^a	-27.0	<.0001	0.26 ^{ab}	-29.7	<.0001
Lime + manure	0.41 ^a	0.32 ^a	-22.0	<.0001	0.31 ^{ab}	-24.4	<.0001
Manure	0.36 ^a	0.28 ^a	-22.2	0.0002	0.27 ^{ab}	-25.0	0.01
Lime	0.42 ^a	0.34 ^a	-19.0	0.0002	0.33 ^{ab}	-21.4	<.0001
Control	0.37 ^a	0.38 ^a	2.7	0.7263	0.39 ^a	5.4	0.3434
P-value	0.9514	0.2669			0.1647		
LSD	0.126	0.122			0.119		

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

Highly acid soils (pH<5) have high concentration of Al³⁺ and H⁺ ions, which negatively affects the availability of basic nutrients for the uptake by crops (Md, 2014). The results showed that treatment with sole lime and manure or combined increased soil pH and reduced exchangeable acidity. The reduction in exchangeable acidity of the soil may be attributed to increase in basic cations (Mg²⁺ and Ca²⁺) (Fageria *et al.*, 2008) and anions (CO₃⁻²) present in lime that enable the exchange H⁺ from exchange sites to form CO₂ + H₂O. This causes rise in soil pH since H⁺ space left behind is occupied by cations on the exchange sites (Fageria *et al.*, 2008).

Application of sole P fertilizer had no significant soil pH increase, nor reduction in soil exchangeable acidity in comparison to the baseline. Kisinyo *et al.* (2005) and Kisinyo *et al.* (2012) reported soil acidification associated to the release of H⁺ ions in

the process of dissolution of P fertilizer. Harter (2007) reported soil acidifying effect from phosphorus-based fertilizer as a result of phosphoric acid, whereby H^+ ions are gradually released to the soil, thus, causing acidifying effect to the surrounding soil band.

4.2.2 Soil exchangeable cations

In 2016SR season, treatments had no significant effect on soil exchangeable cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Mn^{2+}) (Table 4.3). In 2017LR, application of the treatments had a significant effects in all the treatments except for Na ($p = 0.0598$) in both seasons. During the 2017LR the treatments significantly ($p = 0.0117$) increased exchangeable Ca^{2+} values in treatments as follows: lime (58%), manure (33%), lime with manure combined with fertilizer (30%). The sole application of fertilizer significantly ($p=0.0117$) increased soil exchangeable Ca^{2+} with 14% change. In the same period, the control recorded the lowest increase in soil exchangeable Ca^{2+} (-10%) was recorded.

In 2017LR season, treatments application had a significant ($p = 0.0204$) increase in exchangeable Mg^{2+} (Table 4.3). Soil exchangeable Mg^{2+} increase was highest in lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure and lime + manure treatments with +0.30 changes from the baseline. The control had the lowest Mg^{2+} value of 0.76 and 0.36 cmol (+) kg^{-1} in 2016 SR and 2017 long rain, respectively.

Soil available K^+ was comparable in 2016SR ($p = 0.9981$) and 2017LR ($p = 0.1961$). However, in the 2017LR , $\frac{1}{2}$ manure + $\frac{1}{2}$ fertilizer and lime + fertilizer treatments had

the highest changes of +40% and +36%, respectively. The highest numerical values were recorded for lime + fertilizer and ½ manure + ½ fertilizer with 0.57 cmol (+) kg⁻¹ and 0.56 cmol (+) kg⁻¹ soil, respectively. Lowest values were recorded in lime alone (0.42 cmol (+) kg⁻¹ soils) and lime + manure (0.46 cmol (+) kg⁻¹ soils) corresponding to +2% and +11% change, respectively.

In the 2016SR, there was a decline in soil exchangeable Mn²⁺ ($p = 0.7694$). However, in 2017LR there was a significant decrease ($p = 0.0321$) due to treatments application (Table 4.4). The decline of soil exchangeable Mn²⁺ was as the following order of treatments: lime + manure (32%), lime + fertilizer (23%), lime (20%) with application of ½ manure + ½ fertilizer and manure alone having the lowest reduction of the Mn²⁺ cations of 7% and 4%, respectively. Control had 33% change increase in the level of Mn²⁺.

Table 4.3: Changes in Soil exchangeable cations (cmol(+) kg⁻¹ soil) (0-20 cm depth) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatments	Ca ²⁺		Mg ²⁺		K ⁺		Na ⁺		Mn ²⁺	
	16SR	17LR	16SR	17LR	16SR	17LR	16SR	17LR	16SR	17LR
Lime + ½ fertilizer + ½ manure	2.80 ^a	3.64 ^{ab}	0.73 ^b	0.74 ^{bc}	0.45 ^a	0.54 ^{ab}	0.28 ^a	0.37 ^a	0.47 ^a	0.41 ^{ab}
Lime + fertilizer	2.62 ^a	3.26 ^{ab}	0.95 ^{ab}	0.96 ^{ab}	0.42 ^a	0.57 ^a	0.28 ^a	0.37 ^a	0.53 ^a	0.41 ^{ab}
Fertilizer	2.21 ^a	2.51 ^{bc}	0.82 ^{ab}	0.83 ^{abc}	0.41 ^a	0.52 ^{ab}	0.26 ^a	0.35 ^a	0.49 ^a	0.62 ^a
½ Manure + ½ fertilizer	2.55 ^a	3.02 ^{ab}	0.93 ^{ab}	0.94 ^{ab}	0.40 ^a	0.56 ^a	0.28 ^a	0.37 ^a	0.68 ^a	0.63 ^a
Lime + manure	2.37 ^a	3.72 ^a	1.11 ^{ab}	1.12 ^{ab}	0.46 ^a	0.51 ^{ab}	0.25 ^a	0.34 ^a	0.38 ^a	0.26 ^b
Manure	2.42 ^a	3.23 ^{ab}	1.34 ^a	1.35 ^a	0.42 ^a	0.53 ^{ab}	0.26 ^a	0.35 ^a	0.57 ^a	0.55 ^a
Lime	2.20 ^a	3.47 ^{ab}	0.71 ^b	0.72 ^{bc}	0.41 ^a	0.42 ^a	0.26 ^a	0.35 ^a	0.49 ^a	0.39 ^{ab}
Control	2.25 ^a	2.02 ^c	0.76 ^{ab}	0.36 ^c	0.39 ^a	0.29 ^b	0.27 ^a	0.34 ^a	0.54 ^a	0.72 ^a
P-value	0.904	0.012	0.218	0.020	0.998	0.196	0.998	0.059	0.769	0.032
LSD	1.354	1.032	0.518	0.518	0.226	0.226	0.104	0.104	0.330	0.309

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

The plots where manure plus lime was applied recorded significant increase in the soil exchangeable Ca²⁺. The increase of Ca²⁺ ions could be due to the decomposition of manure which released mineral nutrients to the soil. Manure applied had high amount of Ca²⁺ (Table 4.3), and supplied 7.0 g Ca kg⁻¹ to the soil. Liming, on the other hand, provides the basic nutrients to the soil (Ca²⁺ and Mg²⁺) thereby, increases the solubility of Ca²⁺ ions thus increasing their availability to the soil. Elsewhere, a significant increase of the exchangeable Ca²⁺ was reported by Caires *et al.* (2006) and The *et al.* (2001) after application of P fertilizer, lime and/or sole manure. Likewise, Awodun *et al.* (2007), Odedina *et al.* (2011) and Phengsouvana *et al.* (2009), reported significant increases in exchangeable Ca after sole or combined application of manure and lime. Furthermore, the liming effect of sole or combined manure and lime led to improvement of soil properties such as pH, Ca and microbial activity (Kisinyo *et al.*,

2005; Adeleye *et al.*, 2010; Hassan *et al.*, 2010; Kisinyo *et al.*, 2012 and Chimdi *et al.*, 2012).

The increase in the soil pH as a result of the application of manure plus lime could be attributed to increase in soil exchangeable Mg^{2+} thus increasing its availability in the soil through mineralization of the manure and lime dissolution in the soil. Additionally, reduction of the soil pH reduced the Al^{3+} and H^+ content in the soil thus enhancing the availability of the Mg^{2+} to the soil. These corroborate with the findings of Shen and Shen (2001); Rahman *et al.* (2002) and Escobar and Hue (2008) who reported similar findings on increase of soil available Mg on the application of lime combined with manure.

Soil exchangeable K increased with the application of $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure, manure alone or with a combination of fertilizer and lime. This can be attributed to the addition of exchangeable cations by manure through decomposition process. The manure added during the experiment had 0.64% K that might contribute to the addition of significant amounts of K nutrients to the soil. When organic manure was applied alone or combined with fertilizer and lime increased soil available K was reported (Ayeni and Adetunji, 2010; Ewulo, 2005; Adeniyani *et al.*, 2011; Adeleye *et al.*, 2010).

