RESPONSE OF COMMON BEAN (*Phaseolus vulgaris* L.) TO LIME AND CUSTOMIZED MICRONUTRIENT FERTILIZER IN NANDI COUNTY, KENYA

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DECLARATION AND RECOMMENDATION

Declaration

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

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Recommendation

This thesis has been submitted with our approval as University supervisors.

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DEDICATION

This thesis is dedicated to my late grandfather Kipsang Cheboiwo Towwet, my uncle Mr. Samuel Sang, my aunt Mary Sang, my Cousins and friends for their support.

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ABSTRACT

Low soil fertility associated with nutrient mining of both macro and micronutrients and soil acidity is a major constraint affecting crop production in Western Kenya. The objectives of this study were (i) to determine the effect of customized fertilizer and lime on common bean (*Phaseolus vulgaris* L.) growth and yield and (ii) to determine the effect of selected micronutrient (boron, zinc and molybdenum) with lime on their uptake and growth of common bean. In the first experiment, a field experiment was conducted on 2 sites of Kapkerer and Kiptaruswo, Nandi County. A 4 × 2 factorial experiment was set up in randomized complete block design. The treatments were *Mavuno* fertilizer (15:10:18: plus sulphur, calcium, magnesium, iron copper, boron and molybdenum) (0, 185 kg ha^{-1}), *Sympal* fertilizer (0:23:15 calcium, magnesium, sulphur and zinc) (0, 125 kg ha^{-1}), Diammonium phosphate fertilizer (positive control) (0, 62.5 kg ha^{-1}) and lime (0, and 1.6 or 2.0 t ha^{-1} depending on specific lime requirement for the site). Yield, phosphorous uptake, below and aboveground biomass were determined. In the second experiment, a greenhouse experiment was conducted at Egerton University using soil from Kapkerer site. A 2 × 2 × 2 × 2 factorial experiment was set up in completely randomized design. The treatments were, boron (0, 3 kg ha^{-1}), zinc (0, 1.5 kg ha^{-1}) Mo (0, 0.6 kg ha^{-1}) and lime (0, 1.6 t ha^{-1}). Plant tissue analysis for micronutrient uptake (boron, zinc and molybdenum) above and below-ground biomass were determined. The results showed that application of lime increased above and belowground biomass, nutrient uptake and yield in common bean while combined application of *Mavuno* fertilizer with lime further enhanced common bean growth and increased yields by 42%, 30% and 27%, respectively, compared to control, *Sympal* and DAP. Application of DAP and *Sympal* in combination with lime did not have a significant effect on common bean yield. On the other hand, the application of boron with molybdenum significantly increased above and below-ground biomass by 24% and 32%, respectively, compared with the control. The application of boron and lime significantly increased aboveground biomass by 11%, while molybdenum with lime application significantly increased belowground biomass by 29%. The results for this study suggest that the use of *Mavuno* fertilizer formulation can significantly improve common bean productivity in Western Kenya smallholder systems, and inclusion of boron and molybdenum in the fertilizer and liming the soil is necessary for enhanced common bean productivity.

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LIST OF ABBREVIATIONS AND ACRONYMS

CIAT	International Centre for Tropical Agriculture
DAP	Diammonium Phosphate
EDTA	Ethylenediaminetetraacetic acid
IAA	Indole Acetic Acid
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
masl	meters above sea level
NPK	Compound fertilizer containing nitrogen phosphorous and potassium
SAS	Statistical Analysis System
SSA	Sub-Saharan Africa

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Background information

The world population is projected to be 9.6 billion by 2050, with 86.4% of this population expected to live in developing regions, including Sub-Saharan Africa, with East Africa accounting for 42% of this population. (United Nation, 2013: Van Loon *et al*., 2018). As a result, global food demand is expected to rise to 60% by 2050, and the rise will be much more substantial in Sub-Saharan Africa, leading to food insecurity (Van Ittersum *et al*., 2016). Due to the increasing population, the world will face a significant challenge of land degradation caused by continuous cropping, soil erosion, inadequate use of organic and inorganic fertilizers and increasing soil acidity, resulting in loss of productive land for crop production hence in food insecurity, especially in the developing countries (Stagnari *et al*., 2017). Low soil fertility is one way soil degrades, the primary constraint affecting smallholder farmers, especially in agricultural production areas (Kamau *et al*., 2014). The impact of nutrient depletion and toxicities is evident through the declining crop yield, which implicates food deficit and food insecurity (Lal, 2009; Okalebo *et al*., 2006). The major constraint associated with soil degradation is low soil fertility coupled with soil acidity.

Low moisture content, low soil pH, and poor soil fertility, including low phosphorous, nitrogen and bases, especially in acidic soils affects common bean growth (*Pheseolus vulgaris* L.) in Western Kenya (Wortmann *et al*., 1998). In the tropics, the primary constraints affecting common bean production are low soil fertility and soil acidity found in highly weathered soil, mainly the *Acrisols*, *Ferralsols* and *Nitisols* (Okalebo *et al.*, 2009). Low soil fertility is caused by continuous cultivation without nutrient replenishment, resulting in the decline of common bean production. Its restoration is vital in enhancing food security and improving the livelihood of smallholder farmers who accounts for 75% of agricultural production and over 75% of employment in East Africa (Salami *et al*., 2010).

Soil acidity affects crop production through various processes; aluminium and manganese toxicity and inhibition of essential nutrients to crops (Alemu, 2017) hence a threat to food security to the growing population. Phosphorous, calcium, magnesium, potassium and molybdenum are the essential nutrients affected by soil acidity leading to poor crop growth. Most soils in Nandi county, Western region of Kenya, are dominated by *Acrisols* and *Ferralsols*, which are highly weathered and acidic with a $\mathrm{pH} < 5.5$, resulting in the deficiency of essential nutrients, Phosphorous and Nitrogen (Okalebo *et al*., 2009), thus contributing to low yield in common bean in the region. Correction of soil acidity is achieved by applying lime, organic matter and mineral fertilizer application (Crowford *et al*., 2008). Therefore, soil acidity management is essential in enhancing the availably of essential nutrient resulting in improved food security, both globally and regionally.

