# ASSESSMENT OF THE NUTRIENT STATUS AND LIMITING NUTRIENTS FOR MAIZE PRODUCTION IN SMALLHOLDER FARM FIELDS IN KENYA

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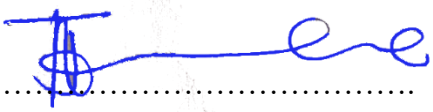
## DECLARATION

This thesis is my original work and has not been submitted for an award of a degree in any other University.



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## DEDICATION

To my family and Dr. Anthony Esilaba for their constant encouragement and unceasing support.

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I thank God above all for enabling me to come this far.

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## ABBREVIATIONS AND ACRONYMS

CBS – Central Bureau of Statistics

CEC- Cation Exchange Capacity

EC-Electrical Conductivity

FAO – Food and Agriculture Organization of the United Nations

GDP – Gross Domestic Product

GEA-Greening the Economy with Agriculture

GoK – Government of Kenya

IFDC– International Fertilizer Development Center

KALRO- Kenya Agricultural and Livestock Research Organization

SOC- Soil Organic Carbon

SSA– Sub Saharan Africa

SSNM-Site Specific Nutrient Management

USAID – United States Agency for International Development

WFP- World Food Programme

WB- World Bank

## ABSTRACT

Low crop yields in Sub Saharan Africa (SSA) are as a result of declining soil fertility. Most farmers rely on nutrient recycling in their farms which is not sustainable as it leaves the soils depleted of nutrients. Consequently, this study was conducted to assess the limiting nutrients in soils of major farming regions in Kenya and to assess the effect of applied nutrients on the growth and development of maize. Thirteen counties in Kenya were selected whereby a total of 23 soil samples at a soil depth of 0 to 30 cm were collected for soil analysis of total nitrogen, total organic carbon, phosphorus, potassium, calcium, magnesium, manganese, copper, iron, zinc, sodium, electrical conductivity, cation exchange capacity (CEC), base saturation and soil pH had mean values were of 0.12%, 1.12, 19.09, 220.43, 1397.39, 163.98, 120, 52, 3.95, 52.78, 1.86, 92.80 mg $kg^{-1}$, 0.11mS/c, 11.98 Cmol (+)/kg, 83.13% and, 5.96, respectively. A nutrient omission trial was set up in the greenhouse at the Kenya Agricultural and Livestock Research Organization (KALRO) Kabete using a completely randomized design. This study had a total of 12 treatments as follows; complete (all macro and micro nutrients added), complete plus lime added, five treatments in which one macro nutrient was removed from the solution of nutrients, another treatment in which micro-nutrient mixture was eliminated from the solution of nutrients, a similar treatment with each of the micro nutrients except zinc, the other with all micronutrients except boron, one treatment with all the micro nutrients except molybdenum and one control (distilled water only). In majority of the soils, significantly ($P<0.05$) higher shoot dry weights were observed in the complete treatment than in the treatments with fewer nutrient elements. The results showed that poor maize growth was mainly due to deficiencies of nitrogen, phosphorus and zinc. Potassium was mainly deficient in western Kenya. Addition of these nutrients improved the yield in majority of the soils. The inherent low soil fertility was correlated with low dry matter yields implying that farmers in areas with declining soil fertility will continue to obtain low crop yields unless organic or inorganic fertilizers are

included in management. Rapid assessment of soil fertility is necessary for tailored soil fertility interventions in most regions of Kenya, to achieve household food security. Meaningful maize yields can only be obtained with soil fertility interventions incorporating all the limiting nutrients in a specific region. Further research is needed to correlate and calibrate the plant availability of macronutrients and micronutrients in laboratory, greenhouse, and field trials for site specific smart fertilizer recommendations in Kenya.

# CHAPTER ONE: INTRODUCTION

## 1.1 Background information

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

Maize in Kenya is considered the main staple food which is in about 40% of cultivated area and responsible for a 2.4% of Kenya's GDP whereby 12.65% is from agricultural GDP. Its production and productivity are below the world average but maize remains the most food source in Kenya's economy (Naseem *et al*., 2018). Most of this maize is grown in small holder farms accounting to approximately 75% of all maize produced in Kenya. According to Kamoni *et al*. (2013), factors such as poor soil fertility, pests and diseases and farm-inputs unavailability limit the optimal production of maize.

A challenge of poor soil fertility in SSA responsible for depressing yield among small scale farmers had been reported by Muthaura *et al*. (2017) Maize productivity grown in different soil types were shown to be enhanced by use of fertilizers.(Ngome *et al.* 2013). SSA has a lowest fertilizer application of about 8 kg/ha which was equivalent to 10% global average as per 2002 (K. et al., 2012). High prices of fertilizers have made it difficult for most small holder farmers to use them for crop production (Bumb et al., 2011).

Soils in SSA have shown to be spatially heterogeneous (Zingore *et al.*,2007; Vanlauwe *et al.*, 2006; Wopereis *et al*., 2006) and therefore soil fertility recommendations should be site specific and should target niches of highest crop responsiveness in heterogeneous farms (Zingore *et al.*, 2007).

Site specific fertilizer recommendations requires soil tests and nutrient omission and optimization trials that can pinpoint the most limiting soil nutrients and establish fertilizer recommendations specific to the sites (Stockdale *et al.,* 2013). However, in most farms, knowledge of limiting soil nutrients is lacking (Kamoni *et al.,* 2013).

### 1.2 Problem statement

In Kenya, approximately 85% of the cereal production is maize. There was over 550,000 metric tons (MT) of maize production drop between 2020 and 2021 which was contributed by factors such as high cost of fertilizers (resulting in lower application rates) and drought (WFP, 2022). The majority of soils in SSA have poor fertility following continuous crop nutrient-mining without replenishment and amendments of fertilizers. (Jones, 2013). In Kenya there has been a declining nutrient stock whereby outputs exceed inputs resulting in acidification of soil, Gicheru and Kimigo (2012).

Between 2021 and 2022, the level of poor soil fertility was approximately 70% in most smallholder farms in Kenya which could be mitigated through fertilizers application (WFP 2022). The high prices of fertilizers have made it difficult for most smallholder farmers to purchase imported fertilizers (Bumb *et al.,* 2011). However, farmers should not apply fertilizers without testing their soils. There is need to assess the capacity at which nutrients are supplied by the soil by carrying out a soil test, as a vital initial step in the development of useful systems of managing crop production, minimizing runoff and leaching of excess fertilizers and precise fertilizer application (Khan Hashim, 2018).

## 1.3 Justification

The ever-increasing population growth and food demands requires sustainable crop production practices. Some farmers are overusing incorrect subsidized fertilizers leading to soil acidity. A challenge of soil acidification, which limits the availability of some nutrients, has previously been reported by Kanyanjua et al. (2002) to be dominant within Western, Eastern, Rift Valley, and Central regions of Kenya. Farmers therefore need to test their soils so as to establish the nutrient needs of the soil and, subsequently, apply the right fertilizer regimes that would increase maize production.

## 1.4 The Objectives of the Study

1. To evaluate the nutrient status of soils in coastal, eastern, rift valley and Western parts of Kenya
2. To determine the nutrient limitations for maize production in soils from coastal, eastern, rift valley and western parts of Kenya and give potential fertilizer recommendations.

## 1.5 Hypotheses

i) Soils from coastal, eastern, rift valley and western parts of Kenya have varying nutrient levels.

ii) Soils from coastal, eastern, rift valley and western parts of Kenya have low nutrient levels.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Importance of agriculture and maize production in Kenya

Agriculture in Kenya contributes immensely to the provision of employment and the economy growth. For instance, agriculture sector contributed approximately 21.9% of gross domestic product (GDP) whereby 56% were from labor force employed in agriculture as indicated by the 19th Kenya Economic Update report between 2013 to 2017. The countries exports are majorly dependent on agriculture, accounting to 65% of merchandise exports in 2017. In parallel to the Kenya Big Four Development Agenda, the agriculture sector aims at a 100% food and nutritional security for all Kenyans by 2022 (World Bank, 2019). Additionally, agriculture had reduced rural poverty by 31.4% by acting as the largest source of income (World Bank, 2019).

Production of maize which is considered the main staple food is under 40% of the cultivated area and contributes to 2.4% and 12.65% of Kenya's GDP and agricultural GDP, respectively (FAO, 2016). Highest maize production of over 75% is from small scale farmers, however, it is only 20% of the production that is availed in the market (Chemonics, 2010). Kenya had a highest per capita maize consumption of 103 kg/person/yr (average for 2012-2014) compared to 73 kg/person/yr, 52 kg/person/yr and 31kg/person/yr for Tanzania, Ethiopia and Uganda, respectively (FAO,2016). Maize productivity and production growth rates in Kenya are below the global average but remains the most important source of food and economy growth (FAO, 2016).

Nationally, maize production has faced a decline over time from about 34 million bags to 25 million bags in the year 2008. At the same time the involvement of the government in terms of expenditure on agriculture has demoralized many farmers (Oluoch-Kosura, 2011). As a result, economic stagnation and increase in poverty levels have been the notion which is brought about by inefficiency in production and marketing of maize (USAID, 2011).

## 2.2 Soil fertility status in Sub Saharan Africa

Fertile soils have been reported to contribute to an increase in the productivity of our farming systems that result in food and nutrition security., income generation and alleviation (Heger *et al*., 2018). According to Jones (2013), continues years of crop nutrient-mining without fertilization and amendments result into poor soil fertility in SSA. Soils in SSA are depleted of nutrients making it difficult to feed the current population, with 236.5 million people undernourished. (FAO, 2017). In SSA, a total of 25% of its productive lands had been heavily degraded due to continuous loss of soil nutrients and organic carbon (Jones et al., 2013). Over the last half century, there was a decrease in yields due to poor soil fertility among SSA cultivated lands (Sanchez 2015; Pradhan et al., 2015). Decline of soil fertility is one of the most serious problems, which has been debatable in the development of sedentary agricultural system for almost a millennium (Hartemink, 2003). According to Herrmann et al. (2014), over 22 kg, 2,5kg and 15kg of nitrogen (N), phosphorus (P) and potassium (K) are annually removed from cultivated land by crops leading to poor soil fertility since there are no soil nutrition remedies.

In numerous research projects and policy documents, issues related to soil fertility have been alarming in Kenya. Soil fertility is among the bio-physical constraints facing food security in SSA (Sanchez *et al*., 1997). Varying proportions of soils in SSA have high erodibility and low retention of moisture, low nutrient contents and poor organic matter. This has resulted into a decline in the crop yields, poor physical properties of the soil such as reduced aggregation of the soil, higher bulk density and low infiltration of water into the soil, and reduced vegetation cover and biodiversity (Swift et al., 2004; Onduru *et al*., 2006).

Nitrogen and phosphorus annual net losses in the East African Highlands were estimated to be 42 kg $ha^{-1}$ and 3 kg $ha^{-1}$, respectively, between 1982 and 1984 (Stroorvogel *et al*., 1993).

Phosphorus losses are very high, ranging between 8 kg $ha^{-1}$ and 13 kg $ha^{-1}$ (Smaling, 1993). All these nutrient losses are due to denitrification, water erosion, leaching and crop harvest.

The outputs of the 'Green Revolution' that advocated for improved plant genetics through biotechnology and advancements in agricultural technologies are limited owing to poor soil fertility among smallholder farmers. With poor soil fertility, efforts in investments on cropping systems in SSA translates to 30% of potential yields (Mueller *et al.,* 2012).

### 2.3 Importance of macro and micronutrients in plants

Fertilizer use is important in achieving increased yield. (Stewart, 2022). Crop yield increased to at least 50% due to fertilizer application in the 20th century. In instances where there is no nitrogen fertilizer application, Yousaf et al. (2017) showed a decrease of 40% and 40-57% in corn and wheat yields. Plant nutrients are important for better yield, increase in size and complexity, they can either be general compounds or chemical elements. They also help in metabolism and external activities (He and Yang, 2007). Macronutrients are needed in huge amounts by plants for survival because of the various metabolic processes they take place in. The macronutrients essential to plants are nitrogen, potassium, phosphorous, magnesium, calcium, and Sulphur. These nutrients assist in increasing the quality, growth and yield of various crops (Morgan and Connolly, 2013).

Micronutrients protect plants from several abiotic and biotic species including the stresses of UV radiation, heavy metals, heat, diseases and insect pest attacks as well as drought (Shanker and Venkateswarlu, 2011; Rowley *et al.,* 2012; Morgan and Connolly, 2013). Micronutrients are used in small quantities by plants. They are essential in plant growth, as their application increases quality and yielding of agricultural products. Copper, zinc, manganese, iron and boron are among the essential micronutrients for plant growth (Singh, 2004; Rengel, 2007; Gao *et al*, 2008).

### 2.3.1 Nitrogen

Nitrogen (N) in plants is an essential nutrient for maize and a key determinant of grain yield particularly through its role in proteins and chlorophyll biosynthesis and mediates several major metabolic pathways of plant biochemistry (Basso and Ceretta, 2000; Sangoi *et al*., 2008) It participates in several major metabolic pathways of plant biochemistry (Andrade et al., 2003). An increase in nitrogen application resulted into an increase in growth and development of most cereals, however, with the same application result to a decrease in grain yield in most legumes (Gaudin et al., 2014) Nitrogen has shown to improve maize yields when applied at appropriate phenological stages. Continuous intensive farming without either soil fertilization or soil amendments and leaching led to poor soil fertility (Bayer et al., 2006)

### 2.3.2 Phosphorus

Phosphorus (P) is important in several plant metabolic processes such as growth and development, photosynthesis and nucleus formation and cell division. P deficiency tends to inhibit or prevent shoot growth. (Annaheim *et al.,* 2015). Application of water-soluble mineral P has a higher efficiency than P supplied through organic fertilizers. There is limited mechanization in fertilizer application, however, fertilizers to enhance phosphorous are largely applied using band placement. For instance, in wheat, integration of field-to-field variability with site-specific nutrient management strategies were shown to have a potential in increasing fertilizer use efficiency (Jat *et al.*, 2014). Energy from photosynthesis and metabolism is stored in phosphate compounds for later use for growth and development of maize (Ayub *et al*., 2002)

### 2.3.3 Potassium

Potassium (K) is considered as most ambient macronutrient required for proper maize growth, development, and sustainable yield (Bukhsh *et al*., 2012). Fan *et al*. (2014) reported an increase in SOC concentrations and maintaining high crop yields following incorporation of manure with NPK inorganic fertilizers.

### 2.3.4 Calcium

Calcium is important in the mediation of enzyme activation, osmotic regulation, and activation of K during transpiration in plants (Hepler, 2005). Calcium in combination with magnesium in lime can control soil acidification and sustainable use of agro-chemicals (Branca et al., 2013).

### 2.3.5 Magnesium

Magnesium is important in enhancing photosynthesis, whereby its optimal amounts with other minerals such as phosphorous, nitrogen and potassium are responsible in increase in plant growth and development (Randhawa and Arora, 2000). Using N for an extended period of time decreases magnesium ($Mg^{2+}$), and potassium ($K^{+}$) levels, exchangeable calcium (Ca2+), and cation exchange capacity (CEC) (Jagadamma et al., 2008).