Application of lime and manure or lime plus fertilizer reduced of manganese significantly. Reduction of manganese in the lime applied treatments may be attributed to the production of OH^- ions from reaction of lime with soil moisture which

neutralizes the H^+ ions, thereby decreasing the activity and bioavailability of Mn toxicity in the soil (Padmavathiamma and Li, 2012). Ewulo (2005) in a study using 6 t ha^{-1} of cattle manure in Nigeria reported an increase in cations exchange capacity (CEC) of Mg, Ca and increased total soil P, K, and and decreased Mn. Similarly, Kheyrodin and Antoun (2012) reported that application of manure led to significant increase in Mg, Ca and K in the top soil.

4.2.3 Soil Available phosphorus

In 2016LR, application of treatments resulted in significant increases in soil available P ($p = 0.0082$) (Table 4.4). The order of increase was lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure (26.00 $mg\ kg^{-1}$), followed by $\frac{1}{2}$ manure + $\frac{1}{2}$ fertilizer (23.50 $mg\ kg^{-1}$) and manure alone (12.00 $mg\ kg^{-1}$). There was also a significant increase of available P in 2017LR (Table 4.4) where an increase was observed in various treatment in the following order; lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure (34.00 $mg\ kg^{-1}$), $\frac{1}{2}$ manure + $\frac{1}{2}$ fertilizer (31.50 $mg\ kg^{-1}$) and manure (29.00 $mg\ kg^{-1}$). The lowest increase in P was recorded in the control treatment with only 18% and 9% in 2016SR and 2017LR, respectively. Application of sole lime increased P by 75% and 92% in 2016SR and 2017LR, respectively over the initial.

Table 4.4: Changes in soil available P (0-20 cm depth) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatments	Available P (mg kg ⁻¹ soil)				
	Baseline (Sept 2016)	2016SR	% Change	2017LR	% Change
Lime + ½ fertilizer + ½ manure	11.50 ^a	26.00 ^a	126.1	34.00 ^a	195.7
Lime + fertilizer	14.00 ^a	25.50 ^a	82.1	33.50 ^a	139.3
Fertilizer	11.00 ^a	22.00 ^a	100.0	30.00 ^a	172.7
½ Manure + ½ fertilizer	10.50 ^a	23.50 ^a	123.8	31.50 ^a	200.0
Lime + manure	13.50 ^a	22.50 ^a	66.7	30.5 ^a	125.9
Manure	9.00 ^a	21.00 ^a	133.3	29.00 ^a	222.2
Lime	12.00 ^a	21.00 ^a	75.0	23.00 ^b	91.7
Control	11.00 ^a	13.00 ^b	18.2	12.00 ^c	9.1
P-value	0.8581	0.0082		<.0001	
LSD	6.686	6.686		6.686	

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

There were higher levels of P in the treatments containing the amendments (lime + fertilizer + manure, ½ manure + ½ fertilizer and lime + fertilizer) than in the control. Onwonga *et al.* (2008) reported higher levels of P in the treatments containing the amendments with lime and manure. This could be as a result of increased soil pH and P desorption following lime and manure application.

Generally, there was a higher increase in P in 2017LR as compared to the 2016SR. This could be associated to the applied P fertilizer that resulted in residual effect over time due to low mobility in the soil. Sole lime and P fertilizer significantly enhanced P content in the soil, this may be as a result of high rate of P applied and its high solubility, hence made the nutrients more available (Kisinyo *et al.*, 2014b). Liming raised the soil pH and increased P availability in the soil. This may be as a result of OH⁻ release that neutralized the H⁺ thus creating a favourable environment for P solubility (Buni, 2014). Application of manure and commercial fertilizers increased

soil extractable P, and P availability in the soil solution. Kisinyo *et al.* (2012) reported a reduction in nutrient toxicities, corresponding to an increase in nutrient availability due to a conducive environment through the application of manure and lime.

4.3 Effects of lime, manure and P fertilizer on maize growth and yield

The plant height was significantly affected by the treatments at 4th, 8th and 12th week after planting (WAP) during the 2016SR season (Table 4.5). During the 2016SR season, application of lime + fertilizer and lime + ½ fertilizer + ½ manure treatments at 4WAP, the tallest in the plants were 63.50 cm and 61.70 cm, respectively (Table 4.5). At 8WAP, maize plants with lime + ½ fertilizer + ½ manure and lime + fertilizer were the tallest plants were 176.60 cm and 169.90 cm, respectively (Table 4.5). At 12WAP during the 2016SR season lime + ½ fertilizer + ½ manure and ½ manure + ½ fertilizer treatments were the tallest, 232.83 cm and 228.50 cm, respectively (Table 4.5). Maize plants were shortest at 4WAP and tallest between 8WAP and 12WAP in the 2016SR season, respectively (Table 4.5).

Table 4.5: Changes in plant height (cm) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatment	2016SR season			2017LR season		
	Plant height (cm)					
	4WAP	8WAP	12WAP	4WAP	8WAP	12WAP
Lime + ½ fertilizer + ½ manure	61.70 ^a	176.60 ^a	232.83 ^a	95.50 ^a	279.50 ^a	296.13 ^a
Lime + fertilizer	63.50 ^a	169.90 ^{ab}	223.00 ^a	90.50 ^a	259.63 ^a	276.38 ^{ab}
Fertilizer	61.30 ^a	167.50 ^{ab}	224.17 ^a	88.88 ^a	255.63 ^{ab}	266.75 ^{ab}
½ Manure + ½ fertilizer	56.80 ^a	173.90 ^{ab}	228.50 ^a	107.25 ^a	282.88 ^a	272.50 ^{ab}
Lime + manure	41.80 ^b	136.90 ^{ab}	199.00 ^{ab}	94.75 ^a	259.75 ^a	270.50 ^{ab}
Manure	41.10 ^b	123.30 ^c	189.00 ^{ab}	81.25 ^a	234.13 ^{ab}	249.50 ^b
Lime	38.90 ^b	112.70 ^c	183.67 ^{ab}	83.38 ^a	210.88 ^{bc}	246.00 ^b
Control	40.90 ^b	134.50 ^{bc}	167.67 ^b	80.63 ^a	203.13 ^c	244.50 ^b
P-value	0.0001	0.0016	0.0388	0.4157	0.0025	0.1144
LSD	12.512	36.931	45.060	24.827	43.634	37.898

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

There was no significant difference among the treatments in 2017LR during the 4WAP ($p=0.4157$) and 12WAP ($p=0.1144$). ½ manure + ½ fertilizer application had the highest height of 107.25 cm and 282.88 cm in the 4WAP and 8WAP, respectively. The plant height was significantly affected by the treatments in the 8WAP ($p=0.0025$). Application of lime + ½ fertilizer + ½ manure and lime + fertilizer had the highest height of 296.13 cm and 276.38 cm, respectively. The control treatment recorded the lowest height in the 4WAP, 8WAP, and 12WAP in 2017LR.

The plant height in 2017LR compared to 2016SR was higher; possibly due to higher rainfall in the long rain in 2017 (Figure 4.1). During the 4WAP and 8WAP in 2016SR, maize supplied with was shortest plant height. This could be due to the low neutralizing activity of lime associated with low rainfall hence low solubility of lime hence aluminum ions inhibiting the uptake of available nutrients to the plant. In 2017LR, lime alone increased the plant height compared to control this could be

attributed to the lime solubility into the soil due to sufficient rainfall in the season, and also the activity of lime residues applied in short season.

Treatment with sole manure or combined with lime and fertilizer led to an increase in maize growth (Table 4.5). This can be attributed due to a combination of different nutrient sources from manure and fertilizer thus improved soil conditions and mineralization (Javaid and Mahmood, 2010; Umoetok *et al.*, 2007). Manure acts as a reservoir for nutrients that through mineralization are released for plant uptake (Chiezey and Odunze, 2009). Manure in combination with P fertilizer leads to nutrient supply increase whereby in this study could have indirectly increased plant height through enhanced vegetative growth (Umoetok *et al.*, 2007). Additionally, manure combined with lime and P fertilizer may have resulted to good performance as a result of increased availability of nutrients and improvement in soil conditions through application of manure, lime; and also addition of P fertilizer that is essential for initial root growth and enhanced nutrient uptake that improves crop development (Abbas *et al.*, 2011).