Liming of acidic soils increases the phytoavailability of essential nutrients and ameliorates other acidity induced constraints hence ensuring optimum yield in crops, attaining chemical and biological changes in the soil, which is beneficial in improving yield in acidic soil when applied at the recommended rate (Kumar *et al*., 2011). Liming acidic soil in legume producing areas is essential in enhancing biological nitrogen-fixation, availability of essential nutrients for plant growth and reduces toxicity associated with and Mn toxicity (Crowford *et al*., 2008). The Ca^{2+} or Mg^{2+} ions in lime displaces H^+, Fe^{3+}, Mn^{4+} and Al^{3+} ions in negatively charged soil colloids, thus, decreasing their concentrations in the soil solution and enhance the availability of phosphorous and other nutrients (Kisinyo *et al*., 2015). Liming depends on the level of soil acidity and the major challenge on its use in Sub-Saharan Africa is lack of awareness among smallholder farmers, lack of appropriate recommendation rates, limited studies done in the region, and unknown agricultural lime quality (Athanase *et al*., 2013). Unfortunately, most farmers in Nandi County rarely use lime because of inadequate information on recommendation rate and its importance resulting in low production. To enhance nutrient availability and increase common bean production, liming ought to be carried out among smallholder farmers in Nandi County.

The dependence on DAP fertilizer in Western Kenya has resulted in stagnation of common bean yield (Keino *et al*., 2015). Therefore, there is a need to address the deficiency of other nutrients, especially micronutrients, to improve common bean production in Nandi County. This study aims to (i) determine investigating the effect of lime and customized fertilizers and (ii) determine the effect of boron zinc, molybdenum and lime application towards improving food security and improving the livelihood of smallholder farmers in Nandi County, Western Kenya

1.2 Statement of the problem

Declining soil fertility is a major problem facing smallholder farmers in Nandi County of Aldai This has been further exacerbated by the use of macronutrient-based fertilizer without micronutrients. Famers are presented with alternatives of inorganic micronutrient fertilizer formulations from different companies without enough information on the behaviour in acidic soils in the region resulting in low common bean production. The yield in the region has stagnated at 0.7 t ha^{-1} against 3 t ha^{-1}. Different approaches have been used to manage the situation, including the promotion and use of fertilizer customized for horticultural crops, including common bean. It is not clear whether those fertilizers effectively increase common bean yields when applied alone or when applied with lime. Soil acidity in the region is also a constraint reducing common bean production. Therefore, there is a need to determine whether micronutrient addition in customized fertilizers and lime application is essential for common bean production and if so, which ones?

1.3 Objectives

1.3.1 General objective

To improve food security and livelihoods of smallholder farmers in Nandi County through the application of customized fertilizers and lime in common bean production.

1.3.2 Specific objectives

i. To determine the effect of customized fertilizer and lime application on common bean growth and yield in Nandi County

ii. To determine the effect of boron, zinc, molybdenum and lime application on micronutrient uptake and growth of common bean in Nandi County.

1.4 Hypotheses

i. Customized fertilizer and lime application have no significant effect on growth and yield of common bean in Nandi County

ii. Boron, zinc, molybdenum and lime applications have no significant effect on micronutrient uptake and growth of common bean in Nandi County.

1.5 Justification

Declining soil fertility associated with soil acidity is a major yield-reducing factor affecting common bean production in Nandi County; this has resulted in low production, low household income and increased poverty level. Therefore, there is a need to introduce lime and customized fertilizer to increase soil fertility, hence improving common bean production. Liming plays an essential role in alleviating soil acidity hence enhances the availability of nutrients, whereas customized fertilizers supply critical nutrient, including micronutrient required for common bean production. Therefore, the application of lime and customized fertilizers will improve soil fertility, thereby enhancing food security, improving the health and livelihood of smallholder farmers in Nandi County. Subsequently, it will provide a basis to extension agents and county agricultural officer for improved recommendations for common bean production using the customized fertilizers with the lime application.

1.6 Definition of terms

Customised fertilisers – these are blended fertilizers containing macro and micronutrients manufactured through a systematic process to suite crop nutritional needs, specific to site and soil type.

CHAPTER TWO

LITERATURE REVIEW

2.1 Common bean production

Common bean (*Phaseolus vulgaris* L.) was first domesticated about 8000 years ago by the Americas and in the present day it is being used as the stable food worldwide (Castro-Guerrero *et al.*, 2016). Common bean is predominantly self-pollinating diploid annual species with 2 main gene pool Mesoamerica and Andean, characterized by partial reproductive variation including wild and cultivated varieties. Common bean is the third most important legume in the world and shows considerable variation in seed characteristics, maturation and growth habits (De Ron *et al*., 2015). Common bean also known as dry bean is an annual legume belonging to genus *Phaseolus* with pinnately compound trifoliate large leaves, an essential component in production system and the primary source of dietary protein for the poor in the east and southern Africa (Katungi *et al*., 2009).

Common bean is important source of nutrition, especially to the low-income people, in the developing countries it is often considered as poor man meat (Tharanathan & Mahadevamma, 2003). Apart from being a dietary protein, it is a source of dietary fibre, iron, carbohydrate and minerals for millions of people in the world (Ozturk *et al.*, 2009). Common bean consumption reduces the risk of chronic diseases such as cancer diabetes cardiovascular diseases and obesity (Hayat *et al*., 2014). It is usually grown with other crops and it matures quickly, supply food, income and enhances soil fertility through nitrogen fixation however, its production is constraint by both biotic and abiotic factors, biotic factors being angular leaf spot (*Xanthomonas fragariae*), anthracnose (*Colletotrichum spp*), bean stem maggot (*Ophiomyia spp*), bruchids (*Callosobruchus chinensis*) and root rot (*Cochliobolus sativus*) (Wortmann *et al*., 1998).

In Kenya common bean contributes Ksh.13.18 billion annually to the national economy and is a source of dietary protein, especially for the rural and urban poor, it is widely grown and consumed particularly by medium and low income households. It is grown in an area of 960,705 ha with an average production of 403,604 tonnes, and it is second after maize (*Zea mays*) as food security crop (CIAT, 2013; Enid *et al.*, 2015). Common bean production in Kenya has not kept pace with demand due to the increasing population. This is attributed to declining soil fertility, nutrient mining and inadequate knowledge among smallholder farmers on the nutrient requirement of common bean (Katungi *et al*., 2011), leading to reduced yields and increased poverty levels among smallholder farmers who are the main producers of common bean in Kenya.