### 2.3.6 Iron, manganese, copper, zinc, boron and molybdenum

Manganese and copper are important components in the chlorophyll formation, however, their deficiency results into yellowing of plant tissue. Zinc, boron, and molybdenum are each involved in protein formation, while Iron is essential for many important enzymes such as cytochrome which is part of electron transport chain, synthesis of chlorophyll, maintenance of chloroplast structure, and enzyme activity (Yadegari, 2014; Eskandari., 2011; Mamatha, 2007).

## 2.4 Importance of soil testing and fertilizer use

A sound nutrient management program should be planned through a soil test to determine the fertility and pH levels. A soil test is important for optimizing production of crops, to protect the surrounding from being contaminated by runoff and leaching. SSA is characterized by low use of fertilizers (IFDC, 2006). In SSA fertilizers are ever increasing in prices; therefore, most farmers cannot afford them (Sanchez et al., 1997). The high-cost fertilizers result to its low use by most small-scale farmers (Bumb et al., 2011) and this has contributed to the heterogeneity in farms as most farmers do not apply the fertilizers as recommended; most of them under apply.

Nourishment of crops, being an important practice in obtaining high yields and good-quality products in large-scale agricultural strategies (FAO, 2011), makes fertilizers a guaranteed requirement for obtaining good yields. Excessive addition of fertilizers leads to pollution of water and soil, and places human and wildlife health in danger. Contemporary nutrient management recommendations require soils to be tested to obtain a maximum fertilizer rate which puts into consideration the spatial and temporal variability of crops. There is evidence of increased crop yields due to fertilizer applications. For instance, Dowswell and Borlaug, (1994) reported a 50% increase in crop yield due to chemical fertilizer applications.

**2.5 Site specific nutrient management to include nutrient omission trials.**

Site specific nutrient management optimizes the soil nutrient supplies over time and space to match the requirements of crops through four key principles. The principles, called the "4 Rs", are all about using the right product, at the right time, at the right rate and at the right place. They date back to at least 1988 and are attributed to the International Plant Nutrition Institute (Bruulselma et al., 2012). The application and management of nutrients are dynamically adjusted to crop needs of the location and season.

Site specific nutrient management can maintain yields and increase by optimizing the balance between supply and demand of nutrients and providing more balanced plant nutrition (Wang et al. 2007). Ortiz-Monasterio and Raun (2007) further showed improvement in nutrient use efficiency from the application of fertilizers. Site-specific nutrient management encourages precision and efficiency in fertilizer application as per the crop requirements and showed potential mitigation occurrences following appropriate application of fertilizers. (Pasuquin *et al*., 2014).

## 2.6 Effect of application of macronutrients and micronutrients on maize growth and yield

The optimal maize yields is 6 ton/ha but it has remained at 2 ton/ha due to inadequate absorption of modern production technologies like inadequate use of fertilizers and poor farmer know-how (Onono et al., 2013). As a mitigation, use of either organic or inorganic fertilizer together with different cropping systems were proven to be effective in increasing crop yields (Herrmann et al., 2014). According to Hauggaard-Nielsen et al. (2013), an increase in levels of N fertilization results in an increase in maize yields. However, availability of N that significantly influence yields, is negatively affected by poor soil texture, drainage and in organic carbon which are responsible for leaching, mineralization and denitrification (Zhu et al., 2015). Maize grown in soil deficient in N and P nutrients were first shown to have poor growth in its canopy and resulted to a reduced grain yield (Muthaura et al., 2017). Ngome et al. (2013) showed the association between soil types and their management and the resultant crop yields, is dependent on use of modern technologies which will in turn address maize production constraints in Kenya.

# CHAPTER THREE: MATERIALS AND METHODS

## 3.1 Site description

The soils were collected from 23 sites in 13 counties. These were the Kenya Cereal Enhancement Programme sites in Kenya namely: Embu (Agricultural Technology Development Centre (ATDC) Siakago), Bungoma (ATDC, Mabanga), Kibwezi (two sites at the University of Nairobi farm), South Eastern University of Kenya, Kitui (two sites), Nandi (Baraton University), Mwingi (Kyuso university), Taita Taveta (farmers field in Wundanyi, Mwatate and Chala), Voi (farmers field), 11 sites distributed in KALRO stations in Katumani, Kambi ya mawe, Msabaha, Tharaka-Nithi, Kitui, Kiboko, Mtwapa, Matuga, Kitale, Kakamega and Njoro (Table 3.1; Figure 3.1).

Composite sampling was used, where soils were collected from different points within a sampling area and homogenised into a single sample of 100 kg each site, for the purposes of soil analysis and pot experiments in the greenhouse to establish the limiting nutrients for maize production. There were 36 pots for each site and each pot constituted 2.5 kg of soil, bringing it to a minimum of 90 kg of soil per site. A sample of the soil was taken to the laboratory for chemical analysis. Pearson correlation was used to assess the relationship between various soil properties.

**Table 3.1: Site characteristics of where soils were sampled.**

| Sample Site | Latitude | Longitude | Altitude (masl) | Soil Type | Rainfall (mm) | Min-Temp | Max-Temp |
|---|---|---|---|---|---|---|---|
| KALRO, Matuga | -4.170172 | 39.600170 | 27.000000 | Gleyic, Luvisols | 800-1200 | 20-23 | 28-31 |
| KALRO, Mtwapa | -3.937203 | 39.742103 | 25.000000 | Gleyic, Luvisols | 800-1200 | 20-23 | 28-31 |
| Mwatate | -3.470481 | 38.400981 | 860.200000 | Rhodic, Ferralsols | 450-900 | 20-23 | 28-31 |
| Voi | -3.394739 | 38.574961 | 547.400000 | Eutric, Fluvisols | 300-900 | 20-23 | 28-31 |
| Wundanyi (Werugha) | -3.376908 | 38.335617 | 1647.200000 | Humic, Cambisols | 1000-1600 | 11-13 | 23-25 |
| Chala Site | -3.282583 | 37.740456 | 894.600000 | Calcic, Cambisols | 450-900 | 15-17 | 27-29 |
| KALRO, Msabaha | -3.268474 | 40.050703 | 22.000000 | Gleyic, Luvisols | 800-1200 | 20-23 | 28-31 |
| KALRO/ICRISAT centre Kambi ya Mawe Makueni | -2.490723 | 38.040761 | 865.000000 | Luvisols | 400-600 | 17-23 | 29-35 |
| University of Nairobi Kibwezi | -2.310001 | 38.028503 | 810.000000 | Luvisols | 400-600 | 17-23 | 29-35 |
| University of Nairobi Kibwezi | -2.310001 | 38.028503 | 810.000000 | Luvisols | 400-600 | 17-23 | 29-35 |
| KALRO, Kiboko | -2.213550 | 37.714575 | 929.000000 | Vertisols | 400-600 | 15-17 | 27-29 |
| KALRO, Katumani | -1.573069 | 37.249642 | 1568.500000 | Ferric, Acrisols | 600-800 | 11-13 | 23-25 |
| KALRO Sub-center Kitui Ithokwee | -1.380681 | 37.969818 | 1131.000000 | Ferric, Acrisols | 800-1200 | 15-17 | 27-29 |
| South Eastern University Kitui | -1.314874 | 37.757380 | 1171.000000 | Ferric, Acrisols | 400-600 | 15-17 | 27-29 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| South Eastern University Kitui | -1.314874 | 37.757380 | 1171.000000 | Ferric, Acrisols | 400-600 | 13-15 | 25-27 |
| Embu, Siakago ATDC | -0.573760 | 37.637890 | 1193.000000 | Ferric, Acrisols | 800-1200 | 15-17 | 27-29 |
| Kyuso Polytechnic Mwingi | -0.546940 | 38.214120 | 889.000000 | Chromic, Luvisols | 400-600 | 17-23 | 29-35 |
| Karlo, Njoro | -0.317669 | 35.938856 | 2155.000000 | Mollic, Andosols | 800-1200 | 11-13 | 23-25 |
| KALRO, Tharaka Nithi | -0.153822 | 37.971538 | 588.000000 | Lixisols | 600-800 | 17-23 | 29-35 |
| Nandi Baraton University | 0.260180 | 35.083820 | 1971.000000 | Humic, Nitisols | 1200-1600 | 11-13 | 23-25 |
| KALRO, Kakamega | 0.282089 | 34.771296 | 1525.000000 | Orthic, Acrisols | 1600-2000 | 15-17 | 27-29 |
| Bungoma Mabanga ATDC | 0.600424 | 34.622588 | 1513.000000 | Acrisols | 1200-1600 | 15-17 | 27-29 |
| KALRO, Kitale | 0.981603 | 35.016856 | 1903.000000 | Rhodic, Ferralsols | 800-1200 | 11-13 | 23-25 |

Min-Temp: Minimum Temperature; Max-Temp: Maximum Temperature

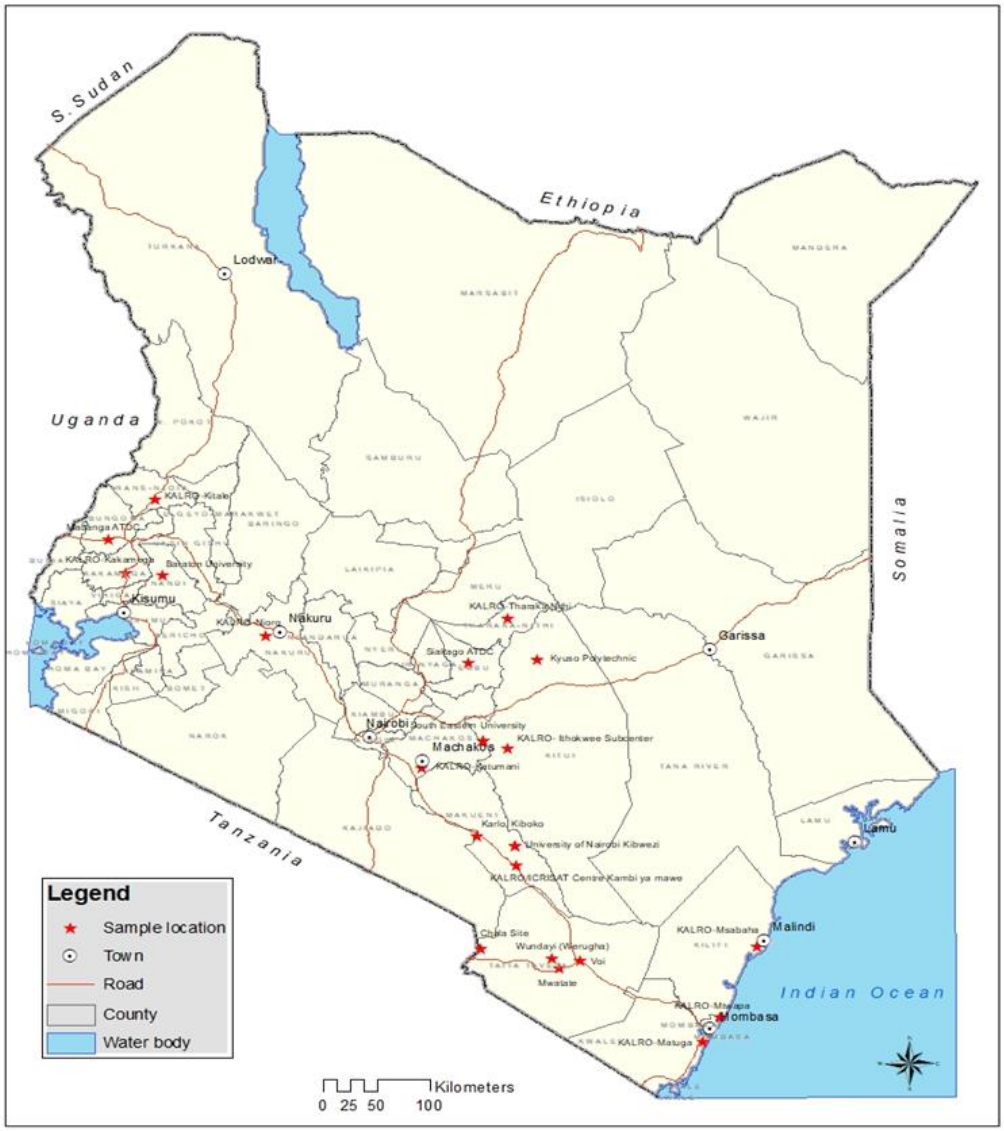



**Figure 3. 1: A map showing the sites where soils were sampled**

### 3.2 Soil analyses

In analyzing for the macro- and micronutrients, the soil samples collected were oven dried ($40^0$C), milled and passed through a 2mm sieve as per the methodology described by Hinga *et al*. (1980). Herein, the analysis in the soil samples target to establish the amounts of nitrogen, magnesium, phosphorus, total organic carbon, calcium, sulphur, manganese, copper, zinc,

potassium, sodium, iron, electrical conductivity (EC), cation exchange capacity (CEC), base saturation and pH.

### 3.2.1 Total carbon

The colorimetric method (Anderson, *et al.,* 1993) was adopted to determine total organic carbon. In brief,1 gram of soil was weighed, and 2 ml of deionized water was added. The soil was wet by the addition of 10 ml of 5% potassium dichromate solution and was followed by addition of 5 ml concentrated $H_2SO_4$. The samples were placed on the digestion block and digested for 30 minutes at 150°C. After addition of 50 ml of 0.4% barium chloride solution, the mixture was subjected to a 600 nm on a spectrophotometer to determine its absorbance.

### 3.2.2 Total nitrogen

It was determined by the Kjeldahl method using Tecator equipment (Hinga, et al., 1980). One gram of soil was weighed and put in digestion tubes. One gram of catalyst mixture was then added and 10 ml of concentrated $H_2SO_4$ was added. The mixture was boiled, and 30 ml of distilled water was then added. Finally, distillation and titration were done until color change was observed from green to pink.

### 3.2.3 Calcium, Potassium and Sodium

Calcium, Potassium and Sodium content were obtained by the Mehlich method (Mehlich, 1984). Two milliliters of working standard series were pipetted. Soil extracts and blanks were put into 25 ml vials. One milliliter of 2% lanthanum chloride was added, 14 ml distilled water was then added, and the mixture shaken by hand. The working standard series, soil extracts and blank solutions were aspirated into the flame photometer and transmissions were recorded.

### 3.2.4 Phosphorus

Phosphorus was determined by two methods depending on the pH of the soil. Mehlich and Olsen methods were used in the cases where the soil pH levels were below and above 7 respectively.

Phosphorus determined by the Mehlich method; 5 ml of the working standard series where soil extracts and blanks were put in test tubes. One milliliter of ammonium vanadate-molybdate mixture was then added, mixed and the optical density was read on the spectrophotometer after one hour at 430 nm.

Phosphorus determined by the Olsen method (Olsen et., al 1962); 2.5 g of soil was weighed out and put in a 250 ml polythene bottle. Fifty milliliters of extracting solution of pH 8.5 was added, using a dispenser and it was shaken mechanically in a horizontal position on a reciprocating shaker (200 revolutions per minute) for a half an hour. The suspension was filtered through fine filter paper. A blank was included and a standard sample in each series. A duplicate sample was included after every ten samples in a batch.