The chlorophyll content was significantly ($p=0.0001$) affected by the treatments at 4WAP ($p=0.0001$) and 8WAP ($p= 0.0124$) in 2016SR season (Table 4.6). At 4WAP during the 2016SR season, lime + fertilizer and lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure treatments had significantly ($p=0.0001$) high chlorophyll content of 41.62 SPAD units and 39.92 SPAD units, respectively (Table 4.6). At 8WAP, the chlorophyll content valued among treatments fertilizer recorded significantly ($p=0.0124$) high chlorophyll content of 37.35 SPAD units followed by $\frac{1}{2}$ manure + $\frac{1}{2}$ fertilizer with 38.59 SPAD

units (Table 4.6). At the 12WAP in the 2016SR season, lime + fertilizer and ½ manure + ½ fertilizer treatments had the highest chlorophyll content of 36.50 SPAD units and 35.97 SPAD units, respectively although this was not significantly different (Table 4.6). Sole lime recorded the lowest chlorophyll content at 4WAP (32.36 SPAD units) and 8WAP (32.43 SPAD units). Control recorded the lowest chlorophyll at 12WAP (29.23 SPAD units) (Table 4.6).

Table 4.6: Changes in chlorophyll content (SPAD units) in the different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatment	Chlorophyll –SR16			Chlorophyll -LR17		
	4WAP	8WAP	12WAP	4 WAP	8WAP	12WAP
Lime + ½ fertilizer + ½ manure	41.62 ^a	37.24 ^{ab}	36.50 ^a	45.16 ^a	55.98 ^a	52.11 ^a
Lime + fertilizer	39.92 ^a	34.72 ^{abc}	35.97 ^a	42.96 ^a	55.59 ^a	51.91 ^a
Fertilizer	39.78 ^a	38.59 ^a	33.62 ^a	43.50 ^a	54.58 ^a	53.13 ^a
½ Manure + ½ fertilizer	39.70 ^a	37.35 ^{ab}	31.52 ^a	47.16 ^a	54.36 ^a	48.56 ^a
Lime + manure	34.24 ^b	33.80 ^{bc}	29.45 ^a	37.24 ^b	47.21 ^b	41.13 ^b
Manure	33.55 ^b	32.86 ^{bc}	33.22 ^a	37.43 ^b	43.70 ^{bc}	38.98 ^b
Lime	32.36 ^b	32.43 ^c	29.70 ^a	37.16 ^b	40.09 ^c	39.18 ^b
Control	33.13 ^b	32.60 ^c	29.23 ^a	38.05 ^b	39.83 ^c	38.25 ^b
P-value	0.0001	0.0124	0.277	0.0001	0.0001	0.0001
LSD	3.968	4.123	7.254	4.223	4.959	6.393

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

In 2017LR, the chlorophyll content was significantly ($p=0.0001$) affected by treatments in the 4WAP, 8WAP, and 12WAP. The application of ½ manure + ½ fertilizer in the 4WAP. The highest chlorophyll content was 47.16 SPAD units. In the 8WAP, the highest chlorophyll content was 56 SPAD units in both lime + ½ fertilizer + ½ manure and lime + fertilizer. The application of fertilizer alone and lime + ½ fertilizer + ½ manure had the highest chlorophyll content of 53.13 SPAD units and 52.11 SPAD units, respectively, in the 12 WAP in 2017LR. Lime treatment recorded the lowest chlorophyll content of 37.16 SPAD units in the 4WAP with control

recording the lowest with 39.83 SPAD units and 38.25 SPAD units, respectively in 8WAP and 12 WAP in 2017LR.

In all the treatments with fertilizer or combined with manure, high chlorophyll content was recorded with control treatment recording the lowest. Yang *et al.* (2003) reported that the interaction of inorganic and organic amendments led to an increase in the chlorophyll contents of plants. The chlorophyll content in plant leaf tissue is influenced by nutrient availability and environmental stresses such as salinity, drought, heat and cold (Alam *et al.*, 2017). Manure being a store of nutrients released through mineralization enhances plant growth (Chiezey and Odunze, 2009). Combination with P fertilizers increases supply of nutrients which increased vegetative growth through improved chlorophyll content and indirectly affecting the plant height (Umoetok *et al.*, 2007). Increase in nitrogen and phosphorus increases plant chlorophyll content and subsequently photosynthetic rate.

On the other hand, low chlorophyll content in control could be attributed to high levels of aluminum toxicity that inhibit the uptake of magnesium which is a central part of chlorophyll molecule of the plant (Tang, and Luan, 2017). High amounts of Al^{3+} in the soil competes with magnesium and binds on plasma membrane of roots therefore interferes with transportation and uptake of magnesium. This impedes growth and nutrient availability for instance P and Mg which are not available in acidic soil. The high leaf chlorophyll content in the lime+fertilizer+manure treatment could be due to reduction of manganese, hydrogen and aluminium ion toxicities.

High chlorophyll content enhances photosynthesis process and influences the physiological growth of a healthy nutritional plant. The amount and availability of phosphorus highly affects leaf growth due to increased chlorophyll enhancing photosynthesis. Maize efficient P utilization affects the nitrogen use efficiency (Zaman-Allah *et al.*, 2015), consequently, it affects crop anatomical, physiological, morphological and growth and development. Additionally, Sim *et al.* (2015) indicated that the highest physiological growth indices are attained with high plant nutrition since the amount of chlorophyll content improves photosynthesis.

4.4 Effects of manure, lime and P fertilizer on dry matter and grain yield

The stover yield during 2016SR and 2017LR was significantly affected by treatments $p=0.0001$ and $p=0.0439$, respectively. The application of lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure had the highest stover yield in 2016SR (3.0 t/ha) followed by lime + fertilizer treatment (2.8 t/ha). In the 2017LR, the highest stover yield was 11.20 t/ha where lime and fertilizer were applied together (combined). The control treatment had the lowest yield in 2016SR and 2017LR of 0.810 t/ha and 5.871 t/ha, respectively (Table 4.7).

The grain yield recorded in 2017LR valued significantly different ($p < .0001$) among the treatments. The highest yield (5.1t/ha) was observed under lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure followed by the application of lime + fertilizer (5.0 t/ha) and $\frac{1}{2}$ manure + $\frac{1}{2}$ fertilizer (4.0 t/ha) in 2017LR, and the lowest yield of 1.5 t/ha in 2017LR. There was no maize grain yield recorded in 2016SR due to insufficient amount of rainfall during the season (see section 4.1). There were high stover and grain yields recorded in treatments with fertilizer, lime and with a combination of manure in 2017 LR.

Table 4.7: Stover yields (t ha^{-1}) in the different treatments during the 2016SR and the 2017LR seasons and maize yields (t ha^{-1}) in the different treatments during 2017LR seasons in Kirege

Treatment	Stover yield (t/ha)		Grain yield (t/ha)
	2016SR	2017LR	2017LR
Lime + ½ fertilizer + ½ manure	3.0 ^a	11.2 ^a	5.1 ^a
Lime + fertilizer	2.8 ^a	10.6 ^{ab}	5.0 ^a
Fertilizer	2.4 ^{ab}	8.9 ^{abc}	4.0 ^a
½ Manure + ½ fertilizer	2.7 ^{ab}	8.3 ^{abc}	3.8 ^{ab}
Lime + manure	1.5 ^{abc}	8.2 ^{abc}	2.5 ^{bc}
Manure	1.3 ^{bc}	6.6 ^{bc}	2.2 ^c
Lime	0.8 ^c	6.5 ^{bc}	1.8 ^c
Control	0.8 ^c	5.9 ^c	1.5 ^c
p-value	<.0001	0.0439	<.0001
LSD	1.354	3.724	1.354

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

The results showed that combination of lime, manure and mineral fertilizers improved crop yield in comparison to the sole mineral fertilizers, sole lime, and sole manure. Similarly, Nyamangara *et al.* (2003) and Mtambanengwe *et al.* (2006) noted an increase in crop yield with manure and P fertilizers compared to the sole application of P fertilizer and manure. The increase could be explained by the fertilizer that supplies readily available plant nutrients from an early stage of crop growth thus promoting sufficient water and nutrient uptake. These results corroborate those of Nziguheba *et al.* (2000); Kimetu *et al.* (2004); Mucheru-Muna *et al.* (2007) and Mugwe *et al.* (2009), who similarly observed increased maize yields attributed to application of organic manure in combination with mineral fertilizer compared to sole organic manure application and mineral fertilizers.

Current results of higher yields where lime, manure combined with mineral fertilizer could be attributed to additional secondary nutrients from manure and

chemical/mineral fertilizer thus achieving a positive rise in recorded grain yield. Integration of inorganic and organic inputs integration increased yields due to supply of nitrogen and phosphorus (Mugwe *et al.*, 2009). Most nutrients become more available at higher soil pH and consequently lead to increased dry matter and grain yields (Fageria and Beligar, 2008). This could be due to nutrients present in manure that supply essential nutrients to the soil e.g. N, P and K that are vital for maize growth.