2.2 Effects of low soil fertility on common bean production

Low soil fertility is a significant constraint limiting common bean production in Africa, with 75 % of the soil being deficient in phosphorous, 65% of nitrogen and 20% of the soil are acidic, causing deficiency of most of the essential nutrient required for common bean production (Lunze *et al*., 2012). In Eastern Africa, the leading soil fertility-related problems are low available nitrogen, phosphorous and exchangeable bases and soil acidity (Wortmann *et al*., 1998), caused by continuous cropping, inappropriate cropping system with little or no input to replenish soil fertility, inadequate resources to allocate to soil improvement by smallholder farmers lack of soil fertility maintenance plan, increasing population, inadequate supply of organic and inorganic fertilizers, nutrient mining, low nutrient use efficiency, inappropriate fertilizer recommendation and different in response to fertilizers(Chianu *et al*., 2012; Rao *et al*., 2016). Because of continuous cropping among smallholder farmers, nitrogen loss is estimated at 4.4 million tonnes, phosphorous (P) at 0.6 million tonnes and potassium (K) at 3 million every year (Sanginga & Woomer, 2009).

Declining soil fertility caused by nutrient mining is the leading cause of decreased yield and low per capita food production in Africa, particularly in Eastern Africa, leading with an annual loss of 41 kg of nitrogen, 4 kg of phosphorous and 31 kg of potassium per hectare (Henao & Baanante, 2006; Rurangwa *et al*., 2018). Macronutrient and micronutrients prone to deficiency due to soil degradation include nitrogen Phosphorous, potassium, magnesium, sulphur and calcium and micronutrients zinc, copper, boron and molybdenum, which affects crop growth leading to low production (Lal, 2009). In Nandi County, Western region of Kenya, common bean production has stagnated at 0.7 t ha^{-1}; this is caused by low soil fertility, continuous cropping, dependence on one type of fertilizer and build-up of pests and diseases (Ojiem *et al*., 2016). In enhancing the production of common bean in Western Kenya, application of both secondary and micronutrient is crucial, yet it had received little attention leading to yield stagnation (Kihara *et al*., 2017).

2.3 Effects of soil acidity on common bean production

Acidic soil covers 40 to 50% of arable land worldwide, and 60% of this acidic soils are found in tropics and subtropics, it dominate most of the developing countries hence these regions are faced with food insecurity due to Aluminium , Manganese and hydrogen toxicity (Kochian *et al*., 2015). Acidic soils are considered to be having a pH of 5.5 or less mainly caused by leaching, excessive use of fertilization harvesting of crops and low nutrient cycling (Ferguson & Gresshoff, 2015). Soil acidity is a major factor limiting crop production worldwide, in Sub-Saharan Africa being principle soil productivity problem as a result of extensive weathering and leaching occupying 29% of land area in Sub-Saharan Africa (Fageria, 2007; Muindi *et al.*, 2016).

Soil acidity affects plant growth by affecting plant-available nutrients, increasing some micronutrients to toxic levels, deficiency of macronutrients, affecting microbial activity, and, most importantly, nitrogen-fixing bacteria resulting in poor nitrogen fixation in common bean, therefore low growth and production of common bean. (Crowford *et al*., 2008; Fageria, 2007). In Western Kenya Nandi County nitrogen fixation has not been effective due to the effect of soil acidity (Odundo *et al*., 2014). The most commonly observed symptoms associated with mineral deficiencies and toxicities in common bean production include poor seed emergence, delayed and prolonged flowering and maturity, leaf yellowing, reduced overall growth, seedling and adult plant stunting, slow growth, low harvest index, reduced seed weight, and pod abortion resulting to 100% yield loss (Singh *et al*., 2003).

Aluminium toxicity is a major constraint affecting crop production, plant growth and development in acidic soil. At soil pH <5,becomes solubilized into the soil solution, as a result, inhibit root growth and function, thus reducing crop yields (Kochian *et al.*, 2005). Toxicity is a significant constraint to crop production in acidic soil where common bean is produced and is a major factor limiting crop production, toxicity inhibit root growth and cell division as a result affecting mineral and water uptake, leading to reduced crop yield (Mendoza-Soto *et al*., 2015; Panda *et al*., 2009). On the other hand, toxicity affects nodulation process by altering infection threats resulting in the reduced number of nodules or completely nodule failure (Jaiswal *et al*., 2018).toxicity depends on soil pH, ionic strength of the solution, concentration of soluble compounds in soil solution and chemical structure (Siecińska & Nosalewicz, 2016).

Manganese is an essential micronutrient for plant growth and development; however, if it is available in excess, it will be toxic to plant at a soil pH < 5.5 and exceed those of aluminium toxicity during the progression of soil acidification (Chen *et al*., 2015; Watmough *et al*., 2007). Soil acidity affects Mn solubility, determined by oxidation potential and soil pH (Hernandez-

Soriano *et al*., 2012). As soil pH decreases below 5.0, Mn (III) and Mn (IV) are reduced to more a soluble form of Mn (II), which accumulate in excess in acidic soil, therefore toxic to plant growth (Chen *et al*., 2015). Manganese toxicity is a crucial growth-limiting factor in acidic soil of subtropics and tropics; it induces oxidative damage and disrupts the photosynthesis system in leaves (Zhao *et al.*, 2017). The toxicity is localized in the shoot and characterized by stunted growth, necrotic lesions in the leaves and chlorosis (Kochian *et al*., 2004).

In Kenya, soil acidity covers an area of 13% about 7.5 million hectares and this area contributes significantly to Kenya economy with the most soil affected by soil acidity being *Nitisols*, *Acrisols* and *Ferralsols* (Kanyanjua *et al*., 2002). In Western Kenya, soil acidity covers about 57,670 hectares and a major cause of low crop productivity in the region especially common bean (Kiplagat *et al*., 2014). One of the major constraint affecting common bean production in Nandi County is soil acidity with a pH < 5.5, caused by weathering of soil over the years; as a result leaching of basic cation and dominance of Aluminium and Manganese causing toxicity hence affecting common bean growth (Okalebo *et al.*, 2009).

2.4 Fertilizer use in bean production

Soil fertility ensures robust plant growth and high yield however, in tropical regions there is severe nutrient depletion and broad decline in soil fertility, leading to low crop yield. This is further aggravated by dismally low use of fertilizer by smallholder farmers, inadequate knowledge in the use of fertilizers, low quality of available fertilizers, inappropriate fertilizer packaging sizes, low farmers literacy and poverty resulting in a huge gap between crop yield obtained and potential yield of common bean production (Chianu *et al*., 2012). Nutrient estimates indicates that NPK mining in Sub-Saharan Africa is about 8 million tons with East Africa accounting for 1.4 million tonnes with an estimation of loss of 1 million tonnes of pulse due to erosion (Henao & Baanate, 2006).