Ten milliliters of the standard series sample extracts and blanks were added into 50ml volumetric flasks. Eight milliliters of the mixed reagent were added, mixed well and filled to 50ml mark with distilled water then mixed again. It was then left on the bench for fifteen minutes for color to develop, the color was then left stable for 24 hours. The concentration (in ppm) was measured on the spectrophotometer at 880 nm.

### 3.2.5 Magnesium

Magnesium was determined by the Mehlich method. One milliliter of working standard series, soil extracts and blanks were put into a test tube. Five milliliters of a solution of magnesium compensation were added, then 2 ml of titan yellow and 2 ml of sodium hydroxide were added and mixed simultaneously. The spectrophotometer optical density was read after one hour at 540 nm. The color was left to stabilize for at least six hours. If a precipitate formed the soil extract was diluted by taking 0-.5 ml of the soil extract and adding 0.5 ml of extracting solution and the proceedings were carried out as above. The corrected concentration was multiplied by dilution factor of 2.

### 3.2.6 Manganese

Manganese was determined by the Mehlich method. One milliliter of working standard series, soil extracts and blanks were put into a test tube and mixed with four milliliters of phosphoric acid –potassium periodate and 2 ml sodium hydroxide. The optical density on the spectrophotometer was read after one hour at 520 nm (Mehlich, et al., 1962)

### 3.2.7 Electrical conductivity

Electrical conductivity was determined by switching the power of the conductivity meter (Thermo Scientific Model Eutech COND 6+) and letting it warm up for 10 minutes, then selecting 'K' using the keypad, then the display reading was adjusted to 1413 µS/cm. The value was recorded in mmhos/cm.

### 3.2.8 Soil pH

Soil pH was measured in a 1:1 soil water suspension where 20 g of soil was sampled into a 50 ml beaker, and an internal reference sample was included in each series. Twenty milliliters of distilled water added with a dispenser. It was stirred and left to stand for an hour, then time was counted from the moment the distilled water was added. The pH meter was calibrated with a glass-calomel combination electrode according to the instructions before use. The samples were stirred with a string rode before placing the electrode was placed in the sample. The electrode was immersed in the suspension and the pH-meter was read when it was stable. The results were then recorded.

### 3.2.9 Cation Exchange Capacity

Cation exchange capacity (CEC) was determined with 1N ammonium acetate (exchangeable cations determined were calcium, magnesium, potassium and sodium). Three grams of air-dried soil was mixed with 10 grams of acid washed quartz sand. The mixture was then transferred to a percolation tube which had been fitted with cotton wool and a 1 cm thick quartz sand. The soil was then leached with four portions of 25 ml of ammonium acetate 1N, pH 7.0.

The leachate was collected in a 100 ml volumetric flask. When the leaching was complete the contents of the flask were made up to 100 ml with ammonium acetate pH 7.0. The leachates were preserved for the determination of exchangeable calcium, magnesium, potassium, and sodium. The samples were leached with 100 ml ethyl alcohol (96%). The leachate was redistilled to recover the alcohol and the outlets of the percolation tubes rinsed well with distilled water. The sample was then divided into four portions of 25 ml, and 1N sodium chloride added to determine CEC.

### 3.3 Treatments and experimental design

Assessment of the limiting nutrients was done at the KALRO Kabete greenhouse (Figure 3.2). The treatments comprised 23 soils and 12 nutrient regimes as indicated in (Table 3.2). Different chemicals and rates were used for the omission trials (Table 3.3). The treatments were laid out in a completely randomized design with a factorial arrangement and replicated three times. The experimental factors were the soils from the 23 sites and the 12 nutrient regimes.

The study adopted the double pot technique (Figure 3.3) which provides quick identification of nutrients that are in short supply in the soil, as reported by Janssen (1974, 1990). The method gave room for assessment of the fertility of the soil in a relatively shorter period, using considerable amounts of soil and minimal space (Lisle *et al.*,2000). The upper pot is filled with soil where the seeds are sown. The second pot is attached to the upper one and it contains a nutrient solution.

The absence of the prototype nutrient from the solution was indicative of nutrient deficiency in the soil. If the soil could not provide the omitted nutrient in sufficient quantity, then deficiency symptoms were observed on the plant. An omission pot experiment displays a visible order in which crops respond to nutrient availability, unlike analyzed results which do not provide the major limiting nutrient. Maize was used as a test plant since it responds well to

nutrient deficiencies, it has rapid growth, as well as a uniform development from the early stages (Bell, 2002).

**Figure 3.2: Set up of the experiment at KALRO Kabete greenhouse.**

**Table 3.2: Treatments used in the experiment.**

**Treatments**

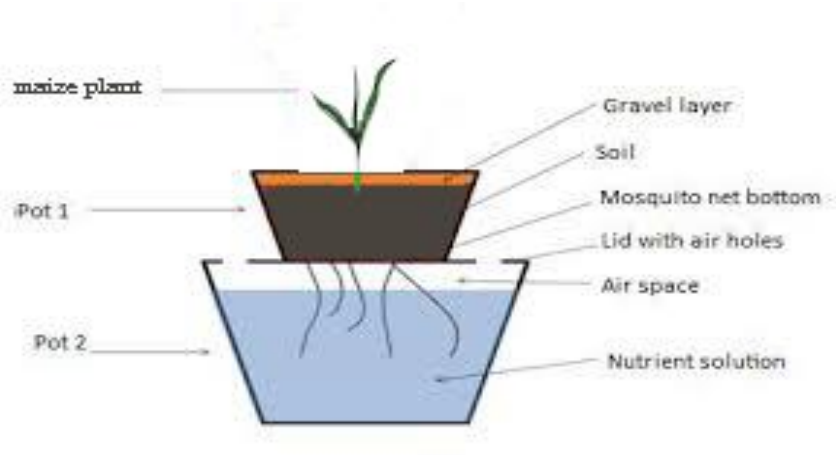
| | Lime | Macro-nutrients | | | | | | Micro- nutrients |
|---|---|---|---|---|---|---|---|---|
| | | N | P | K | Mg | Ca | S | |
| Complete | - | + | + | + | + | + | + | + |
| Complete plus lime | + | + | + | + | + | + | + | + |
| N omitted | - | - | + | + | + | + | + | + |
| P omitted | - | + | - | + | + | + | + | + |
| K omitted | - | + | + | - | + | + | + | + |
| Ca omitted | - | + | + | + | + | - | + | + |
| Mg omitted | - | + | + | + | - | + | + | + |
| Micronutrients omitted | - | + | + | + | + | + | + | - |
| +Micronutrients-zinc | - | - | - | - | - | - | - | +Micronutrients - Zinc |
| +Micronutrients-Boron | - | - | - | - | - | - | - | +Micronutrients-Boron |
| +Micronutrients – molybdenum | - | - | - | - | - | - | - | +Micronutrients-Molybdenum |
| Control | - | - | - | - | - | - | - - | |

The composition of the nutrient solutions was based on Hoagland solution (Hoagland and Arnon 1938).

**Table 3.3: Nutrients, chemical forms and rates used for omission pot trials.**

| Element | Chemical forms | RMM | At. No | Weight (grams) | Volume (ml) | Conc.(ppm) **WRT** element | Hoagland solution ppm's | Nutrient rates (kg-element ha-1*) |
|---|---|---|---|---|---|---|---|---|
| N | $NH_4NO_3$ | 80 | 28 | 2.86 | 1000 | 1000 | 210 | 95.71 |
| P | $KH_2PO_4$ | 136.08 | 31 | 4.39 | 1000 | 1000 | 31 | 10.93 |
| K | $KNO_3$ | 101.1 | 39 | 2.59 | 1000 | 1000 | 235 | 82.89 |
| Ca | $Ca\ (NO_3)_2$ | 236.15 | 40 | 5.90 | 1000 | 1000 | 200 | 70.54 |
| Fe | $Fe_2(SO_4)$. X $H_2O$ | 399.88 | 56 | 7.14 | 1000 | 1000 | 1 | 0.35 |
| Mg | $MgO_4S7H_2O$ | 246.47 | 24 | 10.27 | 1000 | 1000 | 48 | 0.14 |
| B | $H_3BO_3$ | 61.83 | 11 | 5.62 | 1000 | 1000 | 0.5 | 0.18 |
| Mo | $MoNa_2O4.2H_2O$ | 241.95 | 96 | 2.52 | 1000 | 1000 | 0.3 | 0.11 |
| Mn | $MnCl_2.4H_2O$ | 197.91 | 55 | 3.60 | 1000 | 1000 | 0.5 | 0.18 |
| Zn | $0_4SZn.7H_2O$ | 287.56 | 65 | 4.42 | 1000 | 1000 | 0.2 | 0.1 |
| Lime | CaO (43-55%) and Magnesium (20%) | | | | | | | 0.20 |

Calculated from the area of a 19-cm diameter pot for maize using the formula $\boldsymbol{\pi}r^2$. The figure obtained was then converted to hectares to establish the rate of fertilizer to use per pot.
RMM- Relative Molecular Mass; WRT- With respect to; At No- Atomic number




Source: https://doi.org/10.1371/journal.pone.0145202.g001

**Figure 3.3: Illustration of the setup of the double pot experiment**

The upper pot measured 17.5 cm x 19 cm and the lower pot was 15 cm x 16.5 cm. Approximately 2.5 kg of soil was added to the upper pot while the lower pot was filled with 100 ml of each nutrient solution bringing it up to 1000 ml -1200 ml depending on the treatment. Maize variety H614D was used in the experiment. Sowing was done using five seeds per plot which was further thinned to four plants per pot after emergence. Prior to planting, holes were made in the pots that contained the soil and the soils were watered to field capacity.

The soil was saturated with excess water for 24 hours and the surface of the pots covered with a thin plastic film to avoid evaporation. When the gravitational water flow seized, a sample of the wet soils from each pot were weighed to obtain the fresh weight, then oven dried at 150°C for moisture content determination. The pots were watered daily during the experiment using distilled water while at the same time maintaining the soils at field capacity. Additionally, renewal of the nutrient solutions was done once after every two weeks.

### 3.4 Data collection

At 90 days after planting, the plant height of the four plants was determined by measuring the highest point of the arch of the uppermost leaf by use of a tape measure in centimeters and then averaged. The longest leaf in each of the four maize plants was measured for leaf length. The

leaf was measured from the tip of the entire leaf down to the base of the leaf stem in centimeters and averaged. The same leaf in each of the four plants was used to measure leaf width across the widest part of the leaf in centimeters and then averaged. The maize samples were oven-dried at $72^0$C, for 48 hours until constant weight was obtained, and the dry weight determined in grams for the four plants.

### 3.5 Data analysis

Analysis of variance was performed using GenStat $15^{th}$ edition and separation of treatment means conducted using the least significant difference test at $P \leq 0.05$ (GenStat, 2012). Nutrient deficiency symptoms were also monitored through visual assessment. Pearson correlation was used to assess the relationship between various soil properties.

# CHAPTER FOUR: RESULTS

## 4.1 Nutrient status of soils in Eastern, Rift valley and Western parts of Kenya.

### 4.1.1 Soil pH

Soil pH ranged from 4.67 at Mwingi Kyuso Polytechnic to 8.59 at KALRO Kitale (Table 4.1). The mean pH of the soils was 5.96, which is classified as acidic (Table 4.1). Soils from Kibwezi, Msabaha, Mwatate and KALRO Kitale were strongly alkaline.

### 4.1.2 Total soil organic carbon

Total organic carbon varied from 0.21 to 2.80 mg/kg with a mean of 1.12 mg/kg (Table 4.1). Most soils had deficient levels of organic carbon except for KALRO Kakamega which had 2.80 %. Organic carbon was positively correlated (r=0.991**) to total nitrogen (Table 4.2).

### 4.1.3 Total nitrogen

Total nitrogen varied from 0.04 % (KALRO Mtwapa) to 0.26 % (KALRO Kakamega) with a mean of 0.12 % (Table 4.1). Nitrogen was deficient in all soils except KALRO Kakamega and Baraton University Nandi considering the critical limit is 0.2 to 0.5 %. Total nitrogen was positively correlated to total organic carbon (r=0.991**) (Table 4.2).

### 4.1.4 Phosphorus

Phosphorus varied from 2 mg/kg (KALRO Msabaha) to 30 mg/kg (KALRO Mtwapa) with a mean of 19.09 mg/kg (Table 4.3).

### 4.1.5 Potassium

Potassium varied from 117 mg/kg to 585 mg/kg with a mean of 220.43 mg/kg (Table 4.1). Critical potassium values range from 93.60 mg/kg to 585 mg/kg.

### 4.1.6 Sulphur

Sulphur levels ranged from 3.67 mg/kg to 68 mg/kg with a mean of 18.73 mg/kg (Table 4.3).

### 4.1.7 Micronutrients

Calcium, magnesium, sodium, iron, manganese, and copper were at adequate levels. Their values are shown in (Table 4.3). However, zinc was deficient with levels that ranged from 0.20 to 10.80 mg/kg, with a mean value of 1.86 mg/kg. The critical level is 5. mg/kg.

### 4.1.8 Cation exchange capacity

CEC varied from 6 cmol (+)/kg to 23.76 cmol (+)/kg with a mean of 11.98 cmol (+)/kg, which suggests that the study soils had low and moderate CEC. The low and moderate values range from 6 cmol (+)/kg -25 cmol (+)/kg. The exchangeable bases that include calcium, magnesium, potassium and sodium showed significant and positive correlation with each other and also with the sum of cations, base saturation, and Exchangeable Sodium Percentage (ESP) and electrical conductivity (Table 4.2).