Intergrated use of organic and inorganic nutrient sources provides more balanced nutrient supply and other numerous agro-ecological benefits such as increase in soil microbial activity (Giller *et al.*, 2006). Moreover the intergration increases fertilizer use efficiency hence can be considered as better options. Combination of organic and mineral fertilizer nutrient sources has shown to improve synchronization of nutrient release, synergistic effects and uptake by crops (Mucheru-Muna *et al.*, 2007) resulting to higher yields, particularly in a case where relatively low levels of mineral fertilizers are used by most smallholder farmers in tropical farming systems. Fertilizer use leads to increase in crop residues for soil fertility management and increase crop yields, while organic sources are able to restore less responsive soils and make them responsive to fertilizers (Mucheru-Muna *et al.*, 2014; Vanlauwe *et al.*, 2010).

4.5 Effects of manure, lime and P fertilizer on profitability

During the 2016SR season, control had the highest net benefit of -88.05 USD/ha whereas lime combined with manure recorded the lowest (-434.21 USD/ha) (Table 4.8). Benefit-cost Ratio (BCR) was highest under lime + $\frac{1}{2}$ fertilizer + $\frac{1}{2}$ manure (0.79) treatment while lime combined with manure had the lowest (-0.91). The highest

return to labour (-1.7) was recorded in control while lime plus manure treatment gave the lowest return to labour (-8.1) (Table 4.8). In 2017LR, however, net benefit as well as losses were realized and differed significantly among the treatments ($P= 0.0006$). Application of lime plus fertilizer had the highest net benefit of 128.75 USD/ha followed by sole fertilizer (105.94 USD/ha). Application of manure had the highest net loss (-186.20 USD/ha) while lime plus manure recorded (-108.01 USD /ha) (Table 4.8). The net loss may be as a result of high cost of inputs and labour employed in the application of the lime and manure. Benefit-cost ratio (BCR) was highest (0.67) in control followed by 0.34 under sole fertilizer while lime combined with manure had the lowest (-0.34) BCR. The highest return to labour was on lime and fertilizer treatment (3.78) followed by sole fertilizer (3.25) while lime plus manure treatment s recorded the lowest (-1.54) (Table 4.8).

Table 4.8: Profitability of maize under different treatments during the 2016SR and the 2017LR seasons in Kirege

Treatment	2016SR			2017LR		
	Net Benefit	Benefit-Cost Ratio	Return to Labour	Net Benefit	Benefit-Cost Ratio	Return to Labour
Lime + ½ fertilizer + ½ manure	-339.98 ^e	0.79 ^{ab}	-5.7 ^e	48.38 ^{ab}	0.10 ^{bcd}	2.3 ^{abc}
Lime + fertilizer	-287.77 ^d	0.77 ^{ab}	-4.9 ^d	128.75 ^a	0.30 ^{ab}	3.8 ^a
Fertilizer	-170.60 ^b	-0.68 ^a	-3.0 ^b	105.94 ^a	0.34 ^{ab}	3.3 ^{ab}
½ Manure + ½ fertilizer	-228.16 ^c	0.76 ^{ab}	-4.1 ^c	60.70 ^a	0.18 ^{bc}	2.4 ^{abc}
Lime + manure	-434.21 ^f	-0.91 ^b	-8.1 ^f	-108.01 ^{bc}	-0.34 ^d	-1.5 ^d
Manure	-319.33 ^d	-0.89 ^b	-6.2 ^e	-186.20 ^c	-0.23 ^{cd}	-0.6 ^{cd}
Lime	-213.75 ^c	-0.90 ^b	-3.9 ^c	-33.89 ^{abc}	-0.12 ^{bcd}	0.5 ^{bcd}
Control	-88.05 ^a	0.78 ^{ab}	-1.7 ^a	96.10 ^a	0.67 ^a	1.6 ^{abc}
p-value	<.0001	0.1471	<.0001	0.0006	0.0006	0.0042
LSD	-42.25	0.1806	-0.799	150.99	0.446	2.82

*Means with the same letter(s) are not significantly different from each other at 5% level of significance

In this study, the net benefit under combined application of lime and fertilizer was higher compared to separate applications and the control. Manpreet and Dixit (2017) recorded higher net returns in fertilizer application with lime compared to rest of the treatments. The net benefit in long rains was positive in most treatments (Tables 4.8) this shows that most treatments recorded extra yield that was adequate to offset the labor and non-labor costs of production. However, on average, the net benefit, benefit-cost ratio and return to labor were lower during the short rains compared to the long rains season (Table 4.8). This could be as a result of the meteorological drought experienced during 2016SR (Figure 3.2) which adversely affected the maize yield. Buah *et al.* (2017) reported similar season specific responses of net benefits on adverse seasonal change. The smallholder farmers are inherently the most susceptible to the negative impacts of climate variability, as it is aggravated by diminishing soil productivity (Khan and Akhtar, 2015).

In this study, lime + inorganic fertilizer treatment had higher net benefit returns and return to labour in 2017LR which was the best season. The higher economic returns could be associated with low labour input in the farm, thus less cost associated with it, adequate rainfall during the season and the fact that these treatments had relatively higher yields with improved soil pH. Therefore, the optimum fertilizer combined with lime is important to obtain maximum net benefit returns. Sodo *et al.* (2014) reported maximum net profits in lime combined with fertilizer treatment. This is also in agreement with Manpreet and Dixit (2017) who established that incorporation of lime along with recommended level of fertilizers every year is economical, practicable and effective.

The application of lime and manure was found to have good synergy as it consistently resulted in higher yields than when manure was applied without lime. Similar results were reported by Athanase (2013). The higher return to labour under combined manure and fertilizer could be as a result of higher yields and low labour requirements in comparison to their sole application. Mucheru-Muna *et al.* (2007) reported a higher return to labour under integration of organic and inorganic compared to the sole applications. The treatments with P fertilizer had the highest BCR in both seasons, this could be as a result of low labour costs incurred (Mucheru-Muna *et al.*, 2014).

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

During the two seasons under study application of 2 t ha⁻¹ lime plus 10 t ha⁻¹ manure recorded the highest increase in soil pH during 2016SR (4.61 to 5.21) while in 2017 LR, sole lime had the highest increase from 4.51 to 5.28. This is an increase of 13.02% and 17.07%, respectively over the initial soil pH. This was closely followed by 2 t ha⁻¹ lime with 5 t ha⁻¹ of manure plus 30 kg P₂O₅ ha⁻¹ as P fertilizer with 15.3% reduction in soil pH in 2017LR. In comparison with treatment with sole fertilizer, lime and manure treatments had the highest reduction in soil exchangeable acidity.

The influence of the treatments on maize height, chlorophyll content, stover and grain yield was consistent. Application of 2 t ha⁻¹ lime with 5 t ha⁻¹ of manure plus 30 kg P₂O₅ ha⁻¹ had the tallest plants of 232.83 cm and 296.13 cm in 2016SR and 2017LR, respectively. Similarly, this treatment recorded the highest chlorophyll content of 53.13 SPAD units followed by lime combined with fertilizer by 52.11 SPAD. The highest stover and grain yield was attained with application of combined lime, manure plus fertiliser.

Generally, the economic returns were low, with negative net benefits and benefit-cost ratio of less than 1. Lime plus fertilizer had the highest net benefit of 128.75 USD in the 2017LR. The treatments with inorganic fertilizers had the highest BCR in 2017LR due to the low labour input required.

5.2 Conclusions

Treatments with lime and manure, sole or combined had a significant increase in soil pH which increased the availability of soil nutrients. Application of combined lime, manure and fertilizer lime had the highest stover and grain yield compared to those with sole manure, fertilizer, or lime. This is demonstrating the superiority of integrated soil fertility management in yield improvement. This indicates that liming is an effective method of ameliorating soil acidity and offers a better option for increasing maize yields in degraded soils of central highlands of Kenya. Economic returns were significantly affected by interaction of lime, manure and P fertilizer where treatment applied with fertilizer had more benefit compared to those with no fertilizer.

5.3 Recommendations

Based on the findings the following recommendations were derived:

- For improved soil chemical properties and increased maize yields, smallholder farmers should adopt integrated application of manure with lime and P fertilizer.
- Farmers need to consider economic returns when selecting agricultural production technologies to use.

5.4 Areas of further research

- A long-term study needs to be considered using other types of lime (Calcium Oxide and granulated lime) and manure to evaluate change in soil chemical properties and effect on maize yield and profitability.