The application of mineral fertilizers is one of the beneficial ways of increasing crop production. Over the years, there been an increase in the use of nitrogen phosphorous and potassium The most commonly used fertilizers in Sub-Saharan Africa mainly contains NPK fertilizers lacking both secondary nutrients and micronutrients such as calcium, magnesium, sulphur, zinc, copper, manganese, boron and molybdenum, the primary factor limiting plant growth (Adesemoye & Kloepper, 2009; Vanlauwe *et al.*, 2015a). Therefore, it is important to incorporate the secondary and micronutrients fertilizers in order to address food security challenges in Sub-Saharan Africa (Kihara *et al.*, 2017).

Improving awareness and access to fertilizer use is a remedy in addressing declining soil fertility in Sub-Saharan Africa, especially when farmers are aware of the type of fertilizer to apply (Henao & Baanante, 2006). In Western Kenya, the soil has been categorized into two groups responsive and non-responsive based on standard application of NPK fertilizer. Responsive respond well with the application of standard fertilizer, and non-responsive are soil with an insignificant response to standard fertilizer application due to other nutrient limitation (Keino *et al.*, 2015). Responsive soils are found in fertile fields whereas non-responsive soils are found in degraded lands that had been cultivated for an extended period leading to severe deficiency of nutrient resulting in reduced common bean yield below the potential (Vanlauwe *et al.*, 2015a). Responsive soil requires sustained fertilizer application to enhance productivity, while non-responsive need appropriate fertilizer management with multiple fertilizer replenishment to enhance and improve production (Njoroge *et al.*, 2017).

2.5 Macronutrients use in common bean production

Soil with nutrient deficiency particularly, nitrogen and phosphorous which are the major macronutrients are widespread in Sub-Saharan Africa and it is a significant cause of reduced agricultural productivity (Chikowo *et al.*, 2010). Nitrogen and phosphorous are essential element in plant growth; they are essential elements in their biochemical, structural and physiological roles. The deficiency of these elements due to nutrient mining leads to decrease growth and yield of common bean (Sinclair C Vadez, 2002). Common bean is a nutrient demanding crop because of its sensitivity to environmental stresses. One of the significant factors causing low yield in common bean production especially in the tropics is soil fertility associated with soil acidity, causing nutrient deficiency hence limiting plant nutrition especially available phosphorous and nitrogen (Silva *et al.*, 2014).

Nitrogen is one of the most yield-limiting nutrients in agricultural production; it plays an important role in plant biochemistry; it is an essential constituent of the enzyme, nucleic acid, chlorophyll, cell wall, storage of protein and cellular components (Fageria & Moreira, 2011).

Nitrogen is a major nutrient requirement for common bean growth, yet it is deficient in most of the tropical regions, caused by leaching, denitrification, low application rates and soil degradation (Soares *et al*., 2016). Adequate use of nitrogen is fundamental towards improving common bean production. Without nitrogen protein synthesis, enzymes, DNA and RNA required in virtually all plant cells for development, sustained growth and functioning to support plant tissues are hampered (Sinclair & Vadez, 2002).

Phosphorous is an important nutrient after nitrogen and is the most abundant element in natural and agricultural soils and function of three pools; soluble pool, active pool and organic pool, it is important essential nutrient after nitrogen (Sanz-saez *et al*., 2017). The major type of phosphorous fertilizer used for crop production in Africa varies with regions with East Africa dominated by Diammonium phosphate whereas NPK fertilizer used in Western Africa and Southern Africa (Nziguheba *et al*., 2016). Phosphorous play a key role in metabolic process including respiration, photosynthesis, macromolecular biosynthesis, signal transudation and energy transport (Khan *et al*., 2010). Phosphorous also essential in nitrogen fixation and phosphorous deficiency in common bean production results in reduced nodule mass, nitrogen fixation and yields (Turuko & Mohammed, 2014). Although phosphorous is most abundant its availability is limited for plant absorption due to soil acidity. In acidic soil phosphorous react with oxidized and iron forming stable and insoluble aggregate, making it unavailable for the plant (Zheng, 2010). Low phosphorous availability in acidic soil is a major constraint affecting common bean, which arises as a result of toxicities associated with complexes and Manganese which fix phosphorous hence affecting its availability for the plant (Kimani *et al*., 2007; Nian *et al*., 2009).

Soils in Western region of Kenya are acidic therefore, affecting phosphorous availability leading to reduced yield of common bean. Common bean nodules, besides act as a sink for phosphorous, therefore adequate amounts of fertilizer and liming of acidic soils should be applied for the plant to realize the potential rate of nitrogen fixation and to enhance phosphorous availability (Abebe, 2017; Okalebo *et al*., 2009).

2.6 Micronutrients use in common bean production

Micronutrients are essential trace elements required for healthy growth and reproduction in crops. Those trace elements include boron, zinc, chlorine, molybdenum, iron, manganese and nickel. Micronutrient deficiency in Africa is widespread, with little research being done on the impact of deficiency in crop growth (Waals & Laker, 2008). Common bean yield and nutritional status is dependent on the nutrient application, which enhances nutritional equilibrium (Flores *et al.*, 2017). The chemistry of micronutrients is dependent on soil pH; the lower the pH, the more the soluble and available they are to the plant roots, but pH value below 5 enhances high solubility for micronutrients hence deficiency. Micronutrient use as fertilizer increases soil concentration to an adequate level hence enhancing uptake by plant roots. Application of fertilizers containing a combination of macronutrients and micronutrient is a standard practice in highly productive agriculture (Selinus *et al.*, 2013). Increasing population has created pressure towards increasing food production; as a result, high crop yield associated with nutrient removal and use of high intensive fertilizer has resulted in depletion of micronutrient reserve in the soil (Gupta *et al.*, 2008). Micronutrient deficiency in crops has increased significantly due to intensive cropping systems, loss of topsoil due to soil erosion, over liming of acidic soil and use of marginal land for crop production. Relatively little research has been conducted on micronutrient as compared to macronutrients (Fageria, 2002).