**Table 4.1: Chemical analysis of soil**

| Site | soil pH | N% | C% | p (ppm) | K (ppm) | Ca (ppm) |
|---|---|---|---|---|---|---|
| Ithokwee Kitui KALRO Substation) | 5.50 | 0.09 | 0.76 | 15.00 | 273.00 | 840.00 |
| South Eastern University Kitui 1 | 5.21 | 0.08 | 0.55 | 25.00 | 140.40 | 600.00 |
| South Eastern University Kitui 2 | 6.69 | 0.14 | 1.44 | 25.00 | 117.00 | 2760.00 |
| Mwatate Taita Taveta | 5.40 | 0.09 | 0.80 | 15.00 | 179.40 | 800.00 |
| Kibwezi (University of Nairobi 1) | 8.35 | 0.11 | 0.92 | 25.00 | 585.00 | 2000.00 |
| Kibwezi (University of Nairobi 2) | 7.54 | 0.13 | 1.12 | 24.00 | 460.20 | 1960.00 |
| Kambi ya Mawe Wote (KALRO/ICRISAT) | 5.51 | 0.08 | 0.55 | 20.00 | 226.20 | 1180.00 |
| Mwingi Kyuso Polytechnic | 5.61 | 0.06 | 0.45 | 20.00 | 156.00 | 740.00 |
| KALRO Katumani | 5.81 | 0.10 | 0.80 | 5.00 | 179.40 | 860.00 |
| KALRO Tharaka Nithi | 5.89 | 0.06 | 0.40 | 20.00 | 132.60 | 840.00 |
| Embu Siakago ATDC | 5.62 | 0.09 | 0.69 | 5.00 | 140.40 | 800.00 |
| KALRO Kiboko | 5.58 | 0.08 | 0.57 | 20.00 | 390.00 | 1600.00 |
| KALRO Msabaha | 4.67 | 0.14 | 1.54 | 25.00 | 117.00 | 600.00 |
| Chala Taita Taveta | 8.59 | 0.12 | 1.06 | 2.00 | 117.00 | 5540.00 |
| Wundanyi Taita Taveta | 5.20 | 0.18 | 1.91 | 25.00 | 117.00 | 600.00 |
| Voi Taveta | 8.10 | 0.13 | 1.20 | 18.00 | 265.20 | 3400.00 |
| KALRO Mtwapa | 6.41 | 0.04 | 0.21 | 30.00 | 117.00 | 780.00 |
| KALRO Matuga | 5.67 | 0.09 | 0.66 | 25.00 | 117.00 | 600.00 |
| KALRO Kitale | 4.91 | 0.15 | 1.61 | 20.00 | 202.80 | 800.00 |
| KALRO Kakamega | 5.08 | 0.26 | 2.80 | 25.00 | 117.00 | 1100.00 |
| Bungoma Mabanga ATDC | 5.05 | 0.13 | 1.19 | 5.00 | 117.00 | 720.00 |
| Baraton University Nandi | 4.78 | 0.21 | 2.30 | 20.00 | 218.40 | 840.00 |
| KALRO Njoro | 5.82 | 0.19 | 2.18 | 25.00 | 585.00 | 2180.00 |
| **Average** | **5.96** | **0.12** | **1.12** | **19.09** | **220.43** | **1397.39** |
| **Adequate level** | **6 -7.2** | **0.2- 0.5** | **2.66-5.32** | **30-80** | **93.6-585** | **400-3000** |

**Table 4.1 contd': Chemical analysis of soil**

| Site | Mg (ppm) | Mn (ppm) | Cu (ppm) | Fe (ppm) | Zn (ppm) | Na(ppm) | S(ppm) | CEC |
|---|---|---|---|---|---|---|---|---|
| Ithokwee Kitui KALRO Substation) | 164.56 | 195.25 | 2.66 | 37.50 | 1.90 | 131.1 | 34.33 | 7.36 |
| South Eastern University Kitui 1 | 162.14 | 96.25 | 3.32 | 19.30 | 0.30 | 57.50 | 9.00 | 6.56 |
| South Eastern University Kitui 2 | 125.84 | 222.75 | 5.36 | 22.30 | 0.20 | 32.20 | 4.67 | 23.76 |
| Mwatate Taita Taveta | 129.47 | 137.50 | 5.45 | 22.70 | 0.50 | 50.60 | 13.67 | 10.76 |
| Kibwezi (University of Nairobi 1) | 124.63 | 123.75 | 5.80 | 38.40 | 0.68 | 273.70 | 12.00 | 11.76 |
| Kibwezi (University of Nairobi 2) | 121.00 | 123.75 | 3.80 | 23.00 | 1.36 | 172.50 | 8.00 | 15.20 |
| Kambi ya Mawe Wote (KALRO/ICRISAT) | 140.36 | 148.50 | 1.47 | 25.10 | 0.34 | 112.70 | 16.00 | 12.80 |
| Mwingi Kyuso Polytechnic | 146.41 | 55.00 | 4.70 | 29.70 | 0.70 | 32.20 | 49.67 | 11.60 |
| KALRO Katumani | 156.09 | 60.50 | 6.08 | 32.00 | 1.15 | 36.80 | 5.67 | 10.00 |
| KALRO Tharaka Nithi | 127.05 | 30.25 | 1.00 | 29.50 | 0.78 | 62.10 | 51.43 | 10.40 |
| Embu Siakago ATDC | 135.52 | 60.50 | 5.45 | 31.90 | 0.67 | 75.90 | 3.67 | 12.80 |
| KALRO Kiboko | 121.00 | 55.00 | 1.27 | 20.90 | 1.45 | 218.50 | 11.67 | 6.36 |
| KALRO Msabaha | 176.66 | 93.50 | 2.23 | 17.50 | 0.47 | 32.20 | 7.33 | 6.00 |
| Chala Taita Taveta | 216.59 | 30.25 | 4.40 | 13.60 | 1.00 | 23.00 | 4.33 | 16.00 |
| Wundanyi Taita Taveta | 158.51 | 44.00 | 5.40 | 77.90 | 1.58 | 41.40 | 17.67 | 9.60 |
| Voi Taveta | 490.05 | 187.00 | 5.39 | 147.00 | 3.89 | 135.70 | 7.00 | 16.60 |
| KALRO Mtwapa | 146.41 | 82.50 | 1.40 | 181.00 | 1.84 | 55.20 | 9.00 | 7.20 |
| KALRO Matuga | 180.29 | 255.75 | 1.47 | 18.10 | 1.27 | 32.20 | 14.67 | 7.60 |
| KALRO Kitale | 204.49 | 148.50 | 4.30 | 61.90 | 1.27 | 36.80 | 26.00 | 16.80 |
| KALRO Kakamega | 121.00 | 52.25 | 5.65 | 63.90 | 5.89 | 55.20 | 19.00 | 18.00 |
| Bungoma Mabanga ATDC | 121.00 | 115.50 | 6.64 | 78.30 | 1.09 | 23.00 | 16.00 | 8.00 |
| Baraton University Nandi | 169.40 | 184.25 | 5.45 | 53.40 | 3.73 | 103.50 | 68.00 | 20.00 |
| KALRO Njoro | 133.10 | 269.50 | 2.18 | 169.00 | 10.8 | 340.40 | 22.00 | 10.40 |
| **Average** | **163.98** | **120.52** | **3.95** | **52.78** | **1.86** | **92.80** | **18.73** | **11.98** |
| **Adequate level** | **121-363** | **30.25-550** | **<1.0** | **<10** | **<5.0** | **0-460** | **3.67-68** | |

**Table 4.2: Correlation amongst the different soil parameters under study**

| | Soil pH | C% | N% | P | K | S | Mn | Cu | Fe | Zn | Ca | Mg | Na | CEC | SUM | BASE | ESP | Elect Cond mS cm | SAND % | SILT % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C% | 0.136 | | | | | | | | | | | | | | | | | | | |
| N% | 0.091 | .991** | | | | | | | | | | | | | | | | | | |
| P | 0.117 | -0.235 | -0.255 | | | | | | | | | | | | | | | | | |
| K | 0.032 | 0.059 | 0.079 | 0.092 | | | | | | | | | | | | | | | | |
| S | -0.168 | 0.273 | 0.286 | -.657** | -0.044 | | | | | | | | | | | | | | | |
| Mn | 0.008 | -0.018 | -0.040 | 0.216 | 0.133 | -0.052 | | | | | | | | | | | | | | |
| Cu | 0.126 | .533** | .581** | -0.446 | 0.012 | 0.343 | -0.116 | | | | | | | | | | | | | |
| Fe | 0.101 | 0.152 | 0.093 | 0.242 | 0.014 | -0.003 | 0.252 | -0.040 | | | | | | | | | | | | |
| Zn | -0.042 | .542** | .504* | 0.206 | 0.281 | 0.004 | 0.395 | -0.042 | .656** | | | | | | | | | | | |
| Ca | -0.270 | 0.012 | 0.050 | 0.103 | .522* | -0.173 | 0.118 | 0.262 | -0.132 | 0.111 | | | | | | | | | | |
| Mg | -0.215 | 0.005 | 0.020 | 0.254 | 0.283 | -0.322 | 0.176 | 0.234 | -0.161 | 0.008 | .692** | | | | | | | | | |
| Na | -0.238 | 0.039 | 0.063 | 0.132 | .712** | -0.197 | 0.151 | 0.092 | 0.033 | 0.309 | .867** | .718** | | | | | | | | |
| CEC | -0.068 | .456* | .468* | -0.051 | 0.163 | 0.133 | -0.123 | 0.347 | -0.249 | -0.019 | 0.212 | .594** | 0.299 | | | | | | | |
| SUM | -0.265 | 0.015 | 0.051 | 0.134 | .551** | -0.204 | 0.138 | 0.255 | -0.130 | 0.120 | .991** | .772** | .903** | 0.290 | | | | | | |
| BASE | -0.289 | -0.140 | -0.123 | 0.285 | .615** | -0.190 | -0.005 | -0.316 | -0.079 | 0.313 | 0.376 | 0.239 | .504* | -0.072 | 0.398 | | | | | |
| ESP | -0.160 | -0.095 | -0.084 | 0.219 | .768** | -0.260 | 0.288 | -0.061 | 0.153 | 0.389 | .809** | .509* | .916** | -0.042 | .821** | .612** | | | | |
| Elect Cond | -0.324 | -0.155 | -0.138 | 0.225 | .539** | -0.354 | -0.024 | -0.028 | -0.172 | 0.053 | .610** | .689** | .752** | 0.317 | .669** | 0.391 | .634** | | | |
| SAND % | 0.287 | -.452* | -.472* | 0.048 | -0.247 | -0.321 | 0.128 | -0.205 | 0.309 | -0.207 | -0.135 | -0.261 | -0.164 | -.579** | -0.171 | -.426* | -0.002 | -0.207 | | |
| SILT % | -0.319 | .565** | .583** | 0.035 | -0.029 | 0.256 | -0.178 | 0.194 | 0.220 | .518* | -0.133 | -0.004 | -0.020 | 0.318 | -0.111 | 0.287 | -0.122 | -0.095 | -.640** | |
| CLAY % | -0.187 | 0.259 | 0.274 | -0.080 | 0.326 | 0.263 | -0.063 | 0.151 | -.510* | -0.024 | 0.243 | 0.331 | 0.218 | .555** | 0.276 | 0.379 | 0.069 | 0.313 | -.907** | 0.257 |

*** (P≤ 0.01), *** (P≤ 0.001), - (correlation coefficient)*

**Table 4.3: Chemical properties of soil and their optimal levels**

| Properties | Range observed | Mean values | Optimum range |
|---|---|---|---|
| pH | | 5.96 | |
| CEC | | 11.98 | |
| Total organic carbon (mg $kg^{-1}$) | 0.21 – 2.80 | 1.12 | 2.66 – 5.32 |
| Total nitrogen (%) | 0.04-0.26 | 0.12 | 0.2- 0.5 |
| P (mg $kg^{-1}$) | 2.00 - 30.00 | 19.09 | 30.00-80 |
| K (mg $kg^{-1}$) | 117.00-585.00 | 220.43 | 93.60-585 |
| Ca (mg $kg^{-1}$) | 600.00- 5540.00 | 1397.39 | 400-3000 |
| Mg (mg $kg^{-1}$) | 121.00-490.00 | 163.98 | 121-363 |
| S (mg $kg^{-1}$) | 3.67 to 68 | 18.73 | 20 |
| Micronutrients mg $kg^{-1}$ | | | |
| Na | 23.00-340.00 | 92.80 | 0-460 |
| Fe | 13.60-181 | 52.78 | >10 |
| Mn | 44.00-255.75 | 120.52 | 30.25-550 |
| Cu | 1 to 6.64 | 3.95 | >0.2 |
| Zn | 0.2 to 10.8 | 1.86 | <7.5 |

### 4.2 Effects of nutrient omission on shoot dry weight, number of leaves, plant height and leaf width

All the treatments were compared to the complete treatment in terms of shoot dry weights number of leaves, plant height and leaf width to determine their extent of limitation. The optimal nutrient condition of the complete treatment should enable it to perform better than other treatments. If there was any significant difference between a treatment missing a nutrient element and complete treatment, then the element was limiting.

Lower dry shoot weights were observed in all the treatments as compared to the complete treatment in both trials (Table 4.4). Plant height and leaf width for trial one did not show any significant differences in trial one while in trial two there were significant differences among the treatments, with the omission of potassium and control treatments being the lowest in plant height. In leaf width the omission of calcium and control treatments were the lowest (Table 4.4).

There were significant differences amongst the treatments in the number of leaves. Omission of molybdenum and control treatments were different ($p<0.05$) from the complete treatment in the first trial. All the other treatments had relatively lower number of leaves than the complete treatment while in the second trial all the treatments were significantly limiting compared to the complete treatment (Table 4.4).

There were no significant differences in plant height in the first trial while in the second trial the complete treatment was significantly different ($p<0.05$) from the other treatments. (Table 4.4). The complete treatment was significantly different from other treatments in both trials in most of the study sites (Table 4.5). There was low dry shoot weight in omission of Nitrogen and Phosphorous as compared to the complete in most study sited. All the other treatments did

not show significant differences from each other. The control was the most limiting from the study (Table 4.5).

**Table 4.4: Means for shoot dry weight, number of leaves, plant height and leaf width for first trial and second trial.**

| Treatment | Shoot dry weight (g) Trial 1 | Shoot dry weight (g) Trial 2 | No of leaves Trial 1 | No of leaves Trial 2 | Plant height (cm) Trial 1 | Plant height (cm) Trial 2 | Leaf width (cm) Trial 1 | Leaf width (cm) Trial 2 |
|---|---|---|---|---|---|---|---|---|
| **Complete** | 5.38a | 15.07a | 5.97a | 10.34a | 38.78a | 63.74a | 0.91a | 1.53a |
| **complete plus lime** | 4.89abc | 4.64c | 5.78ab | 6.32bcd | 36.47a | 35.87bc | 0.90a | 0.91bc |
| **N Omitted** | 4.99ab | 5.58b | 5.78ab | 6.60bc | 34.60a | 36.18bc | 0.89a | 0.92bc |
| **P Omitted** | 4.78abcd | 4.27c | 5.92ab | 5.81d | 35.65a | 33.62bc | 0.92a | 0.89bc |
| **K Omitted** | 4.99ab | 4.47c | 5.75ab | 6.00cd | 33.35a | 31.54c | 0.86a | 0.85bc |
| **Ca Omitted** | 4.73bcd | 4.67c | 5.76ab | 6.41bcd | 34.14a | 33.58bc | 0.85a | 0.84c |
| **Mg Omitted** | 4.98ab | 4.93c | 5.72ab | 6.19bcd | 36.51a | 35.45bc | 0.89a | 0.92b |
| **Micronutrients Omitted** | 4.37bcd | 4.65c | 5.62ab | 6.86b | 36.42a | 37.00b | 0.90a | 0.92bc |
| **Plus Micronutrients minus Zinc** | 4.30cd | 4.66c | 5.77ab | 6.44bcd | 34.79a | 35.06bc | 0.92a | 0.91bc |
| **Plus Micronutrients minus Boron** | 4.36bcd | 5.09bc | 5.64ab | 6.44bcd | 35.26a | 34.99bc | 0.90a | 0.90bc |
| **Plus Micronutrients minus molybdenum** | 4.18d | 4.61c | 5.59b | 6.51bcd | 35.74a | 35.60bc | 0.88a | 0.91bc |
| **Control** | 2.77e | 2.60d | 4.23c | 3.73e | 29.14ab | 19.85d | 0.72b | 0.67d |
| **L.s. $d_{0.05}$** | 0.64 | 0.84 | 0.37 | 0.70 | 7.92 | 4.70 | 0.09 | 0.08 |

Figures in a column with the same letter(s) are not significantly different at $P \leq 0.05$.