- Further research should be conducted to explore more rates of lime, different types of lime and their effects in long-term to determine the optimum liming level of different types of lime for acid soils.
- Further research to assess the economic return in the long-term use of lime, manure and fertilizer is suggested.

REFERENCES

- Abbas, G., Abbas, Z., Aslam, M., Malik, A. U., Ishaque, M. and Hussain, F. (2011). Effects of organic and inorganic fertilizers on Mungbean (*Vigna radiata* L.) yield under arid climate. *International Research Journal of Plant Science*, 2 (4): 094-098.
- Adeleye, E. O., Ayeni, L. S and Ojeniyi, S. O. (2010). Effect of poultry manure on soil physico-chemical properties, leaf nutrient contents and yield of Yam (*Dioscorea rotundata*) on Alfisol in Southwestern Nigeria. *Journal of American Science*, 6 (10):871-878.
- Ademba, J. S., Esilaba, A. O. and Ngari, S. M. (2010). Evaluation of organic and inorganic amendments on nutrient uptake, phosphorus use efficiency and yield of maize in Kisii region. In L. A. Wasilwa, J. Ouda, I. W. Kariuki, N. S. Mangale and M. N. Lukuyu (Eds). *Transforming Agriculture for Improved Livelihoods through Agricultural Product Value Chain. Proceedings of the 12th KARI Biennial Scientific Conference*. November 8-12, 2010. Nairobi-Kenya.
- Adeniyani, O. N., Ojo, A. O., Akinbode, O. A. and Adediran, J. A. (2011). Comparative study of different organic manures and NPK fertilizer for improvement of soil chemical properties and dry matter yield of maize in two different soils. *Journal of Soil Science and Environmental Management*, 2 (1): 9-13.
- Adiel, R. K. (2004). Assessment of on-farm adoption potential of nutrient management strategies in Chuka division, Meru South, Kenya. *M.Sc Thesis, University of Kenyatta, Kenya*.
- Akinrinade, E. A., Iroh I., Obigbesan, G. O., Hilger T., Romheld, V. and Neumann, G. (2006). The response of cowpea varieties to phosphorus supply on an acidic alumi-haplic-Acrisol from Brazil. *Nigerian Journal of Soil Science*, 16: 115-120.
- Alam, R., Das, D. K., Islam, M. R., Murata, Y. and Hoque, M. A. (2017). Exogenous proline enhances nutrient uptake and confers tolerance to salt stress in maize (*Zea mays* L.). *Progressive Agriculture*, 27(4), 409-417.
- Anetor, M. O. and Akinrinde, E. A. (2006). Response of Soybean [*Glycine max* (L.) Merrill] to lime and phosphorus fertilizer treatments on an acidic Alfisol of Nigeria. *Pakistan Journal of Nutrition*, 5 (3): 286-293.
- Antil, R. S., and Singh, M. (2007). Effects of organic manures and fertilizers on organic matter and nutrients status of the soil. *Archives of Agronomy and Soil Science*, 53(5), 519-528. doi:10.1080/03650340701571033

- Athanase, N. (2013). "Effects of Different Limes on Soil Properties and Yield of Irish Potatoes (*Solanum Tuberosum*. L) in Burera District, Rwanda." *M.Sc Thesis, University of Kenyatta, Kenya*.
- Awodun, M. A., Omonijo, L. I. and Ojeniyi, S. O. (2007). Effects of goat dung and NPK fertilizer on soil and leaf nutrient content, growth, and yield of pepper. *International Journal of Soil Science*, 2 (2): 142-127.
- Ayeni, L. S and Adetunji, M. T. (2010). Integrated application of poultry manure and mineral fertilizer on soil chemical properties, nutrient uptake, yield and growth components of maize. *Nature and Science*, 8 (1): 60 – 67.
- Bhatta, G. D., and Doppler, W. (2016). Smallholder peri-urban organic farming in Nepal: A comparative analysis of farming systems. *Journal of Agriculture, Food Systems, and Community Development*, 1(3), 163-180.
- Blackwell, P., Riethmuller, G., and Collins, M. (2009). Biochar application to soil. *Biochar for environmental management: science and technology*, 1, 207-226.
- Bolan, N. S and Hedley, M. J. (2003). Role of carbon, nitrogen and sulfur cycles in soil acidification. In D. Marcel, *In "Handbook of soil acidity"* (pp. 29-56). New York: Rengel. Z.
- Bolan, N. S., Adriano, D. C. and Curtin, D. (2003). Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Advances in Agronomy*, 78, 215-272.
- Brown, T. T., Koenig, R. T., Huggins, D. R., Harsh, J. B. and Rossi, R. E. (2008). Lime effects on soil acidity, crop yield, and aluminum chemistry in direct-seeded cropping systems. *Soil Science Society of America Journal*, 72(3), 634-640.
- Buah, S. S., Ibrahim, H., Derigubah, M., Kuzie, M., Segtaa, J. V., Bayala, J. and Ouedraogo, M. (2017). Tillage and fertilizer effect on maize and soybean yields in the Guinea savanna zone of Ghana. *Agriculture and Food Security*, 6(1), 17.
- Buni, A. (2014). Effects of Liming Acidic Soils on Improving Soil Properties and Yield of Haricot Bean. *Journal Environ Anal Toxicol* 5:248.
- Busari, M., Salako, F. and Adetunji, M. (2008). Soil chemical properties and maize yield after application of organic and inorganic amendments to an acidic soil in Southwestern Nigeria. *Spanish Journal of Agricultural Research*, 6 (4), 691.
- Caires, E. F., Churka, S., Garbuio, F. J., Ferrari, R. A. and Morgano, M. A. (2006). Soybean yield and quality as a function of lime and gypsum application. *Scientia Agricola (Piracicaba, Brazil)*, 63 (4): 370 – 379.

- Caires, E. F., Garbuio, F. J., Churka, S., Barth, G. and Corrêa, J. C. (2008). Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield. *European Journal of Agronomy*, 28(1), 57-64.
- Chen, M., Xu, P., Zeng, G., Yang, C., Huang, D., and Zhang, J. (2015). Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: applications, microbes and future research needs. *Biotechnology Advances*, 33(6), 745-755.
- Chiezey, U. F. and Odunze, A. C. (2009). Soybean response to application of poultry manure and phosphorus fertilizer in the Sub-humid Savanna of Nigeria. *Journal of Ecology and Natural Environment*, 1 (2): 025 - 031.
- Chimdi, A., Gebrekidan, V., Kibret, K. and Tadesse, A. (2012). Effects of liming on acidity related chemical properties of soils of different land use systems in Western Oromia, Ethiopia. *World Journal of Agricultural Science*, 8 (6): 560-567.
- Craswell, E. T. and Lefroy, R.D. (2001). The role and function of organic matter in tropical soils. *Nutrient Cycling in agroecosystems*, 61:7-18.
- Danga, B. O., Ouma, J. P., Wakindiki, I. I. and Bar-Tal, A. (2010). Chickpea-Wheat rotation for higher production in a humid tropical region. *Agronomy Journal*, 102 (2): 363 –371.
- Douglas, B. B. and Lingenfelter, D. D. (1995). Soil acidity and aglime; Crop and soil sciences, Agronomy Facts 3, The Pennsylvania State University. Available online at <http://cropsoil.psu.edu/extension/facts/agronomy-facts-3>
- Eakin, H. (2000). Smallholder maize production and climatic risk: A case study from Mexico. *Climatic change*, 45(1), 19-36.
- Escobar, M. E. and Hue, N. V. (2008). Temporal changes of selected chemical properties in three manure-amended soils of Hawaii. *Bioresource Technology*, 99: 8649 – 8654.
- Ewulo, B. S. (2005). Effects of poultry dung and cattle manure on chemical properties of clay and sandy clay loam soil. *Journal of Animal and Veterinary Advances*, 4 (10): 839 - 841.
- Fageria, N. K. and Baligar, V. C. (2008). Ameliorating Soil Acidity of Tropical Oxisols by Liming For Sustainable Crop Production. In E. Inc, and D. L. SPARKS (Ed.), *Advances in Agronomy* (Vol. 99, pp. 345-389). Brazil: Academic Press.
- Fageria, N. K. and Stone L. F. (2004). Yield of common bean in no-tillage system with application of lime and zinc. *Pesq. Agropec. Braas*, 73-78.