Micronutrient is an essential plant nutrient required for plant growth in lesser amounts, yet it plays a critical role in plant growth, development and metabolism, deficiency of micronutrients lead to plant diseases affecting both the quality and quantity of the plant (Tripathi *et al.*, 2015). Research done had shown that deficiency of micronutrients in soil severely affects plant resulting in poor plant growth and abnormalities directly affecting the quality and yield of the crop (Kumar *et al.*, 2016b). Micronutrient requirement for optimum crop production has been increasing due to agricultural intensification and the dependency on the high concentration of NPK fertilizers, which has resulted in its depletion in the soil (Kachinski *et al.*, 2020).

Micronutrient plays a critical role in improving yield in common bean production by enhancing metabolic and cellular functions like energy metabolism, primary and secondary metabolism, cell protection, gene replication and hormone perception (Hänsch & Mendel, 2009). Molybdenum plays a crucial role in nitrogen fixation, and it is deficient in highly weathered acidic soil, which affects nitrogen fixation, resulting in low production of common bean (Hernandez *et al.*, 2009). On the other hand, boron plays an essential role in nodulation, cell integrity, carbohydrate transport, and reproductive growth, improving common bean growth (Da Silva *et* *al*., 2015). Zinc plays an essential role in activating enzymes, carbohydrate metabolism, protein synthesis, and seed production; its deficiency affects the nutritional quality of grain (Kachinski *et al*., 2020; Rehman *et al*., 2018).

There is an indication that the application of micronutrients improves the diversity of microorganisms in the soil, when applied in the right rate benefits it enhances microbial colonization, mycorrhizae development and improve symbiotic nitrogen fixation resulting in improved nitrogen fixation in common bean (Kihara *et al*., 2020). Application of boron at the rate of 3 kg ha^{-1} has been shown to increase soil fungal and bacterial activities and enhances the activation of enzyme phosphatase and dehydrogenize compared with the soil that boron has not been applied (Bilen *et al*.,2011). Phosphatase enzyme is essential in the hydrolyses of occluded phosphorous in the soil into inorganic form which improves the availability of phosphorous for plant growth and development phosphatases enzymes are important in solubilisation and remobilization of phosphorous (Margalef *et al*., 2017).

The application of molybdenum at rate of 3 mg kg^{-1}increases the nitrogenase enzymatic activity and enhance nodule growth hence improving the rate of nitrogen fixation through nitrogen fixing bacteria (Alam *et al*., 2015), during nitrogen fixation molybdenum act as a cofactor for nitrogenase enzyme which catalyse oxidation reduction to convert N to NH^{4+} (Mendel & Hänsch 2002). Molybdenum deficient soil show poor nodulation which affects the nitrogen availability leading to poor growth and development especially to sensitive crop to low molybdenum deficiency like common bean (Marschner, 2012). Zinc is an important nutrient involved in nitrogen fixation and nodulation, the application of zinc increases the number of nodules, because it is involved in the synthesis of leghaemoglobin and its deficiency in legume reduces the number of nodules (Edulamudi *et al*., 2017)

In Western Kenya, common bean yield had stagnated due to non-responsive soil due to the application of only macronutrient fertilizer (Keino *et al*., 2015). This is further affected by the fact that most micronutrient fertilizers are not included in most fertilizer formulation, yet they play an essential role in common bean growth. Therefore, they could be deficiency of micronutrient, causing the soils to be non-responsive hence the need to introduce customized fertilizer in addressing micronutrient deficiency. Integration and balances use of macro and micronutrients is important in enhancing nutrient use efficiency, improving plant productivity and sustaining soil fertility, thus essential to find techniques of improving and enhancing micronutrient efficiencies (Choudhary & Suri, 2013)

2.6 Micronutrient interactions with other nutrients

Micronutrients interaction can either yield synergistic or antagonistic effects. A synergistic effect occurs when there is a positive effect between nutrients, while the antagonistic effect occurs when there is a negative effect between nutrients (Malvi, 2011). The interaction is affected by soil pH, nutrient concentration, moisture content, plant transpiration and respiration rate, plant species, and internal plant nutrient concentration which contributes to the crop yield (Fageria, 2001). The resultant effect of this interaction contributes to the crop's final yield.

Zinc positively interact with nitrogen, potassium and negatively with phosphorous, calcium, iron and copper. The negative interaction is attributed to the inference of phosphorous, calcium, iron and copper in the adsorption of Zinc in the root surface (Prasad *et al*., 2016). Zinc interaction with boron enhances boron concentration in Zn deficient soil, while zinc application reduces boron toxicity in areas with high boron content (Fageria *et al*., 2002). A high concentration of copper in the soil reduces the availability of Zn to the plants due to the competition of the same sites for absorption into the plant roots (Mousavi *et al*., 2012). Molybdenum interaction with phosphorous is positive and important in improving plant growth, and it has a beneficial effect on molybdenum and phosphorous adsorption and translocation (Liu *et al*., 2010).

2.7 Effects of liming in common bean

Healthy soil is fundamental towards increasing food production and food security, but the challenge is soil degradation due to soil acidity (Holland *et al*., 2018). Liming is essential management in reducing the impact of soil acidity. Common bean grows at a pH range of 5.8 to 6.5 (Lunze *et al.*, 2012), hence addressing soil acidity problem through liming aim at maintaining this range. Liming improves physical, biological and chemical properties of soil. It has a direct effect on amelioration of soil acidity, mobilization of plant nutrients, immobilization of toxic heavy metals, improved soil structure and hydraulic conductivity, furthermore, availability of plant nutrients especially phosphorous and molybdenum by increasing their solubility hence availability to common bean. The quality of liming material determines lime requirement for agricultural production in acidic soil. Soil pH saturation and base saturation are relevant indices in determining lime requirement in acidic soil (Fageria & Moreira, 2011). Lime requirements for agricultural production in acidic soil are determined by the quality of liming material, crop species and cultivar within species, soil fertility status, economic considerations and crop management practices

Liming acidic soil reduces the level of exchangeable Aluminium, iron and Manganese hence reducing phosphorous sorption; therefore, availability of phosphorous to the plant (Kisinyo *et al*., 2014). Liming is also essential in providing optimum conditions for biological activities that include Nitrogen-fixation, mineralization of nitrogen phosphorous and sulphur in soils and increasing the number of earthworms in the soil which improves soil condition for plant growth especially for common bean by increasing grain yield dry mass of the shoot, the number of pods per plant and soil quality (Bolan *et al*., 2003; Fageria *et al*., 2008; Goulding, 2016).