**Table 4.5: Combined means of shoot dry weights per site**

| Treatment | Kambi ya mawe KALRO ICRISAT Centre | Mwingi kyuso polytechnic | South Eastern University Kitui 1 | South Eastern University Kitui 2 | KALRO Tharaka-Nithi | KALRO Kiboko | Ithokwee Kitui KALRO sub station |
|---|---|---|---|---|---|---|---|
| **Complete** | 3.81abc | 7.53a | 7.67a | 8.33a | 9.33a | 8.67a | 7.97a |
| **Complete plus lime** | 4.11ab | 1.40b | 5.93ab | 3.13b | 5.20b | 3.63b | 3.57b |
| **N Omitted** | 4.51bcd | 1.37b | 5.00ab | 2.83b | 4.47b | 4.33b | 4.13b |
| **P Omitted** | 4.33a | 1.63b | 5.10ab | 1.73b | 3.30b | 3.57b | 2.87b |
| **K Omitted** | 3.77abc | 1.63b | 4.37ab | 2.30b | 3.83b | 3.63b | 3.03b |
| **Ca Omitted** | 4.19cd | 2.23b | 4.80ab | 2.50b | 4.57b | 3.60b | 3.63b |
| **Mg Omitted** | 4.07abcd | 2.33b | 4.30ab | 3.03b | 3.77b | 3.90b | 3.20b |
| **Micronutrients Omitted** | 3.91ab | 2.07b | 5.80ab | 2.53b | 3.57b | 4.27b | 4.00b |
| **Plus Micronutrients minus Zinc** | 4.33abc | 2.61b | 6.97a | 2.57b | 3.80b | 3.63b | 2.33b |
| **Plus Micronutrients minus Boron** | 4.27ab | 2.27b | 4.37ab | 2.43b | 3.63b | 5.27b | 4.07b |
| **Plus, Micronutrients minus molybdenum** | 4.2abc | 1.43b | 4.63ab | 2.67b | 4.50b | 4.47b | 3.30b |
| **Control** | 2.53d | 2.20b | 2.60b | 2.10b | 2.53b | 2.30b | 3.03b |
| **l.s.d$_{0.05}$** | 1.76 | 1.27 | 2.22 | 1.06 | 1.80 | 1.70 | 1.74 |

Figures in a column with the same letter(s) are not significantly different at $P \leq 0.05$.

**Table 4.5 cont'd: Combined means of shoot dry weights per site**

| Treatment | KALRO Katumani | Kibwezi (University of Nairobi 1) | Kibwezi (University of Nairobi 2) | Bungoma Mabanga ATDC | KALRO Kakamega | KALRO Kitale | Chala Taita taveta |
|---|---|---|---|---|---|---|---|
| **Complete** | 8.87a | 15.00a | 14.40a | 9.00a | 10.67a | 10.33a | 9.17a |
| **Complete plus lime** | 3.50b | 8.27bcd | 8.70ab | 2.87b | 4.07bc | 4.87b | 5.17bc |
| **N Omitted** | 3.77b | 9.60bc | 8.3ab3 | 3.37b | 6.43abc | 6.27ab | 5.63abc |
| **P Omitted** | 2.53b | 7.50bcd | 6.57b | 2.87b | 5.90abc | 4.87b | 5.70abc |
| **K Omitted** | 2.93b | 9.80bc | 9.47ab | 2.83b | 3.77bc | 4.87b | 7.20ab |
| **Ca Omitted** | 1.87b | 11.53ab | 7.77ab | 4.70b | 4.53bc | 5.53b | 6.37abc |
| **Mg Omitted** | 3.27b | 8.60bcd | 6.23b | 3.30b | 4.07bc | 5.53b | 5.87abc |
| **Micronutrients Omitted** | 3.30b | 8.73bcd | 5.73b | 3.60b | 4.9bc | 5.20b | 5.43bc |
| **Plus Micronutrients minus Zinc** | 5.37ab | 6.10cd | 5.93b | 3.27b | 8.2ab | 5.13b | 5.60abc |
| **Plus Micronutrients minus Boron** | 2.53b | 10.47abc | 6.67b | 3.80b | 6.23abc | 6.13ab | 7.00abc |
| **Plus Micronutrients minus molybdenum** | 3.07b | 9.30bc | 5.17b | 3.07b | 5.13bc | 5.47b | 5.13bc |
| **Control** | 1.9b | 3.80d | 2.67b | 2.63b | 1.80c | 4.1b | 3.40c |
| **l.s.d$_{0.05}$** | 2.893 | 2.884 | 3.928 | 1.797 | 3.033 | 2.447 | 2.124 |

Figures in a column with the same letter(s) are not significantly different at $P \leq 0.05$.

**Table 4.5 cont'd: Combined means of shoot dry weights per site.**

| Treatment | KALRO Mtwapa | Mwatate Taita-Taveta | Voi Taveta | Wundanyi Taita Taveta | KALRO Msabaha | KALRO Matuga | KALRO Njoro | Embu Siakago ATDC | Baraton University Nandi |
|---|---|---|---|---|---|---|---|---|---|
| **Complete** | 9.67a | 8.40a | 13.13a | 8.33a | 9.37a | 4.67a | 11.67a | 8.90a | 13.67a |
| **Complete plus lime** | 4.40bc | 3.73b | 5.57ab | 4.10bcd | 4.67bc | 1.63b | 8.60a | 3.47b | 5.60de |
| **N Omitted** | 4.73bc | 2.73b | 10.70ab | 4.27bcd | 3.43bc | 2.00b | 8.53a | 4.40b | 7.60bcd |
| **P Omitted** | 4.43bc | 2.10b | 6.10ab | 5.03bc | 3.53bc | 1.47b | 7.17a | 3.43b | 6.63cde |
| **K Omitted** | 3.13cd | 3.40b | 55.13ab | 4.60bcd | 3.97bc | 1.87b | 6.87a | 2.43b | 7.80bcd |
| **Ca Omitted** | 3.40cd | 2.40b | 5.13ab | 4.03bcd | 3.90bc | 1.30b | 8.37a | 3.97b | 7.37bcd |
| **Mg Omitted** | 5.87b | 2.37b | 9.17ab | 4.33bcd | 5.40b | 1.17b | 7.57a | 4.57b | 6.87cde |
| **Micronutrients Omitted** | 3.97bc | 1.93b | 7.50ab | 4.33bcd | 4.93b | 2.43ab | 7.60a | 3.57b | 6.97bcde |
| **Plus Micronutrients minus Zinc** | 2.63cd | 2.17b | 7.63ab | 6.83ab | 3.4bc | 1.47b | 7.27a | 4.33b | 7.33bcd |
| **Plus Micronutrients minus Boron** | 4.07bc | 2.83b | 10.50ab | 4.00bcd | 3.10bc | 1.33b | 8.83a | 3.50b | 10.17b |
| **Plus Micronutrients minus molybdenum** | 3.13cd | 2.83b | 7.87ab | 3.57cd | 3.467bc | 0.96b | 9.17a | 4.40b | 9.43bc |
| **Control** | 1.30d | 1.47b | 2.93b | 4.60bcd | 1.03c | 1.23b | 6.63a | 1.97b | 4.03e |
| **l.s.d$_{0.05}$** | 1.37 | 1.59 | 5.79 | 1.86 | 2.14 | 1.49 | 3.66 | 2.13 | 1.84 |

Figures in a column with the same letter(s) are not significantly different at *P≤0.05.*

The coefficient of variation affirms that soils are different and would respond differently when subjected to the same fertilizer application (Table 4.6). Significantly lower dry shoot weights ($p < 0.05$) than the complete treatment, were observed in all treatments. Equally, leaf

width, length and plant heights were significantly different($p<0.01$) in all the treatments as shown in figure 4.1, 4.2, 4.3 and 4.4.

**Table 4. 6: Summary of maize dry weights for trial 1 and trial 2 obtained under different nutrient omission treatments in 23 sites in Kenya.**

| Treatment | Mean | Minimum | Maximum | l.s.d. | s.e. mean | CV (%) |
|---|---|---|---|---|---|---|
| Complete | 9.33 | 2.81 | 16.80 | 2.81 | 0.34 | 30.1 |
| Complete plus lime | 4.62 | 1.00 | 9.60 | 2.19 | 0.26 | 47.4 |
| N Omitted | 5.15 | 0.90 | 15.80 | 2.67 | 0.32 | 51.8 |
| P Omitted | 4.28 | 1.10 | 10.60 | 2.20 | 0.27 | 51.5 |
| K Omitted | 4.44 | 1.30 | 11.90 | 2.58 | 0.31 | 58.1 |
| Ca Omitted | 4.68 | 0.50 | 12.40 | 2.56 | 0.31 | 54.7 |
| Mg Omitted | 4.90 | 0.20 | 17.90 | 2.81 | 0.34 | 57.3 |
| Micronutrients Omitted | 4.62 | 0.30 | 11.70 | 2.05 | 0.25 | 44.4 |
| Plus Micronutrients minus Zinc | 4.74 | 0.50 | 12.50 | 2.88 | 0.35 | 60.8 |
| Plus Micronutrients minus Boron | 5.11 | 0.50 | 13.50 | 3.06 | 0.37 | 60.0 |
| Plus Micronutrients minus molybdenum | 4.63 | 0.80 | 11.80 | 2.48 | 0.30 | 53.6 |
| Control | 2.61 | 0.20 | 7.80 | 1.36 | 0.16 | 52.2 |