- Fageria, N. K. and Baligar V. C. (2004). Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production (Vol. 99). (L. Donald, Ed.) Elsevier Inc. Academic press.
- Fageria, N. K., Baligar, V. C. and Jones, C. A. (2010). Growth and mineral nutrition of field crops. CRC Press.
- Fageria, N. K., Baligar, V. C. and Li, Y. C. (2008). The role of nutrient efficient plants in improving crop yields in the twenty first century. *Journal of plant nutrition*, 31(6), 1121-1157.
- Fankem, H., Ngo, N., Deubel, A., Quinn, J., Merbach, W., Etoa, F. and Nwaga, D. (2008). Solubilization of inorganic phosphates and plant growth promotion by strains of *Pseudomonas fluorescens* isolated from acidic soils of Cameroon. *African Journal of Microbiology Research*, 2: 171-178.
- FAO. (2001). Irrigation Water Management: Irrigation Water Needs. FAO.org.
- Fischer, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research*, 182, 9-18.
- Giller, K. E., Rowe, E. C., de Ridder, N., and van Keulen, H. (2006). Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural systems*, 88(1), 8-27.
- Gudu, S. O., Okalebo, J. R., Othieno, C. O., Kisinyo, P. O., Obura, P. A. and Ligeyo, D. O., (2007). Improving P acquisition and Al tolerance of plants. Presented at the France workshop, October, 2007.
- Hailin, Z. (1998). Animal Manure can Raise Soil pH. Production technology PT 98-7 February, 1998 Vol. 10 No. 7. Retrieved from <http://www.animalwaste.okstate.edu> on 10th May 2011.
- Harter, R. D. (2007). Acid soils of the tropics. ECHO Technical notes.
- Harun, I. G., Benson, E. M. and Benjamin, O. D. (2015). Effect of lime and goat manure on soil acidity and maize (*Zea mays*) growth parameters at Kavutiri, Embu County- Central Kenya. *Journal of Soil Science and Environmental Management*, 6(10), 275-283. doi:10.5897/jssem15.0509.
- Hassan, A., Mohamad, A., Abdu, A., Idrus, R. M. and Besar, N. A. (2010). Soil properties under *Orthosiphon stamineus* (Benth) intercropped with *Durio zibethinus* (Murr) and treated with various organic fertilizers. *Paper presented on 19th World Congress of Soil Science, Soil Solutions for a Changing World*, 1st – 6th August 2010, Brisbane, Australia.
- Havlin, J. L., Beaton, J. D., Tisdale, S. L and Nelson, W. L. (2005). Soil fertility and fertilizers: An introduction to nutrient management (7 ed.). New Jersey: Pearson prentice hall.

- Haynes, R. J. and Mokolobate, M. S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems*, 59: 47–63.
- Hue, N. V., Craddock, G. R. and Adams, F. (1986). Effect of organic acids on Aluminium toxicity in sub soils. *Soil Science Society of American Journal*. 50: 28–34.
- Isherwood, K. F. (2003). Fertilizer consumption and production. *International Fertilizer Society*, 507: p 28. York, UK
- Jaetzold, R., Schmidt, H., Hornet, Z. B. and Shisanya, C. A., (2007). FarmManagement Handbook of Kenya. Natural Conditions and Farm Information. 2nd Edition. Vol. 11/ C. Eastern Province. Ministry of Agriculture/GTZ, Nairobi, Kenya
- Jagadeeswaran, R., Murugappan, V. and Govindaswamy, M. (2005). Effect of Slow Release NPK Fertilizer Sources on the Nutrient use Efficiency in Turmeric (*Curcuma longa* L.). *World Journal of Agricultural Sciences*, 1(1), 65–69.
- Javaid, A. and Mahmood, N. (2010). Growth, nodulation and yield response of soybean to biofertilizers and organic manures. *Pakistan Journal of Botany*, 42 (2): 863 - 871.
- Kafle, S., and Sharma, P. K. (2015). Effect of Integration of Organic and Inorganic Sources of Nitrogen on Growth, Yield and Nutrient Uptake by Maize (*Zea mays* L.). *International Journal of Applied Sciences and Biotechnology*, 3(1), 31-37.
- Kaitibie, S., Epplin, F. M., Krenzer, E. G. and Zhang, H. (2002). Economics of lime and phosphorus application for dual purpose winter wheat production in low pH soils. *Agronomy Journal*, 1139-1145.
- Kanyanjua, S. M., Ileri, L., Wambua, S. and Nandwa, S. M. (2002). Acid soils in Kenya: constraints and remedial options. *KARI Technical Note No. 11, June 2002*. KARI Headquarters, Nairobi, Kenya.
- Khan, M. A., and Akhtar, M. S. (2015). Agricultural Adaptation and Climate Change Policy for Crop Production in Africa. In *Crop Production and Global Environmental Issues* (pp. 437-541). Springer International Publishing.
- Khan, M. N., Mobin, M., Abbas, Z. K., and Alamri, S. A. (2018). Fertilizers and Their Contaminants in Soils, Surface and Groundwater. *MN Khan, M. Mobin, ZK Abbas, SA Alamri//Reference Module in Earth Systems and Environmental Sciences.–2017.–doi, 10*.
- Kheyrodin, H. and Antoun, H. (2012). Tillage and manure effect on soil physical and chemical properties and on carbon and nitrogen mineralization potentials. *African Journal of Biotechnology*, 10 (48): 9824 - 9830.

- Khoi, C. M., Guong, V. T., Trung, P. N and Nilsson, S. I. (2010). Effects of compost and lime amendment on soil acidity and N availability in acid sulfate soil. *Paper presented on 19th World Congress of Soil Science, Soil Solutions for a Changing World*, 1st – 6th August 2010, Brisbane, Australia.
- Kifuko, M. N., Othieno, C. O., Okalebo, J. R., Kimenye, I. N., Ndung'u, K. W., and Kipkoech, A. (2007). Effect of combining organic residues with minjingu phosphate rock on sorption and availability of phosphorus and maize production in acid soils of Western Kenya. *Experimental Agriculture*, 43(01), 51.
- Kimetu, J. M., Mugendi, D. N., Palm, C. A., Mutuo, P. K., Gachengo, C. N., Bationo, A., Nandwa, S. and Kung'u, J. (2004). Nitrogen fertilizer equivalences by organics of differing quantity and optimum combinations with organic nitrogen source in central Kenya. *Nutrient Cycling in Agroecosystems* 68: 127-135.
- Kisinyo, P. O. (2012). Effects of lime, phosphorus, and rhizobia on *Sesbania sesban* performance in a Western Kenyan acid soil. *African Journal of Agricultural Research*, 7(18).
- Kisinyo, P. O., Gudu, S. O., Othieno, C. O., Okalebo, J. R., Opala, P. A., Maghanga, J. K., Agalo, J. J., Ng'etich, W. K., Kisinyo, J. A., Osiyo, R. J., Nekesa, A. O., Makatiani, E. T., Odee, D. W. & Ogola, B. O. (2012). Effects of lime, phosphorus, and rhizobia on *Sesbania sesban* performance in a Western Kenyan acid soil. *African Journal of Agricultural Research*, 7 (18): 2800 - 2809.
- Kisinyo, P. O., Othieno, C. O., Okalebo, J. R., Kipsat, M. J., Serem, A. K. and Obiero, D. O. (2005). Effects of lime and phosphorus application on early growth of *Leucaena* in acid soils. *African Crop Science Conference Proceedings*, 7: 1233 - 1236.
- Kisinyo, P. O., Otieno, C. O., Gudu, S. O., Okalebo, J. R., Opala, P. A., Ng'etich, W. K. and Too, E. J. (2014b). Immediate and residual effects of lime and phosphorus fertilizer on soil acidity and maize production in western Kenya. *Experimental Agriculture*, 50(1), 128-143.
- Kisinyo, P. O., Opala, P. A., Gudu, S. O., Othieno, C. O., Okalebo, J. R., Palapala, V. and Otinga, A. N. (2014a). Recent advances towards understanding and managing Kenyan acid soils for improved crop production. *African Journal of Agricultural Research*, 9(31), 2397-2408.
- Liao, H., Wan, H., Shaff, J., Wang, X., Yan, X. and Kochian, L. V. (2006). Phosphorus and aluminum interactions in soybean in relation to aluminum tolerance. Exudation of specific organic acids from different regions of the intact root system. *Plant Physiology*, 141(2), 674-684.