Liming acidic soils enhances a conducive environment for leguminous plants and associated microorganisms and increasing the availability of nutrient by raising soil pH and precipitating exchangeable aluminium (Kisinyo *et al.*, 2015). Availability of nutrient and biological activities is found at near-neutral pH where organic matter is decomposed to release nutrients (Alemu, 2017). Fageria *et al*. (2008) reported that there was a significant increase in common bean production in acidic soil after liming by 40%. Therefore, the application of an adequate rate of lime is effective soil management in the amendment of soil acidity hence increase in common bean yield. However, over liming results in deficiencies of some micronutrients such as Manganese boron zinc copper and iron if soils are deficient in those elements (Fageria, 2002). In Western Kenya, however, liming had not been adopted by smallholder farmers due to inadequate awareness of its importance in improving common bean yield.

2.8 Factors affecting micronutrient availability

Availability of micronutrients in soil is dependent on soil texture, clay content, organic matter soil moisture nutrient interactions aeration redox reaction and microbial activities (Kihara *et al*., 2016) Soil texture affect micronutrient availability sandy soils are always deficient in micronutrient due to leaching resulting in low availability for plant uptake, soil with low organic matter content are also low in micronutrients (Choudhary & Suri, 2009). The availability of micronutrients decreases as the temperature and moisture content reduces due to root activity, low rate of dissolution and diffusion of nutrients (Kihara *et al*., 2020).

Soil pH is another important factor affecting micronutrient availability in the soil, Soil pH regulates the solubility, mobility and concentration of ions in the soil solution, in acidic soil the solubility of micronutrients is high (Fageria *et al*., 1997). Under acidic soil condition carbonates or hydroxyl complexes are formed, therefore micronutrients and other toxic ions increases with increasing soil acidity, the availability of boron, copper, iron and zinc usually decreases with increase in soil pH while Mo increases with an increase in soil pH (Kihara *et al*., 2016). At low pH, boron is soluble and available in soil in form of boric acid while availability of molybdenum in acidic soil is a major limitation due to the fixation of aluminium, iron compound and silicates thus unavailable for utilization by the plants (Choudhary & Suri, 2009; Deb *et al*., 2009)

Nutrient interaction is also another important factor affecting nutrient uptake interaction of micronutrient can either yield antagonistic or synergistic interaction. When one nutrient affect the level of the other nutrient antagonism effect occurs, too much iron in the soil induces manganese and Zinc deficiencies, high application of Zn induces copper deficiencies; copper and molybdenum have antagonistic effects (Kihara *et al*., 2016). The condition of rhizosphere also play a significant role in micronutrient availability, micronutrients in the rhizosphere continuously produce a chelating agents during the decay of plant and animal materials which have the ability to transform solid phase micronutrients cations into soluble complexes therefore enhancing the availability of the micronutrients for plant use (Deb *et al*., 2009).

Soil organic carbon is an important component due to important role in improving soil physical chemical and biological properties, soil organic matter increases the water soluble exchangeable form of micronutrients in soil which further enhances availability for plant uptake (Dhaliwal *et al*., 2019). Soil organic matter turn over positively affects the solubility of Zinc as the decomposition of litter in the soil releases Zn into soil solution but it may be leached or adsorbed to the organic matter, it also restricts Zn solubility in soil solution due to formation of complex with humic substance in organic matter (Scheid *et al*., 2009). Soil organic matter is considered the leading source of boron reserve because it complexes with B removing it from soil solution when the levels are high, Mo availability also increases with increase in soil organic matter (Dhaliwal *et al*., 2019).

CHAPTER THREE

GROWTH AND YIELD RESPONSE OF COMMON BEAN TO CUSTOMIZED FERTILIZER AND LIME APPLICATION ON

Abstract

Soil degradation associated with the deficiency of micro and macro-nutrients and low soil pH is a major constraint in legume production in Western Kenya. Farmers in the region have been presented with alternatives of micronutrient fertilizer formulation, from different companies, but there is no clear information if they are effective in improving common bean production in the region. Therefore, a field experiment was conducted in two sites at Kapkerer and Kiptaruswo of Nandi County, Western Kenya, to determine the effect of using customized fertilizer containing macro and micro-nutrients with lime on nutrient uptake and improved legume yield. A 4 × 2 factorial in randomised complete block design was used. The treatments were, *Mavuno* (0, 185 kg ha^{-1}), *Sympal* (0, 125 kg ha^{-1}), Diammonium phosphate (positive control) (0, 62.5 kg ha^{-1}) and lime (0, and 1.6 or 2.0 t ha^{-1} depending on specific lime requirement for the site). The experiment was conducted in the 2019 long rainy season. Application of *Mavuno* fertilizer significantly increased soil pH, aboveground biomass, Ca and Mg uptake and yield by 3.1%, 22%, 3.6%, 4.2% and 21%, respectively, compared with the control. In contrast application of *Sympal* fertilizer significantly increased Ca and Mg uptake and belowground biomass by 12.9%, 4.2% and 11%, respectively, but decreased aboveground biomass and yield by 8.8% and 4.9%, respectively, compared with control. The combined application of *Mavuno* fertilizer with lime significantly increased P uptake, above and belowground biomass and yield by 2.3%, 40%, 18% and 42%, respectively, compared with the control. However, the combined application of *Sympal* fertilizer with lime significantly increased the above and belowground biomass by 16.5% and 39%, respectively, but did not significantly affect yield. The application of DAP and *Sympal* did not have a significant effect on common bean growth and yield. Generally, lime improved the performance of *Mavuno* fertilizer. *Mavuno* fertilizer with boron, molybdenum, iron and copper micronutrients, when applied with lime, was shown to be better in improving bean yield compared to the standard practice (DAP) and introduce *Sympal* fertilizer. These results demonstrate the importance of determining and selecting the right type of specially formulated legume fertilizer for bean production in Western Kenya.