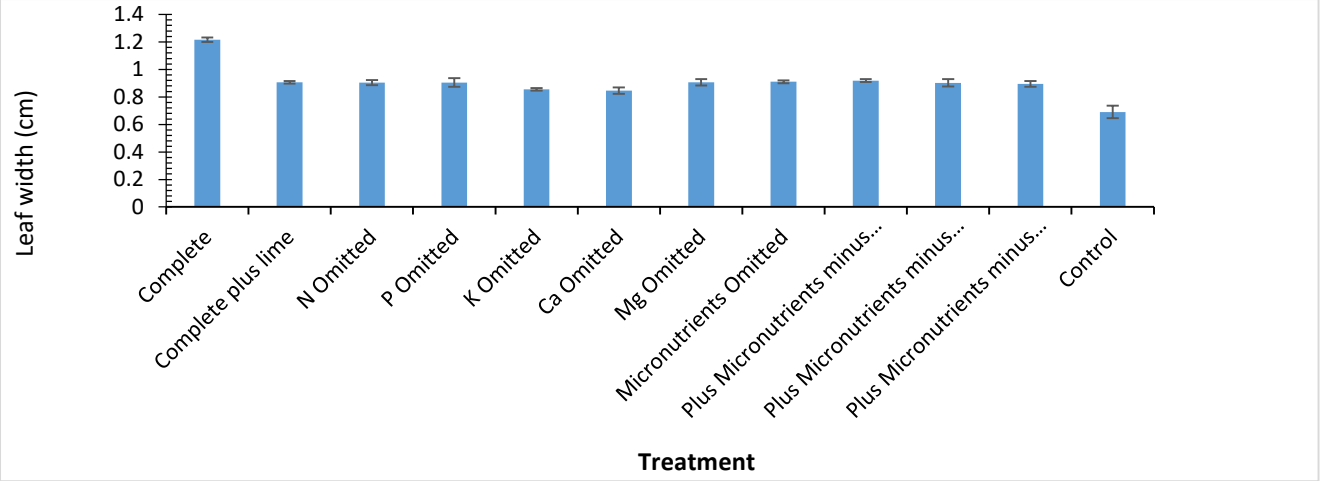



**Figure 4.1: Standard error bars showing maize leaf width obtained under different fertilizer treatments.**

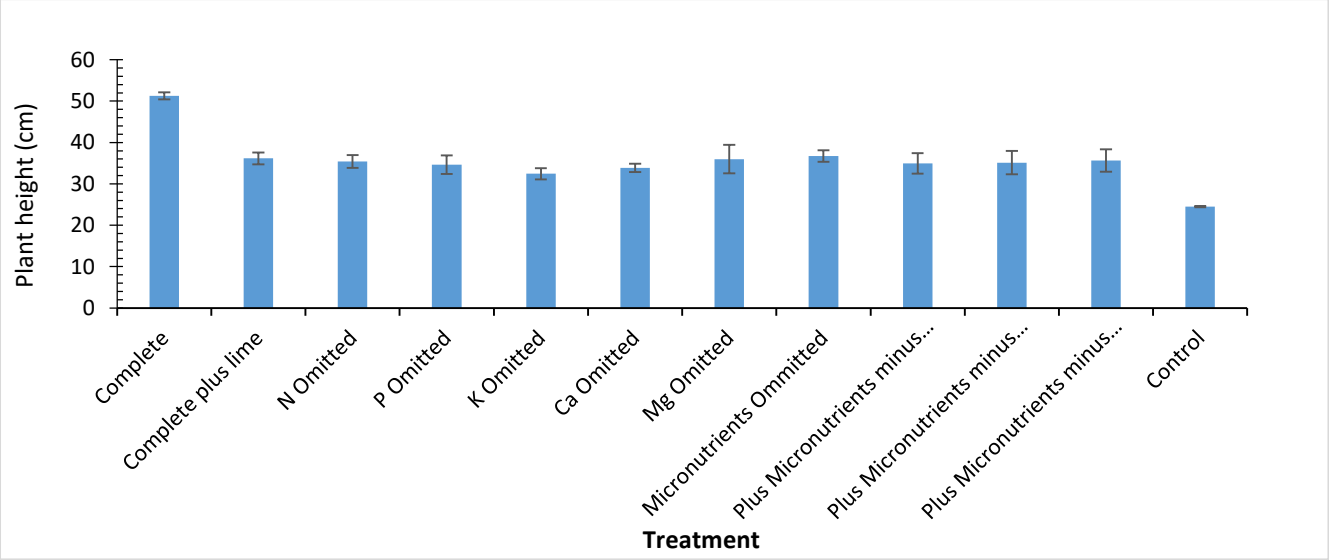



**Figure 4.2: Standard error bars showing maize plant height obtained under different fertilizer treatments.**

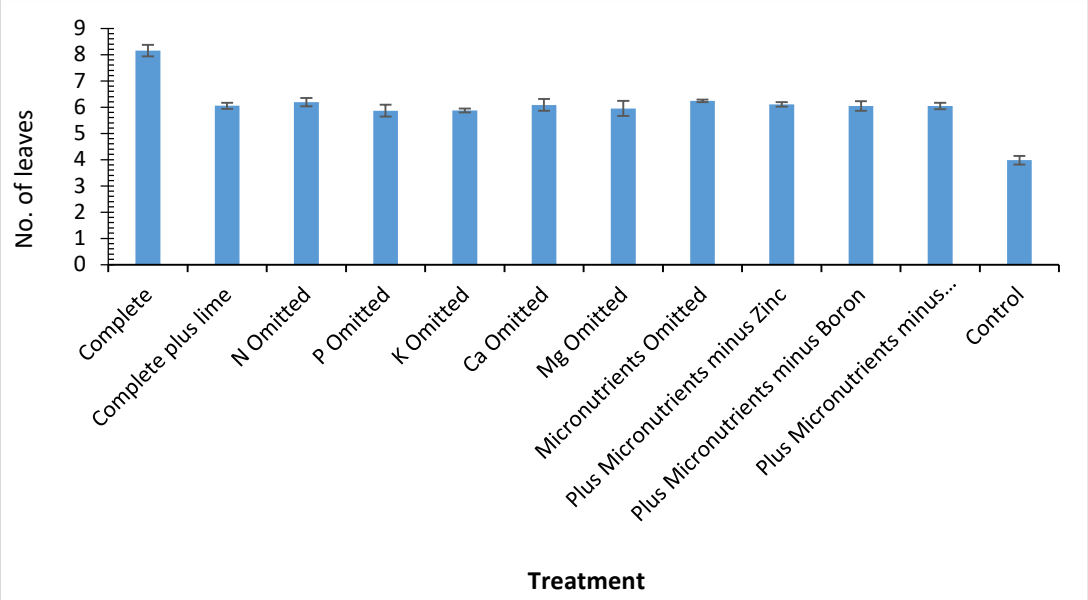



**Figure 4. 3: Standard error bars showing number of maize leaves obtained under different fertilizer treatments.**

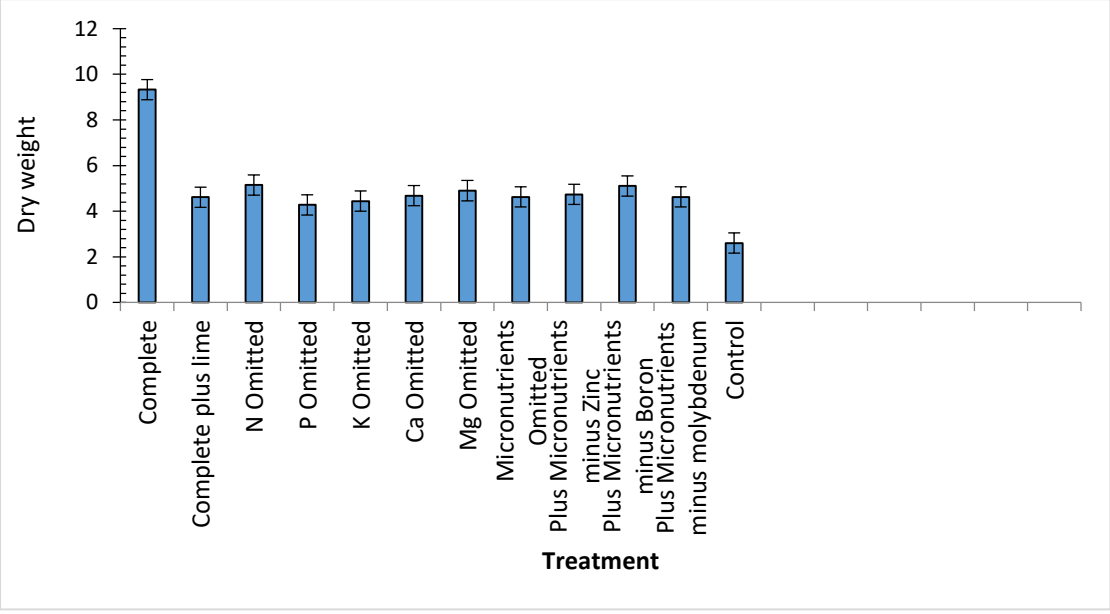



**Figure 4. 4: Standard error bars showing shoot dry weight of maize obtained under different fertilizer treatment.**

### 4.3 Visual observations

There was interveinal chlorosis, early leaf drop, bronzing, yellow or white spots developed on leaves with brown waxy raised streaks as the effects of the deficiency developed. (Figure 4.5), which was an indication of boron deficiency, it was common in maize growing in soils from Kiboko. (Kumar, Ajeet, 2020). Zinc deficiency was observed especially in maize that was grown in soils from Taita-Taveta. The maize leaves had a yellow colouration in the midrib. These symptoms were generally showed in older leaves. Internode growth was reduced thus the plant had dwarf appearance. (Figure 4.6) (Kumar, Ajeet, 2020). At harvesting, most maize had pale yellow leaves, which was an indication of possible nitrogen deficiency across all the soils. The most common visual deficiencies observed were purpling and general stunting of the plants (Figure 4.7) This was common with maize grown in soils from Katumani, Matuga, Mtwapa, Msabaha and Mwingi. Stunted growth was observed in maize from Voi, Matuga, Mtwapa, Msabaha and Mwingi (Figures 4.7 & 4.8). (Kumar, Ajeet, 2020). There were differences in growth of maize depending on the treatment applied. Complete treatment had better biomass formation than all the other treatments in (Figure 4.9). These visual observations correlated with the nutrients deficiencies in analyzed soils. The visual symptoms served as a quick overview of soil fertility conditions of soils from those regions.


**Figure 4. 5: Leaf bronzing**


**Figure 4. 6: Leaf chlorosis**

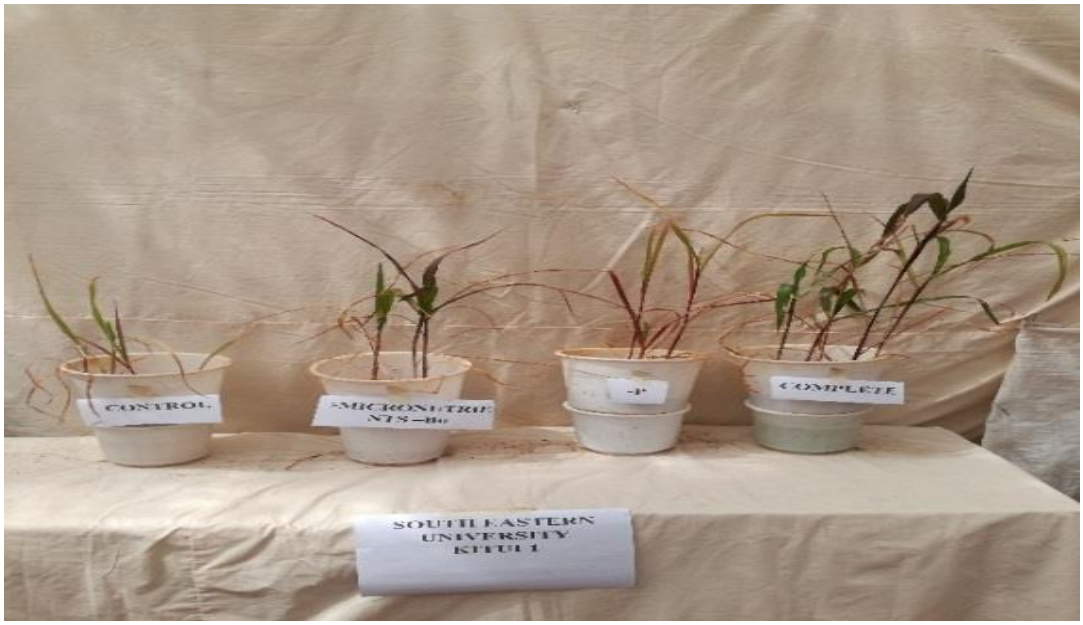



**Figure4. 7: Leaf purpling**


**Figure4. 8: Stunted growth**


**Figure 4. 9: Differences in growth of maize**

# CHAPTER FIVE: DISCUSSION

## 5.1 Nutrient status of soils in Kenya

Generally, most of the soils were acidic with a pH less than 7. Globally soil acidity is considered to significantly limit productivity of most crops (Brady and Weil 2008). The current results show that some of the study soils were acrisols which are known to be highly acidic soils, NAAIAP (2014). Kanyanjua *et al.*, (2002) classifies soils with pH value less than 7.0 as acid, and in Kenya, the acid soils occupy over 7.5 million hectares of land. Kenya acid soils contain high aluminium (normally>20% saturation), low phosphorus (<5 mg P/kg soil) and low nitrogen (0.2% total nitrogen) and this reduce maize yields by 16, 28 and 30%, respectively (Kisinyo. 2011). Soil acidity greatly affects crop productivity and is the most yield limiting factor (Sumner and Noble, 2003; Fageria and Nascente, 2014).

Phosphorus was deficient in most study soils. Besides crop harvest and soil erosion depleting phosphorus, high prevalence of phosphorous fixation is the most challenging soil fertility issue (Nziguheba, 2007). NAAIAP (2014) reported that over 65% of the samples taken in the whole country had values lower than the critical limit, which is 10 to 20 mg/ kg. Phosphorus showed negative correlations with organic carbon and nitrogen which may indicate a potential for soil Phosphorus deficiency.

Most soils had deficient levels of organic carbon of >1.1%. The deficiency in most soils can be attributed to extensive tillage in smallholder farms similar to the report by Pandey *et al.* (2014). Continuous depletion of soil organic carbon without replenish using either organic or inorganic fertilizers and adhering to soil conservation measures contributed poor crop yields (Branca *et al*., 2013).

From the study findings, majority of 98% of soil samples had <0.2% of nitrogen, which is below the critical limit, thereby confirming the rating by NAAIAP (2014) that N is the most limiting nutrients in Kenya, where 86% of the farms sampled country wide were below the

critical limit. Nitrogen was deficient in most soils. The most critical indices of soil fertility according to Liu *et al.* (2011) are both total nitrogen and soil organic carbon. Additionally, the total nitrogen and soil organic carbon were further shown by Shibu *et al*. (2012) to sustainably enhance crop production. The C/N ratio in these soils was 9.3 which is way below the normal rating which is between15-25. This shows declining soil fertility in most soils, and this can be associated with low maize yields in small holder farms.

Most of the soils had adequate Potassium. Potassium is widely reported as sufficient in Kenya (NAAIAP, 2014). This is supported by the findings by Gikonyo *et al*. (2018) and Kimani *et al*. (2018) which indicated that crop response to potassium application was quite small, and no significant effects were observed, being attributed to sufficient level of potassium in the soil. Over 50% of the study soils had sufficient Sulphur. These results were similar to those obtained by Esilaba and Ssali (1987).

In this study, the levels of calcium, copper, magnesium, manganese, sodium and iron were established to be adequate. These findings agree to those by Bassirani *et al*. (2011); Jiang *et al*. (2009); Verma *et al*. (2007); Singh *et al*. (2006) and Lindsay and Norvell (1978). Zinc was deficient in the study soils. According to NAAIAP (2014), 30% of the farms sampled country wide had zinc value lower than the critical limit. A study by Manzeke *et al*. (2012) showed that poor growth and development in most cereals grown in Africa was due to low zinc. Murphy *et al*. (1992) indicated that zinc deficiency among children under 2.5 years in Kenya had a 90% prevalence. The zinc deficiency symptoms among children include mental impairment, general body weakness and reduce body immune system against other diseases. Nearly 50% of cereal growing areas in the world have soils with low plant available zinc resulting in zinc concentrations in cereal grains of as little as 5-12 mg/kg against a requirement of 40–60 mg/kg (Manzeke *et al*., 2012).

The CEC of the study soils was low and moderate. The low and moderate values range from 6 cmol (+)/kg -25 cmol (+)/kg as reported by Metson (1961). Soils with a low CEC are more likely to develop deficiencies in potassium, magnesium, and other cations, while high CEC soils can overcome these limitations (Saikat and Geon-Ha Kim, 2021).

In general, the most limiting soil fertility attributes of interest were nitrogen, carbon, phosphorus, and zinc. Nitrogen and carbon positively correlated with each other ($P \leq 0.01$). In most soils, more than 90% nitrogen is bonded with carbon in organic forms. This indicates that carbon mineralization should be closely coupled with nitrogen mineralization, hence showing the positive correlation between carbon and nitrogen (Li Qianru *et al.,* 2014). Phosphorous on the other hand was negatively correlated with carbon and nitrogen possibly due to Phosphorous fixation, unavailable Phosphorous or deficiencies (Nziguheba, 2007).

Zinc negatively correlated with soil pH while zinc was positively correlated with carbon, this means that reduction or increase in soil pH causes reduction or increase in the levels of these nutrient bases, hence the explanation of the reduced levels of the nutrients with increased soil acidification, caused by the increased rate of chemical degradation as reported by Muya *et al.* (2014). Therefore, to ensure efficient utilization and uptake of these nutrients, soil pH must be corrected to the optimally favorable limit (Johnston, 2011).

### 5.2 Effects of nutrient treatments on shoot dry weight and number of leaves

Most of the study soils were deficient in micronutrients as their omission led to significantly lower maize dry shoot weights. The micronutrient-deficient soils do not support optimum crop yields because plant growth becomes retarded by the deficiency, leading to low yields (Chude *et al*., 2004). They are essential for growth and development of crop plants (Dwivedi *et al.,* 2013).

The findings revealed that zinc was deficient as its omission showed reduced maize growth. The finding confirmed the soil analysis results where the soils had inadequate Zinc (Table 6), and the findings reported by NAAIAP (2014) which showed the same. Low zinc threatens crop production and food nutrition in most cereal- based cropping systems in Africa (Manzeke *et al.,* 2012). Zinc omission could have led to a decline in plant photosynthesis, hence compromising biomass accumulation (Mousavi *et al.,* 2007; Efe and Yarpuz, 2011).

Maize dry shoot weights in the lime treatment were better than other treatments. Liming is a standard agricultural practice used to overcome acidic limitations in soil and achieve maximum yields of all crops cultivated in acidic soils worldwide (Kalkhoran et al., 2021). Application of agricultural lime containing calcium and/ or magnesium compounds to acidic soils increases $Ca^{2+}$ and/or $Mg^{2+}$ ions and reduces $Al^{3+}$, $H^{+}$, $Mn^{4+}$ and $Fe^{3+}$ ions in the soil solution. This leads to an increase in soil pH and available P due to reduction in P sorption (Kisinyo, 2011). In addition to neutralization of soil acidity, lime enhances root development, water and nutrient uptakes, necessary for healthy plant growth (Van Straaten, 2007).

There were significant differences amongst the treatments in the number of leaves. Omission of molybdenum and control treatments were different ($p<0.05$) from the complete treatment in the first trial. All the other treatments had relatively lower number of leaves than the complete treatment while in the second trial all the treatments were significantly limiting compared to the complete treatment. Many cereal and legume crops growing at deficient molybdenum levels usually experience a decrease in overall plant growth accompanied by necrotic leaf margins (Agarwala *et al.,* 1978; Chatterjee and Nautiyal, 2001). Omission of molybdenum in maize shortens internodes, decreases leaf areas and causes the development of chlorotic leaves (Agarwala *et al.,* 1978).