- Maheshbabu, H. M., Hunje, R., Patil, N. K. B. and Babalad, H. B. (2008). Effect of organic manures on plant growth, seed yield and quality of soybean. *Karnataka Journal of Agricultural Science*, 21 (2): 219 - 221.
- Manpreet, S. and Dixit, S. P. (2017). Yield, profitability and nutrient uptake of wheat under soil test crop response based fertilizer application with different levels of lime in an acid Alfisol. *Journal of Pharmacognosy and Phytochemistry*, 6(6): 1985-1988.
- Masulili, A., Utomo, W. H. and Syechfani, M. S. (2010). Rice husk biochar for rice based cropping system in acid soil 1. The characteristics of rice husk biochar and its influence on the properties of acid sulfate soils and rice growth in West Kalimantan, Indonesia. *Journal of Agricultural Science*, 2(1), 39.
- Mayfield, J. L., Ozanne, L., Mitchell, C. C., Simonne, E. H. and Sibley, J. L. (2004). Laboratory and greenhouse evaluation of quicklime sources for suitability as agricultural liming materials. *Communications in soil science and plant analysis*, 35(7-8), 1167-1183.
- McCauley, A., Jones, C. and Jacobsen, J. (2009). Commercial fertilizers and soil amendments. *Nutrient Management-A self-study course from MSU extension continuing education series*, 449-510.
- Md, I. (2014). Effect of elevated Al and pH on the growth and root morphology of Al-tolerant and Al-sensitive wheat seedlings in an acid soil. *SJSS*, 4(1), 61.
- Mehlich, A. (1953). Determination of P, Ca, Mg, K, Na, NH₄. Short test methods used in soil testing division, Department of Agriculture, Raleigh, North Carolina. S.T.D.P. No.1-53.
- Merckx, R., Diels, J., Vanlauwe, B., Sanginga, N., Deneff, K. and Oorts, K. (2001). Soil organic Matter and soil fertility. *Soil Science Society of American Journal*, 58:69-89.
- Mtambanengwe, F., Mapfumo, P. and Vanlauwe, B. (2006). Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. *Nutrient Cycling Agroecosystem*. 76:271–284.
- Mucheru-Muna M. W., Mugendi D., Pypers P., Mugwe J., Kung'u J., Vanlauwe B. and Merckx R. (2014). Enhancing maize productivity and Profitability using organic inputs and Mineral Fertilizer in central Kenya small-hold farms. *Experimental Agriculture*, 50, 250-269.
- Mucheru-Muna, M. W., Mugendi, D., Kung'u, J., Mugwe, J. and Bationo, A. (2007). Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agroforestry Systems* 69:189-197.

- Mugai, E. N. (2004). Salinity characterization of the Kenyan saline soils. *Soil Science and Plant Nutrition*, 50(2), 181-188.
- Mugendi, D. N., Nair, P. K. R., Mugwe, J. N., O'Neill, M. K. and Woome, P. (1999). Alley cropping of maize with calliandra and leucaena in the subhumid highlands of Kenya. Part 1: Soil fertility changes and maize yield. *Agroforestry Systems* 46:39–50.
- Mugwe, J., Mugendi, D., Kungu, J. and Mucheru-Muna, M. (2007). Effect of plant biomass, manure and inorganic fertilizer on maize yield in the Central Highlands of Kenya. *African Crop Science Journal*, 15(3).
- Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J. and Vanlauwe, B. (2009). Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the Central Highlands of Kenya. *Experimental Agriculture* 45:61–75.
- Muindi, E. M., Semu, E., Mrema, J. P., Mtakwa P. W. and Gachene C. K. (2016). Soil Acidity Management by Farmers in the Kenya Highlands. *Journal of Agriculture and Ecology Research International* 5(3): 1–11.
- Mukuralinda, A. (2007). Influence of phosphorus resources on soil phosphorus dynamics and crop productivity in Rwanda. *M. Sc Thesis. Makerere University, Uganda*.
- Mullen, C. L., Scott, B. J., Evans, C. M. and Conyers, M. K. (2006). Effect of soil acidity and liming on lucerne and following crops in central-western New South Wales. *Australian Journal of Experimental Agriculture*, 46(10).
- Nabahungu, L. N. (2003). Effects of limestone, Minjingu phosphate rock and green manure application on improvement of acidic soils in Tonga, Burate, Rwanda. *M. Sc Thesis. Sokoine University, Tanzania*.
- Nekesa, A. O., Okalebo, J. R., Othieno, C. O., Thuita, M. N., Bationo, A. and Waswa, B. S. (2011). The potential of increased maize and soybean production in uasin gishu district, Kenya, resulting from soil acidity amendment using minjingu phosphate rock and agricultural lime. In A. Bationo *et al.* (Eds.), *Innovations as key to the green revolution in Africa*.
- Nekesa, A. O. (2007). Effect of Minjingu phosphate rock and agricultural lime in relation to maize, groundnut and soybean yields on acid soils of western Kenya. *M. Sc Thesis. Moi University, Kenya*.
- Nurlaeny, N., Marschner, H. and George, E. (1996). Effects of liming and mycorrhizal colonization on soil phosphate depletion and phosphate uptake by maize (*Zea Mays* L.) and soybean (*Glycine max* L.) grown in two tropical acid soils. *Plant Soil*, 275-285.

- Nwite, J. C., Onunwa, A. O., Igwe, C. A., and Wakatsuki, T. (2016). Sawah Rice Farming Eco-technology Options for Enhancing Sustainable Nutrient Management and Rice Production in Degraded Inland Valleys of Southeastern Nigeria. *International Journal of Plant and Soil Science*, 9(4), 1-19.
- Nyamangara, J., Piha, M. I. and Giller, K. E. (2003). Effect of combined cattle manure and mineral nitrogen on maize N uptake and grain yield. *African Crop Science Journal*. 11:289–300.
- Nyambati, E. M., Mureithi, J. G. and Wamuango, J. W. (2003). Soil fertility improvement technologies for Western Kenya. Synthesis report of the soil management research project (1994-2002). *KARI Technical note series No.13*.
- Nziguheba, G., Merckx, R., Palm, C. A. and Rao, M. R. (2000). Organic residues affect the phosphorous availability and maize yields in Nitisol of Western Kenya. *Biology Fertility Soils* 32: 328 – 339.
- Obiri-Nyarko, F. (2012). Ameliorating soil acidity in Ghana: A concise review of approaches. In *Proceedings of the International Conference on Agriculture, Science and Engineering (ICASE2012)* (pp. 289-299).
- Odedina, J. N., Odedina, S. A. and Ojeniyi, S. O. (2011). Effect of types of manure on growth and yield of cassava (*Manihot esculenta*, Crantz). *Researcher*, 3 (5): 1 – 8.
- Oguike, P. C, Chukwu G. O. and Njoku N. C. (2006). Physico-chemical properties of a Haplic Acrisol in Southeastern Nigeria amended with rice mill waste and NPK fertilizer. *Proceedings of the 30th Annual Conference of the Soil Science Society of Nigeria, 5th – 9th December 2006, held at University of Agriculture, Markudi, Pp. 38-45*.
- Okalebo, J. R., Othieno C. O., Nekesa A. O., Ndungu-Magiroi K. W. and Kifuko-Koeh M. N. (2009). Potential for agricultural lime on improved soil health and agricultural production in Kenya. *African Crop Science Conference Proceedings*, 9: 339 – 341.
- Omoyo, N. N., Wakhungu, J. and Oteng’i, S. (2015). Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya. *Agriculture and Food Security*, 4(1), 8.
- Onwonga, R. N., Lelei, J. J., Freyer, B., Friedel, J. K., Mwonga, S. M. and Wandhawa, P. (2008). Low-cost technologies for enhancing N and P availability and maize (*Zea mays* L.) Performance on acid soils. *World Journal of Agricultural Sciences*, 4 (5): 862 -873.
- Onwonga, R. N., Lelei, J. J. and B. Mochoge, B. (2010). Mineral Nitrogen and Microbial Biomass Dynamics under Different Acid Soil Management Practices for Maize Production. *Journal of Agricultural Science*, 2(1).