3.1 Introduction

Low soil fertility in Sub-Sahara Africa is a significant constraint limiting agricultural production. Caused by low inherent soil fertility, low use of fertilizers, soil acidity and continuous cropping without adequate nutrient replenishment (Henao & Baanante. 2006). Soil acidity is an important limitation to legume production as it affects the availability of essential nutrients for crop growth (Chianu *et al*., 2012). Crop growth and productivity depend on nutrient availability which is primarily influenced by soil pH and organic matter content (Kundu *et al*., 2018). Low soil pH causes poor plant growth resulting from Al^{3+} and Mn^{2+} toxicity. It also causes the deficiency of essential nutrients such as phosphorous calcium and magnesium. Therefore amendments, such as lime application, that improve soil pH enhance nutrient availability and crop growth. Calcium and or magnesium in lime displaces iron, hydrogen and Manganese ions, therefore lowering their concentration in soil solution (Kisinyo *et al*., 2015). Unfortunately, most smallholder farmers in Western Kenya rarely use lime due to limited awareness, lack of appropriate recommendation rates, inadequate studies done in the region and unknown agricultural lime quality (Athanase *et al*., 2013)

Fertilizer use is a cornerstone in improving crop production and maintaining soil nutrient status (Chianu *et al*., 2012). Most of the research done in Western Kenya majorly focus on alleviating deficiency of macronutrients nitrogen, phosphorous and potassium. However, the common bean yield in the region has remain low at a rate of 0.14 t ha^{-1} to 0.7 t ha^{-1} against a potential yield of 3 t ha^{-1} (Barkutwo *et al*., 2020). There are indications of deficiencies of both secondary and micronutrients limiting crop production in Sub-Sahara Africa, particularly under continuous cropping without nutrient replenishment (Njoroge *et al*., 2017; Vanlauwe *et al*., 2015b). Soils in Western Kenya is classified into responsive and non-responsive based on the application of NPK fertilizer; the highly weathered and nutrient-depleted soils classified as *Acrisols* and *Ferralsols* fall into the non-responsive class (Keino *et al*., 2015; Kihara *et al*., 2016). Therefore, soil fertility management through balanced crop nutrition that considers both macro and micronutrients is essential towards increasing crop yields, hence enhancing food security (Kihara *et al*., 2016).

The core principal value of crop production is adoption of crop management strategies which include micronutrient fertilization specific growth condition this will enhance nutrient use efficiency, profitability and crop nutritional quality goals achieved compared with uniform application rate over a large area (Gebbers & Adamchuk, 2010; Kihara *et al*., 2020) To address the micronutrient deficiency in Western Kenya fertilizer industry have been promoting the use of two fertilisers *Sympal* and *Mavuno* fertilizers. These fertilizers are specifically formulated for legume production and are thought to supply both primary macronutrients, secondary micronutrients and micronutrients essential for common bean production. However there is no clear scientific evidence whether this fertilisers are effective in improving common bean in the area whether applied alone or in combination with lime. Therefore this study was set up investigate whether these fertilizers are effective in increasing common been when applied alone or when applied with lime

3.2 Materials and methods

Field experiments were carried out at two sites, Kapkerer (0°0′N, 34°48′ E, 1530 masl) and Kiptaruswo (0°2′N, 34°55′ E, 1582 masl) located in Nandi County, Western Kenya. The area has an average annual rainfall of between 1200 - 1700 mm, and annual maximum and minimum temperatures of 29ºC and 12ºC, respectively. The rainfall pattern is bimodal with the long rains season from March to August (average of 700 - 780 mm) and the short rains season from September to January (average of 630 - 780 mm). The predominant soils in the area being well-drained, moderately deep to deep, strong brown, friable to firm *humic Acrisol.* The main crops grown area are maize, beans, kales, cabbage, sweet potatoes, cassava and sugarcane (Jaetzold *et al*., 2010)

.

Table 3.1 Geographical information of field experiment sites in Nandi County, Aldai Sub-County

Site	Perceived fertility level	Predominant soil type	Location	Altitude (masl)	Years of Arable farming
Kapkerer	Low	*Humic Acrisol*	N0°0′31.18212” E34°48′12.503532”	1530	70 - 105
Kiptaruswo	Medium	*Humic Acrisol*	N0°2′51.71784” E34°55′59.74248”	1582	40 - 60

Source: Jaetzold *et al*. (2010)

3.3 Customized fertilizer

Sympal® and *Mavuno*® are customized fertilizers locally explicitly blended for use in horticultural crop production, including legumes. They are blended as multi-nutrient carriers fortified with micronutrients to suit specific requirements of the crop.

Sympal fertilizer blend was developed by N2Africa for use with legumes and is commercially produced and distributed by MEA Limited. It contains no mineral nitrogen, and therefore, it is used with biofix as a nitrogen source. It offers a balanced supply of phosphorous, potassium, calcium, magnesium, sulphur and zinc. It contains 7 parts of TSP, 7 parts of SSP, 5 parts of MOP, 1 part magnesium sulphate and 0.1% zinc. *Sympal* fertilizer has the formulation 0:23:15 plus 10% Ca, 4% S, 1% Mg and 0.1% Zn. The recommended rate is 125 kg ha^{-1} which translate to 0 kg N ha^{-1} 28.75 kg P ha^{-1}, 18.75 kg K ha^{-1}, 10 kg Ca ha^{-1}, 4 kg S ha^{-1}, 1 kg Mg ha^{-1} and 0.1 kg Zn ha^{-1}.

Mavuno Horticulture is a customized fertilizer formulated for legumes and vegetables by Athi River Mining Company. *Mavuno* Horticulture has the formulation 15:10:18 plus sulphur, calcium, magnesium, iron, copper, boron and molybdenum. The recommended application rate is 185 kg ha^{-1}, which translates to 27.75 kg N ha^{-1}, 18.5 kg P ha^{-1}, 33.3 kg K ha^{-1}. The equivalent amounts of the micronutrients cannot be deduced, as their content in the fertilizer is not available.

3.4 Experimental design and treatments

The experiment was laid out in 4 × 2 factorial in randomized complete block design, with three replicates. The treatments included *Mavuno* fertilizer at two levels (0, 185 kg ha^{-1}), *Sympal* fertilizer at two levels (0, 125 kg ha^{-1}), Diammonium phosphate fertilizer at two levels (0, 62.5 kg ha^{-1}) and lime (0, 1.6 t ha^{-1}) Kapkerer, (0, 2 t ha^{-1}) Kiptaruswo as shown in Table 3.2. The fertilizer levels used was based on the rates recommended for horticultural production in the region. The lime levels were determined for each site, using incubation method (Brupbacher, 1968).