The control treatment in both seasons was the most limiting treatment, thus suggesting that most of the study soils were depleted of nutrients and any addition of nutrients to the soil improved the plant growth. In general, for plants to reach their potential yield farmers must apply synthetic or organic amendments to boost nutrient sufficiency and enhance soil fertility since most soils rarely have sufficient nutrients (Ahmad *et al.,* 2009)

There was low maize shoot weight in treatments where nitrogen was omitted. This finding agrees with the research by NAAIAP (2014) which rated nitrogen as one of the most limiting nutrients in Kenya, where 86% of the farms sampled country wide were below the critical limit (Table 4.5). Also, phosphorus was limiting in over 65% of the soil sampled. The low dry shoot weights in phosphorous omitted treatments could be due to phosphorus fixation in soils (Asio *et al.,* 1996), reducing phosphorous available for plant uptake at an early initial growth stage. Kihara *et al.* (2016) found out that soils in Kenya, Tanzania, Nigeria, and Mali had low phosphorus levels ranging from 3.6 mg/kg to 9.9 mg/kg, which falls way below the critical level of 15 mg/kg. When a soil is deficient in nutrients such as phosphorus and nitrogen, fixation is reduced (Sanginga, 2003).

The results from nutrient omission trials (Table 4.6) showed a significant maize shoot weight difference of more than 4.5 ton/ha when one of the essential nutrients was omitted. Furthermore, the results show that complete treatment plus either lime, micronutrients with omission of either Zn, Bo and Mo introduces either imbalance or complexing that inhibits full release of all the essential nutrients to roots for uptake, hence low yield. Low soil Zn threatens crop production and food nutrition in most cereal- based cropping systems in Africa (Manzeke et al., 2012).

Lack of application of a complete set of essential plant nutrients reduces maize shoot weights by three-fold, whereas application of other nutrients can double the yield to some degree.

However, if the soils lack N, P, K, Zn and Mo, yields will still be low as compared with complete treatment. Hence, farmers who attempted to grow crops without or marginal fertilizer application could not produce enough even to feed their own family for a year (Selassie, 2015). The results also show a strong correlation between inherent soil fertility and dry shoot weights of the maize; low fertility soils will produce low shoot weights unless complete nutrients are added to the soil. The expression of this correlation was observed in the leaf length, widths, and number of maize leaves at tasseling stage. In areas of low soil moisture conditions like the Eastern and Coast regions, the expression of low fertility could be stunted growth while in Western region it could be yellowing of leaves or purple colour among other deficiency symptoms in maize crop as shown by the visual observations.

The results of soils, plant and visual observations have shown that N, P, K, Mg, Zn and Bo are limiting nutrients in maize producing areas in Kenya. The results have shown a clear correlation between inherent soil fertility and dry matter yield, implying that in a low fertilizer input system, farmers will continue to experience low maize yields. A recent study on fertilizer use optimization in SSA by Wortmann and Sones (ed.) 2017, showed that resource poor farmers hardly add organic and inorganic fertilizers, and this has had a limiting effect on maize yield. Soil fertility management technologies have come up in Africa as a result of depleted soils. (Esilaba et al., 2005). However, blanket soil fertilizer recommendation limits the use of site-specific fertility variation shown by these results. Fertilizer recommendations have often been based on trials without detailed characterization and clustering of production systems (Muya et al., 2015).These results affirm that in all soils, minimum fertilization by either organic or inorganic fertilizers is necessary for obtaining food security at household level in Kenya.

# CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

## 6.1 Conclusion

Soil analysis results have shown that soils from different sites differ in fertility. In all the soils, most of the macronutrients were deficient and varied with locality. The omission of nitrogen, phosphorous and zinc were responsible for the poor growth in maize. From the study it was evident that addition of any nutrient improved the yields, as the control treatments were seen to be most limiting. This stresses the importance of fertilizer-use to achieve increased yield. The dry matter and number of leaves responded well to nutrient treatments other than other parameters, they can therefore be used in such omission pot trials as growth indices.

The soil test results, and the greenhouse experiment corresponded, as the most limiting nutrients were nitrogen, phosphorous and zinc. The approach taken by this study increased the knowledge of the nutrient status of some Kenyan soils, with a view of knowing the limiting nutrients in the selected soils. This is an important aspect of soil management as it enables a researcher give proper fertilizer recommendation, while targeting soil fertility management strategies in Kenya.

## 6.2 Recommendations

1. Since one maize variety was used to assess the fertilizer responses, further on-site field tests with area specific recommended varieties would be advisable.
2. The study involved pot experiments whose recommendations have limited applications, hence the need to conduct similar studies in fields.
3. Since only selected few farms were sampled in this study, more farms in the study areas should be tested for soil fertility.
4. The results obtained confirm the Janssen double-pot technique as a rapid method of accessing soil fertility status at a low-cost option, thus the need to calibrate it with site specific testing. As seen in this study, soil analysis results and green house trials

corresponded with each other, therefore research should focus on laboratory, greenhouse, and field trials to correlate and calibrate the plant availability of macronutrients and micronutrients for site specific smart fertilizer recommendations.

## REFERENCES


Agarwala, S.C., Sharma C.P., Farooq S., & Chatterjee C. (1978). Effect of molybdenum deficiency on the growth and metabolism of corn plants raised in sand culture. Canadian Journal of Botany 56: 1905-1909.

Ahmad, W., Niaz A., Kanwal S. & Rasheed M.K. (2009). Role of boron in plant growth: a review. Journal of Agricultural Research 47 (3): 329-338.

Andrade, A.C., Fonseca, D.M., Queiroz, D. S., Salgado, L.T. & Cecon, P. R. (2003). Elephant grass nitrogen and potassium fertilization (*Pennisetum purpureum* Schum. Cv. Napier). Ciencia e Agrotecnologia, Lavras, p. 1643-1651.

Anderson, J. M., & Ingram, J. S. I. (Eds.) (1993). Tropical soil biology and fertility A handbook of methods (2nd ed.). Wallingford CAB International.

Annaheim, K. E., Doolette, A. L., Smernik, R. J., Mayer, J., Oberson, A., Frossard, E., & Bünemann, E. K. (2015). Long-term addition of organic fertilizers has little effect on soil organic phosphorus as characterized by 31P NMR spectroscopy and enzyme additions. Geoderm 257–258: 67–77. https://doi.org/10.1016/j.geoderma.2015.01.014.

Asio, V.B. (1996). Characteristics, weathering, formation and degradation of soils from volcanic rocks in Leyte, Philippines. Published Ph.D. thesis. University of Hohenheim, Stuttgart, Germany.

Ayub, M., Nadeem, M.A., Sharar, M.S., & N. Mahmood. (2002). Response of maize (*Zea mays* L.) fodder to different levels of nitrogen and phosphorous. Asian Journal of Plant Science. 1:352-354.

Bassirani, N., Abolhassani, M., Galavi, M. (2011). Distribution of available Micro-nutrients as related to the soil characteristics of Hissar; Haryana (India). African Journal of Agricultural Research. 6:4239- 4242.

Basso, C.J., Ceretta, C.A (2000). Manejo do nitrogenio no milho em sucessaoa plantas de cobertura de solo, sob plantio direto. Revista brasileira de ciencia do solo, 24:905-915.

Bell, L. C. (2002). Remediation of chemical limitations. In M. H. Wong & A. D. Bradshaw (Eds.), The restoration and management of derelict land: Modern approaches (pp. 112-127). Singapore: World Scientific Publishing.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Dieckow, J., & Amado, T. J. C. (2006). C and N stocks and the role of molecular recalcitrance and organomineral interaction in stabilizing soil organic matter in a subtropical Acrisol managed under no-tillage. *Geoderma*, *133*(3–4), 258–268. https://doi.org/10.1016/j.geoderma.2005.07.012

Brady, N. C., Weil, R. R., & Weil, R. R. (2008). *The nature and properties of soils* (Vol. 13, pp. 662-710). Upper Saddle River, NJ: Prentice Hall.

Branca, G., Hissa, H., Benez, M. C., Medeiros, K., Lipper, L., Tinlot, M., Bockel, L., & Bernoux, M. (2013). Capturing synergies between rural development and agricultural mitigation in Brazil. **Land Use Policy, 30(1), 507–518**. https://doi.org/10.1016/j.landusepol.2012.04.021

Bruulselma, TW., Fixen, PE., Sulewski, GD. (eds) (2012) 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition. International Plant Nutrition Institute (IPNI), Norcross, GA, USA

Buksh, MA., Ahmed, R., Iqbal, J., Maqbool, MM., Ali, A., Ishaque, M., Hussain, S. (2012) Nutritional and physiological significance of potassium application in maize hybrid crop production. Pakistan Journal of Nutrition 11 (2):187-202

Bumb, B., & Johnson, Michael & Fuentes, Porfirio. (2011). Policy Options for Improving Regional Fertilizer Markets in West Africa. IFPRI Discussion paper.

Chatterjee, C., Nautiyal, N. (2001). Molybdenum stress affects viability and vigour of wheat seeds. Journal of Plant Nutrition 24: 1377–1386

Chemonics. (2010). Staple Foods Value Chain Analysis: Country Report Kenya. Washington, DC. Chemonics International

Chude, VO., Malgwi, WB., Amapu, IY & Ano, AO. (2004). Manual on Soil Fertility Assessment. Federal Fertilizer Department/National Special Food Programme for Security, Abuja. p.89.

Dowswell, C.R., & Borlaug, N. E. (1994). Feeding a human population that increasingly crowds a fragile planet. Paper presented at the 15th World Congress of Soil Science, 10 16 July 1994, Acapulco, Mexico.

Dwivedi, S., Sahrawat, K., Upadhyaya, H., & Ortiz, R. (2013). Food, Nutrition and Agrobiodiversity Under Global Climate Change. In *Advances in Agronomy* (Vol. 120). Elsevier. https://doi.org/10.1016/B978-0-12-407686-0.00001-4

Esilaba, A. O., Nyende, P., Nalukenge, G., Byalebeka, J. B., Delve, R. J., & Ssali, H. (2005). Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. Agriculture, Ecosystems and Environment, 109(3–4), 192–201. https://doi.org/10.1016/j.agee.2005.03.013

Efe, L., Yarpuz, E. (2011). The effect of zinc application methods on seed cotton yield, lint and seed quality of cotton (Gossypium hirsutum L.) in east Mediterranean region of Turkey. African Journal of Biotechnology. 10: 8782-8789.

Esilaba, A. O., and Ssali, H. (1987). Sulphur status of selected Kenya soils. East Africa Agricultural and Forestry Journal. 52, 230-235.

Eskandari, H. (2011). The Importance of Iron (Fe) in Plant Products and Mechanism of Its Uptake by Plants. Journal of Applied Environmental and Biological Sciences, 1(10): 448-452.

Fageria, Nanda & Nascente, Adriano. (2014). Management of Soil Acidity of South American Soils for Sustainable Crop Production. 10.1016/B978-0-12-802139-2.00006-8.

FAO. (2010). Roles of women in agriculture. Prepared by the SOFA team and Cheryl Doss. Rome.

FAO. (2011) (forthcoming). World Census of Agriculture: analysis and international comparison of the results (1996-2005). FAO Statistical Development Series No. 13. (Columns 3 and 4). Rome.

FAO. (2016). FAOSTAT Retrieved from faostat.fao.org. faostat.fao.org

FAO. (2017). State of food security and nutrition in he world. Rome, Italy: Food and Agricultural Organization.

FURP. (1994). Final Report of the Fertiliser Use Recommendation Program (FURP) Volumes V and VII Busia and Kakamega districts. National Agricultural Research Laboratory.

Gao, S., Yan, R., Cao, M., Yang, W., Wang, S., Chen, F. (2008). Effect of copper on growth, antioxidant enzymes and phenyalanine ammonialyse activities in Jatropha curcas I., seedling. Plant, Soil and Environment. 54. 10.17221/2688-PSE.

Gaudin, A. C. M., Janovicek, K., Martin, R. C., & Deen, W. (2014). Approaches to optimizing nitrogen fertilization in a winter wheat-red clover (Trifolium pratense L.) relay cropping system. Field Crops Research, 155, 192–201. https://doi.org/10.1016/j.fcr.2013.09.005

Genstat. (2012) Genstat for windows. Fifteenth Edition. VSN International Ltd.

Gikonyo, E. W., Kimani, S.K., Kibunja, C.N., Esilaba, A.O., & Mbuthia, L.W. (2018). Rice response to potassium fertilization in Mwea, Kenya. Research Findings in Electronic International Fertilizer Correspondent (***e-ifc)*** No. 52, March 2018. International Potash Institute

Gicheru, Patrick & Kimigo, Jeremiah. (2012). Gicheru, Kimigo - 2012 - Impact on soil quality of land-use change and continuous cultivation in Sasumua Catchment, Kenya. Pedologist (2012). Vol 12, 326-331.

Hartemink, A.E. (2003). Soil Fertility Decline in the Tropics with Case Studies on Plantations, CABI Publishing, UK, Retrieved on 8 November, 2015.

Hauggaard-Nielsen, H., Johansen, A., Carter, M. S., Ambus, P., & Jensen, E. S. (2013). Annual maize and perennial grass-clover strip cropping for increased resource use efficiency and productivity using organic farming practice as a model. European Journal of Agronomy 47: 55–64. https://doi.org/10.1016/j.eja.2013.01.004

Heger, M., Zens, G., Bangalor, M. (2018). Does the environment matter for poverty reduction? The role of soil fertility and vegetation vigor in poverty reduction. Washington DC: The World Bank.

Hepler, PK. (2005) Calcium: a central regulator of plant growth and development. Plant Cell 17(8):2142–2155.

He ZL, Yang XE. (2007) Role of soil rhizobacteria in phytoremediation of heavy metal contaminated soils. J Zhejiang Univ Sci 8(3):192–207.

Hinga, G., Muchena, F.N., Njihia, C.M. (Eds.) Physical and chemical methods of soil analysis [in Kenya] [1980]. Ministry of Agriculture, Nairobi (Kenya). National.

Hoagland, D.R., & Arnon, D.I. (1938) The water culture method for growing plants without soil. California Agricultural Experiment Station Circulation, 347, 32.

IFDC. (2006). Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development.

Jagadamma, S., Lal, R., Hoeft, R. G., Nafziger, E. D., & Adee, E. A. (2008). Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA. Soil and Tillage Research, 98(2), 120–129. https://doi.org/10.1016/j.still.2007.10.008

Janssen, B. H. (1974). A double pot technique for rapid soil testing. Wageningen, [s.n.].

Janssen, B.H. (1990). A double pot technique as a tool in plant nutrition studies. pp. 759-763. In: M.L. van Beusichem (ed.), Plant Nutrition Physiology and Applications. Kluwer Academic Publishers, Dordrecht, Netherlands

Jat, M. L., Bijay-Singh, & Gerard, B. (2014). Nutrient Management and Use Efficiency in Wheat Systems of South Asia. In *Advances in Agronomy* (1st ed., Vol. 125). Elsevier Inc. https://doi.org/10.1016/B978-0-12-800137-0.00005-4

Jiang, Y., Zhang, YG., Zhou, D., Qin, Y., Liang, WJ. (2009). Profile distribution of Micro-nutrients in an aquic brown soil as affected by land use. Plant Soil Environ. 55:468-476.

Johnstone, J. (2011). Assessing soil fertility, the importance of soil analysis and its interpretation. Rothamsted Research, Herpenden, AL52JQ,UK.