- Padmavathiamma, P. K. and Li, L. Y. (2012). Rhizosphere influence and seasonal impact on phytostabilisation of metals a field study. *Water, Air, and Soil Pollution*, 223(1), 107-124.
- Palm, C. A., Giller, K. E. and Swift, M. J. (2000). Soil organic matter: An overview. In: *The Biology and Fertility of Tropical soils: A TSBF Report 1997-98*. Pp 46-48.
- Phengsouvana, V., Attanandana, T. and Yost, R. S. (2009). Lime application to two acidic upland soils for soybean production in Champasak Province, Lao PDR. *Kasetsart Journal (Natural Sciences)*, 43: 19 – 27.
- Philip, J. W. and Martin, R. B. (2003). Calcium in Plants, *Annals of Botany* 92(4): 487-511. Principles, Practices and Developmental Process. Nairobi, Kenya: *Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture*.
- Proietti, P., Federici, E., Fidati, L., Scargetta, S., Massaccesi, L., Nasini, L. and Gigliotti, G. (2015). Effects of amendment with oil mill waste and its derived-compost on soil chemical and microbiological characteristics and olive (*Olea europaea* L.) productivity. *Agriculture, Ecosystems and Environment*, 207, 51-60.
- Ragasa, C., and Chapoto, A. (2017). The role of price subsidies in fertilizer use and maize productivity in Ghana. *Food Security*, 9(2), 329-353.
- Rahman, M. A., Meisner, C. A., Duxbury, J. M., Lauren, J. and Hossain, A. B. (2002). Yield response and change in soil nutrient availability by application of lime, fertilizer, and micronutrients in an acidic soil in a rice-wheat cropping system. *Paper presented in 17th WCSS, 14th – 21st August 2002. Thailand*.
- Repsiene, R. and Skuodiene, R. (2010). The influence of liming and organic fertilization on the changes of some agrochemical indicators and their relationship with crop weed incidence. *Zemdirbyste=Agriculture*, 97 (4): 3 – 14.
- Reuss, J. O., and Johnson, D. W. (2012). Acid deposition and the acidification of soils and waters (Vol. 59). Springer Science and Business Media.
- Robert, W. and Burgholzer. (1998). Importance of soil analysis on crop production. *Crop and Soil Science*, 57: 80-83.
- Rowell, D. L. (2014). Soil science: Methods and applications. Routledge.
- Ruganzu, V. (2009). Potential of improvement of acid soils fertility by incorporation of natural fresh plant biomass combined with travertine in Rwanda. Gembloux, Belgique: Agricultural University.

- Ryan, J., Estefan, G. and Rashid, A. (2011). Soil and Plant Analysis Laboratory Manual (2nd ed.). International Center for Agricultural Research in the Dry Areas (ICARDA) and the National Agricultural Research Center (NARC).
- Sanchez, P. A. and Jama, B. A. (2002). Soil fertility replenishment takes off in East and Southern Africa. In *Integrated Nutrient Management in Sub-Saharan Africa: From Concept to Practice*, 23–46 (Eds B. Vanlauwe, N. Diels, N. Sanginga, and R.Merkx). Wallingford, UK: CABI.
- Sanginga, N. and Woomer, P. (Eds.)(2009). *Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process*. Nairobi, Kenya: Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture.
- Santos, E. O., Gontijo, I., Silva, M. B and Partelli, F. L. (2017). Sampling Design of Soil Physical Properties in a Conilon Coffee Field. *Revista Brasileira de Ciência do Solo*, 41.
- SAS Institute Inc. (2003). SAS User's Guide: Statistics. SAS Institute, Inc., Cary, NC.
- Scott, B. J., Fisher, J. A. and Cullins, B. R. (2001). Alluminium tolerance and lime increase wheat yield on the acidic soils of central and southern. *Australian Journal of Experimental Agriculture*, 523-532.
- Sharief, A. E., El-Kalla, S. E., Salama, A. M. and Mostafa, E. I. (2010). Influence of organic and inorganic fertilization on the productivity of some soybean cultivars. *Crop and Environment*, 1 (1): 6 – 12.
- Shen, Q. R. and Shen, Z. G. (2001). Effects of pig manure and wheat straw on the growth of mung bean seedlings grown in aluminum toxicity soil. *Bioresource and Technology*, 76: 235– 240.
- Shrestha, B. M., Singh, B. R., Forte, C., and Certini, G. (2015). Long-term effects of tillage, nutrient application and crop rotation on soil organic matter quality assessed by NMR spectroscopy. *Soil use and management*, 31(3), 358-366.
- Sim, C. C., Zaharah, A. R., Tan, M. S., and Goh, K. J. (2015). Rapid determination of leaf chlorophyll concentration, photosynthetic activity and NK concentration of *Elaeis guineensis* via correlated SPAD-502 chlorophyll index. *Asian Journal of Agricultural Research*, 9(3), 132-138.
- Smaling, E. M. (1997). Soil nutrient depletion in Sub-Saharan Africa. In *The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa*, 47–61 (Eds H. Van Reuler and W.Prins). Leidschendam, Netherlands: VKP.
- Snapp, S. S., Nyiraneza, J. and O'Neil, K. (2003). Organic inputs and a cover crop short rotation for improved potato productivity and quality. In: Michigan Potato Research Report. Vol. 34. Michigan State University Agricultural

Experimental Station in cooperation with the Michigan Potato Industry Commission, East Lansing, pp 139–144

- Sodo, N. A. W., Ethiopia, S. and Shirko, M. (2014). Effect of Application of Lime (CaCO₃) and Phosphorus on Yield and related Traits of Maize (*Zea Mays* L.) on Nitisols at Wolaita Sodo, Southern Ethiopia *M.Sc Thesis, Haramaya, Ethiopia*.
- Sumner, M. E., and Noble, A. D. (2003). Soil acidification: The world story. In: Rengel, Z, (eds). *Handbook of Soil Acidity*. Pp. 1–28. Marcel Dekker, New York.
- Tan, K. H. (2010). *Principles of soil chemistry*. CRC press.
- Tang, R. J., and Luan, S. (2017). Regulation of calcium and magnesium homeostasis in plants: from transporters to signaling network. *Current opinion in plant biology*, 39, 97-105.
- Tang, Y., Zhang, H., Schroder, J. L., Payton, M. E. and Zhou, D. (2007). Animal Manure Reduces Aluminum Toxicity in an Acid Soil. *Soil Science Society of America Journal*, 71(6), 1699.
- Tejada, M., Garcia, C., Gonzalez, J. L. and Hernandez, M. T. (2006). Use of organic amendment as a strategy for saline soil remediation: influence on the physical, chemical and biological properties of soil. *Soil Biology and Biochemistry*, 38(6), 1413-14
- Thapa, B. (2015). Soil Fertility. *Soil Science Division*, 1.
- The, C., Calba, H., Horst, W. J. and Zonkeng, C. (2001). Maize grain yield correlated responses to change in acidic soil characteristics after 3 years of soil amendments. *Paper presented on Seventh Eastern and Southern Africa Regional Maize Conference*, 11th – 15th February 2001. pp. 222 – 227.
- Tittonell, P., Vanlauwe, B., De Ridder, N. and Giller, K. E. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? *Agricultural Systems*, 94(3), 376–390.
- Uchida, R. and Hue, N. V. (2000). Soil acidity and liming. In S. J, and U. R, *Plant nutrient management in Hawaii soils, approaches for tropical and subtropical agriculture*. Manoa, Hawaii: College of tropical agriculture and human resources, University of Hawaii.
- Umoetok, S. B. A., Uko, A. E., Archibong, B. E., Ukeh, D. A. and Udo, I. A. (2007). Effect of application of inorganic fertilizer and poultry manure on insect pests and yield of soybean (*Glycine max* L.) in the rainforest zone of Nigeria. *Journal of Food, Agriculture, and Environment*, 5 (2): 149 – 152.

- USDA (United States Department of Agriculture). (1999). Natural Resources Conservation Service Soil Quality Institute 411 S. Donahue Dr. Auburn, AL 36832 334-844-4741 X-177, Technical Note No. 8, May 1999. Available online at: http://soils.usda.gov/sqi/management/files/sq_atn_8.pdf.
- Van Lagen, B. (1996). Soil analyses. *Manual for Soil and Water analysis*, 2-116.
- Van, J. J. (2007). Book review. *The Nature and Properties of Soils*. By N. C. Brady and R. R. Weil. 12th ed. Prentice Hall, Upper Saddle River, NJ, 1999; 881 pp.; ISBN 0 13 852444 0. *Sedimentology*, 47(6), 1230-1230.
- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R. and Six, J. (2010). Agronomic use efficiency of N fertilizer in maize-based systems in Sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339:35–50.
- Vanlauwe, B., Wendt, J. and Diels, J. (2001). Combined application of organic matter and fertilizer. *Sustaining soil fertility in West Africa*, (sustainingsoil), 247-279.
- Wong, M. T. and Swift, R. S. (2003). Role of organic matter in alleviating soil acidity. *Handbook of soil acidity*. Marcel Dekker, New York, 337-358.
- Wood, M. (1993). Nitrogen Fixation in Tropical Cropping Systems. By K. E. Giller and K. J. Wilson. Wallingford: CAB International (1991), pp. 313. ISBN 0-85198-671-4. *Experimental Agriculture*, 29(02), 250.
- Yang, W. H., Peng, J., Sanico A. L., Buresh R. J. and Witt. C. (2003). Using leaf color charts to estimate leaf nitrogen status of rice. *Agronomy Journal*, 95: 212 - 217.
- Zaman-Allah, M., Vergara, O., Araus, J. L., Tarekegne, A., Magorokosho, C., Zarco-Tejada, P. J., and Olsen, M. (2015). Unmanned aerial platform-based multi-spectral imaging for field phenotyping of maize. *Plant methods*, 11(1), 35.