Jones, A., Breuning-Madsen, H., Brossard, M., et al., (eds) (2013). Soil atlas of Africa. Luxembourg: Publications Office of the European Union.

Kalkhoran, S.S.; Pannell, D.; Polyakov, M.; White, B.; Haghighi, M.C.; Mugera, A.W.; Farre, I. A (2021) dynamic model of optimal lime application for wheat production in Australia. Australian Journal of Agricultural and Resource Economics. 2021, 65, 472–490.

Kamoni, P.T. & Gicheru, Patrick & Wokabi, S.M., & Easter, Mark & Milne, Eleanor & Coleman, Kevin & Falloon, Pete & Paustian, Keith. (2013). Predicted soil organic carbon stocks and changes in Kenya between 1990 and 2030. Agriculture Ecosystems & Environment. 105-113. 10.1016/j.agee.2007.01.024.

Kanyanjua, S., Ireri, ML., Wambua, S., Nandwa, SM. (2002). Acid soils in Kenya: Constraints and remedial options. KARI Technical note No. 11.

Kenya National Bureau of Statistics (2021). Kenya Economic Survey 2021. Nairobi, Kenya.

K., F., A., C., Mugwe, J., Mucheru-Muna, M., & Mugendi, D. (2012). The Potential of Organic and Inorganic Nutrient Sources in Sub-Saharan African Crop Farming

Systems. *Soil Fertility Improvement and Integrated Nutrient Management - A Global Perspective*. https://doi.org/10.5772/28728

Khan, Hashim. (2018). Importance of Soil tests.

Kihara, J., Nziguheba, G., Zingore., Coulibaly, S., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J(2016) Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa Agricultural Ecosystems and Environment. 229: 1-12

Kisinyo, PO. (2011). Constraints of soil acidity and nutrient depletion on maize (Zea mays L.) production in Kenya. PhD Thesis, Moi University Kenya.

Kumar, Ajeet. (2020). TB1 2013 Nutrient Deficiency symptoms in Maize.

Lindsay WL, Norvell WA. (1978). Development of DTPA soil test for Zn, Fe, Mn and Cu. Soil Science Society of American Journal 42:421-428.

Lisle, M., Leanne, Rod D. B., Lefroy & Graeme J, Blair. (2000) Method for rapid assessment of nutrient supply capacity of soils, Communication in Soil Science and Plant Analysis, 31: 15-16, 2627-2633.

Liu, M., Li, Z. pei, Zhang, T. lin, Jiang, C. yu, & Che, Y. ping. (2011). Discrepancy in response of rice yield and soil fertility to long-term chemical fertilization and organic amendments in paddy soils cultivated from infertile upland in subtropical China. Agricultural Sciences in China, 10(2), 259–266. https://doi.org/10.1016/S1671-2927(11)60003-5

Li, Qianru and Sun., Yue and Zhang., Xinyu and Xu., Xingliang and Kuzyakov., Yakov. (2014) Relationship between carbon and nitrogen mineralization in a subtropical soil. EGU

GeneralAssemblyConferenceAbstracts-https://ui.adsabs.harvard.edu/abs/2014EGUGA.1613120L.

Maatman, A., M.C.S. Wopereis, K.S. Debrah, and J.J.R. Groot. 2007. From Thousands to Millions: Accelerating Agricultural Intensification and Economic Growth in Sub-Saharan Africa. Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities: 75-84.

Manzeke, G. M., Mapfumo, P., Mtambanengwe, F., & Chikowo, R. (2012). Soil fertility management effects on maize productivity and grain zinc content in smallholder farming systems of Zimbabwe. 57–69. https://doi.org/10.1007/s11104-012-1332-2

Mehlich, A., A. Pinkerton, W. Robertson, and R. Kempton. 1962. Mass Analysis methods for Fertility Evaluation. Internal publication, Ministry of Agriculture, Nairobi, Kenya.

Mehlich, A. (1984) Mehlich 3 Soil Test Extractant. A Modification of the Mehlich 2 Extractant. Communications in Soil Science and Plant Analysis, 15, 1409-1416. http://dx.doi.org/10.1080/00103628409367568

Metson, A.J. (1961). Methods of Chemical Analysis for Soil Survey Samples, Soil Bureau Bulletin No. 12, New Zealand Department of scientific and Industrial Research, pp. 168-175. (Government printer: Wellington, New Zealand.)

Morgan JB, Connolly EL (2013) Plant-soil interactions: nutrient uptake. Nat Educ Knowl 4(8):2 Mbithi L and Huylenbroeck GV (2000) A comparison of maize production in Kenya before and during liberation period. Tropicultura, 18(4); 181-186.

Mousavi SR, Galavi M, Ahmadvand G, 2007. Effect of zinc and manganese foliar application on yield, quality and enrichment on potato (Solanum tuberosum L.). Asian Journal of Plant Sciences, 6:1256-1260.

Mueller, N., Gerber, J., Johnston, M. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257 (2012). https://doi.org/10.1038/nature11420

Murphy, SP., Beaton, GH., Calloway, DH. (1992) Estimated mineral intakes of toddlers: predicated prevalence of inadequacy in village populations in Egypt, Kenya, and Mexico. Am J Clin Nutr; 56: 565–572.

Muthaura, C., Mucheru-muna, M., Zingore, S., Kihara, J., & Muthamia, J. (2017). Effect of Application of Different Nutrients on Growth and Yield Parameters of Maize (Zea Mays), Case of Kandara Murang'a County. *ARPN Journal of Agricultural and Biological Science*, *12*(1), 19–33.

Muya , E.M. (2014). Characteristics, productivity and potential response of acid soils to agricultural inputs in Uasin Gishu, Kakamega, Kisii and Machakos Counties. Technical Report

Muya, E., Kirigua, V., Wasike, V., Nafuma, L., Macharia, E., Thuranira, E., Owenga, P., Goro, H., Waruru, B., Chek, A., Kimigo, J., & Maingi, P. (2015). Evaluating the Impacts of Land Degradation on the Quality of Soils and Their Variations between Different Clusters in Mosiro Irrigation Scheme, Narok County, Kenya. American Journal of Experimental Agriculture, 7(1), 1–9. https://doi.org/10.9734/ajea/2015/10659

NAAIAP. (2014). Evaluation of soil suitability for maize in Kenya. A technical report.

Naseem, A., Nagarajan, L., & Pray, C. (2018). The role of maize varietal development on yields in The role of maize varietal development on yields in Kenya. 10th International Conference of Agricultural Economists July 28-August 2, 1–26.

Ngome, A. F., Becker, M., Mtei, M. K., & Mussgnug, F. (2013). Maize productivity and nutrient use efficiency in Western Kenya as affected by soil type and crop management. International Journal of Plant Production, 7(3), 517–536.

Nziguheba, G. (2007). Overcoming phosphorus deficiency in soils of Eastern Africa: recent advances and challenges.

Olsen, S.R., Kemper, W.D., Jackson, R.D. (1962) Phosphate Diffusion to Plant Roots.

Oluoch-Kosura, W., Karugia, JT., Wambugu, SK. (2011) Conditions for achieving sustained agricultural intensification in Africa: evidence from Kenya.

Onduru, Davies & De Jager, A & Wouters, A & N Muchena, F & Gachimbi, L & N Gachini, G. (2006). Improving Soil Fertility and Farm Productivity under Intensive Crop-Dairy Smallholdings: Experiences from Farmer Field Schools in the Highlands of Kiambu District, Central Kenya.

Onono, P. A., Wawire, N. W. H., & Ombuki, C. (2013). The response of maize production in Kenya to economic incentives. International Journal of Development and Sustainability, 2(2), 530–543.

Ortiz-Monasterio, JI., Raun, W. (2007) Reduced nitrogen and improved farm income for irrigated spring wheat sensor-based Valley, Mexico, using sensor based nitrogen management. J Agric Sci 145:215–222. Doi: 10.1017/S0021859607006995

Pandey, D., Agrawal, M., & Bohra, J. S. (2014). Effects of conventional tillage and no tillage permutations on extracellular soil enzyme activities and microbial biomass under rice cultivation. Soil and Tillage Research, 136, 51–60. https://doi.org/10.1016/j.still.2013.09.013

Pasuquin, JM., Pampolino, MF., Witt C, et al. (2014) Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. Food Crop Research 156:219– 230. Doi: 10.1016/j.fcr.2013.11.016

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, DE., Kropp, JP. (2015). Closing yield gaps: how sustainable can we be? PLoS ONE 10, E0129487.

Rowley, S., Cardon, G., Black, B. (2012) Macronutrient management for Utah Orchards. USU Extension Publication Horticulture/Fruit/2012-01pr

Saikat, C. and Geon-Ha, K. (2021). Role of cultural and nutrient management practice in carbon sequestration in agricultural soil. Advances in Agronomy. 166,131-196

Sanginga, N. (2003), Role of biological nitrogen fixation in legume based cropping systems: a case study of west Africa farming systems, Plant and Soil 252: 25-39

Sangoi, L., Almeida, M.L., Pucci, A.L.R ., Strieder, M., Zanin, C.G.,Silva, L. Vieira,L.J. 2008. Early nitrogen side-dress application does not increase wheat grain yield at the aluminum presence. Ciencia Rural, 4:912-920.

Smaling, Eric & Stoorvogel, Jetse & N. Windmeijer, P. (1993). Calculating soil nutrient balances in Africa at different scales - II. District scale. Fertilizer Research. 35. 237-250. 10.1007/BF00750642.

Sanchez, P.A. and Logan, T.J. (1989). Myths and Science about the chemistry and fertility of soils in the tropics. SSSA Special Publication no. 29, pp 35-46. American Society of Agronomy and Soil Science, Madison, USA.

Sanchez, PA., Shepherd, KD., Soule, MJ. (1997). Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh RJ, Sanchez PA and Calhoon F(eds)

Replenishing soil fertility in Africa, pp 219-236. Soil Science Society of America Special Publication No. 51, Madison, Wisc., USA

Sanchez, PA. (2015). En route to plentiful food production in Africa. Nature Plants 1, 14014. (Pub Med)

Selassie, Y. G. (2015). The effect of N fertilizer rates on agronomic parameters , yield components and yields of maize grown on Alfisols of North - western Ethiopia. *Environmental Systems Research*. https://doi.org/10.1186/s40068-015-0048-8

Shanker, AK., Venkateswarlu, B. (2011). Abiotic stress in plants-mechanisms and adaptations. Tech Publisher, pp1–428, ISBN 978-953-307-394-1

Shibu, M. E., Van Keulen, H., & Leffelaar, P. A. (2012). Long-term dynamics of soil C and N in intensive rice-based cropping systems of the Indo-Gangetic Plains (IGP): A modelling approach. *Ecological Modelling*, *232*, 40–63. https://doi.org/10.1016/j.ecolmodel.2012.02.020

Singh, MV. (2004). Micronutrient deficiencies in Indian soils and field usable practices for their correction. IFA International Conference on Micronutrients Feb. 23-24, 2004, at New Delhi.

Singh RD, Kumar S, Panse H (2006). Micro-nutrient status of soils under different vegetations in Uttaranchal Hills. Journal of Indian Society and Soil Science. 54:115-116.

Stewart, R.E. (2022) Fertilizer Encyclopedia Britannica. Available online: https://www.britannica.com/topic/fertilizer

Stockdale, E.A., Goulding, K.W.T., George, T.S., & Murphy, D.V. (2013). Soil fertility In Gregoty, P.J. & Nortcliff, S. (2013). Soil Conditions and Plant Growth, Ed. Wiley-Blackwell, U.K. Retrieved on18 rebmetpeS 2014.

Stoorvogel, Jetse & Smaling, Eric & Janssen, Bert. (1993). Calculating soil nutrient balances in Africa at different scales - I Supra-national scale. Nutrient Cycling in Agroecosystems. 35. 227.

Sumner, M., Noble, A. (2003) Handbook of soil acidity. In: Rengel Z (ed) Marcel Dekker, New York, pp 1–28 235. 10.1007/BF00750641.

Swift, M.J. & Izac, Anne-Marie & Van Noordwijk, Meine. (2004). Biodiversity and ecosystem services in agricultural landscapes - Are we asking the right questions? Agriculture, Ecosystems& Environment. 104. 113-134. 10.1016/j.agee.2004.01.013.

United Nations. (2015) Food and Agriculture Organization of the The Economic Lives of Smallholder Farmers.

USAID. (2011). Kenya maize programme. Retrieved on 20th July 2011. http://www.usaid.gov/our_work/humanitarian_assistance/foodcrisis.

Vanlauwe, B., Tittonell, P., and Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya, Nutrient Cycle. Agroecosystems. 76, 171–182.

Van Straaten, P. (2007). Agro geology: the use of rocks for crops. Enviroquest Ltt, 352 River Road, Cambridge, Ontario N3C 2B7, Canada.

Verma, VK., Setia, RK., Sharma, PK., Khurana, MPS., Kang, S (2007). Pedospheric distribution of micronutrient cations in soil developed on various land forms in north-east Punjab. Journal of the Indian Society of Soil Science. 55:515-520.

Wang, G., Zhang, QC., Witt, C., Buresh, RJ. (2007) Opportunities for yield increases and environmental benefits through site specific nutrient management in rice systems of Zhejiang province, China. Agric Syst 94:801–806. Doi: 10.1016/j.agsy.2006.11.006.

Wopereis, MCS., Tamélokpo, A., Ezui, K., Gnakpénou, D., Fofana, B., Breman, H. (2006) Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crop Res 96:355–362

World Bank. (2014) Fertilizer consumption (Kilogram per hectare of arable land). Available online http://data.worldbank.org/indicator/AG.CON.FERT.ZS.

World Bank Group. (2019) Kenya Economic Update : Unbundling the Slack in Private Sector Investment – Transforming Agriculture Sector Productivity and Linkages to Poverty Reduction (English). Kenya economic update, no. 19 Washington, D.C. http://documents.worldbank.org/curated/en/820861554470832579/Kenya-Economic-Update-Unbundling-the-Slack-in-Private-Sector-Investment-Transforming-Agriculture-Sector-Productivity-and-Linkages-to-Poverty-Reduction

World Food Programme. (2022) Impact of increasing fertilizer prices on maize production in Kenya.

Wortmann S., and Keith Sones (eds). (2017) Fertilizer Use Optimization in Sub-Saharan Africa Published by *CABI*.

Yadegari, M. (2014). Irrigation periods and Fe, Zn foliar application on agronomic characters of medicinal plants. Advances in Environmental Biology, 8(4): 1054-1062.

Yadvinder-Singh, Bijay-Singh, & Timsina, J. (2005). Crop Residue Management for Nutrient Cycling and Improving Soil Productivity in Rice-Based Cropping Systems in the Tropics. *Advances in Agronomy*, *85*, 269–407. https://doi.org/10.1016/S0065-2113(04)85006-5.

Yousaf, M., Li, J., Lu, J., Ren, T., Cong, R., Fahad, S., & Li, X. (2017). Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system. *Scientific reports*, *7*(1), 1-9.

Zingore, S., Murwira, HK., Delve, RJ., Giller, KE. (2007) Soil type, historical management, and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on African smallholder farms. Field Crop Res 101:296–305