Table 3.2 Field treatment combination

Treatment	Fertilizer type	Fertilizer rate (kg ha^{-1})	Lime (t ha^{-1})		Description
			Kapkerer	Kiptaruswo	
1. F_0L_0	None	0	0	0	No fertilizer application
2. MF_1L_0	*Mavuno*	185	0	0	*Mavuno* fertilizer at recommended rate
3. SF_1L_0	*Sympal*	125	0	0	*Sympal* fertilizer at recommended rate
4. FC_1L_0	DAP	Farmers rate	0	0	Farmers common fertilizer type estimated rate
5. F_0L_0	None	0	1.6	2	Limed but no fertilizer
6. MF_1L_1	*Mavuno*	185	1.6	2	*Mavuno* fertilizer at recommended rate
7. SF_1L_1	*Sympal*	125	1.6	2	*Sympal* fertilizer at recommended rate
8. FC_1L_1	DAP	Farmers rate	1.6	2	Farmers common fertilizer type estimated rate)

F_0L_0= No fertilizer applied, MF_1= *Mavuno* fertilizer, SF_1= *Sympal* fertilizer and FC_1= Farmers common fertilizer type estimated rate, L1= Lime applied at recommended rate and L_0= No lime applied.

3.5 Establishment of field experiment

The land was prepared by hand hoe to produce fine seedbed. The experimental plot measured 3 m by 2 m, as shown in Figure 3.1. Seeds were sown at a spacing of 50 cm between rows and 10 cm within rows at a rate of 1 seed per hill to give a plant population of 200000 plants per hectare. Weeding was carried out on the 3rd, 6th and 9th week after emergence. Pests white fly and aphids and diseases late and early blight were managed by using *Duduthrin*® and *Ridomil*®, respectively.

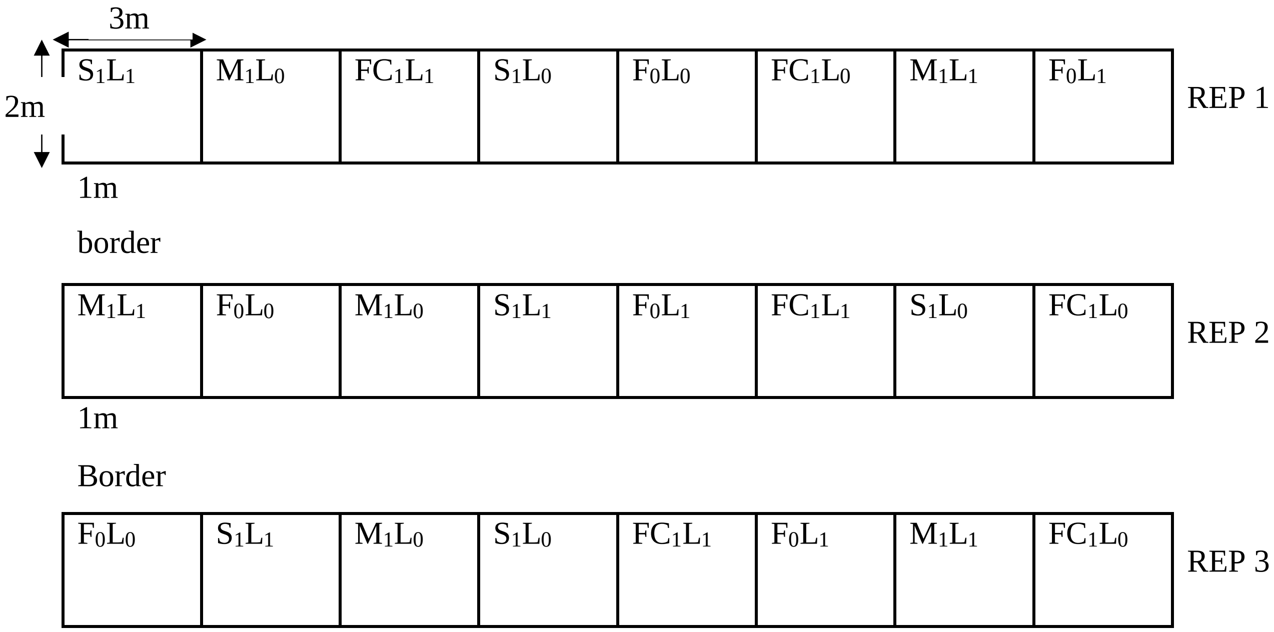

Figure 3.1 Field layout

F_0L_0 - Control, M_1L_1 - *Mavuno* fertilizer and lime (185 kg ha^{-1}, 2.0 t ha^{-1} for Kiptaruswo and 1.6 t ha^{-1} for Kapkerer), M_1L_0 - *Mavuno* fertilizer without lime (185 kg ha^{-1}, 0 t ha^{-1}), FC_1L_1 - DAP with lime (62.5 kg ha^{-1}, 2.0 t ha^{-1} for Kiptaruswo and 1.6 t ha^{-1} for Kapkerer), SF_1L_0 - *Sympal* fertilizer without lime (125 kg ha^{-1}, 0 t ha^{-1}), F_0L_I - Control with lime (62.5 kg ha^{-1}, 2.0 t ha^{-1} for Kiptaruswo and 1.6 t ha^{-1} for Kapkerer), FC_1L_0 - DAP without lime (62.5 kg ha^{-1}, 0 t ha^{-1}) and S_1L_1 - *Sympal* fertilizer and lime (125 kg ha^{-1}, 2.0 t ha^{-1} for Kiptaruswo and 1.6 t ha^{-1} for Kapkerer)

3.6 Data collection

3.6.1 Soil sampling for general characterization

Soil samples (0-20 cm depth) were collected at the beginning of the study at the two study sites for chemical characterization in a zig-zag manner using a soil auger. The soils were air-dried and sieved through 2 mm sieve and analysed for soil pH, lime requirement, available phosphorous and exchangeable potassium, calcium, magnesium and micronutrients boron and zinc. Soil pH was determined using a glass electrode pH meter at the soil to water ratio of 1:2.5, while the lime requirement was determined using the incubation method using methods described by (Brupbacher, 1968). Available phosphorous was extracted using the Mehlich 3 solution, and phosphorous content determined calorimetrically by the ammonium vanadate method using a UV-VIS spectrophotometer at a wavelength of 430 nm (Okalebo *et al.*, 2002). Exchangeable potassium, calcium, magnesium and micronutrients boron and zinc was determined using the Morgan method (Jones, 2001). The soils were extracted with EDTA solution and the concentration of K, Ca, Mg, B and Zn in the filtrate determined using ICP-AES (Jones, 2001).

3.6.2 Determination of phosphorous calcium and magnesium uptake in plant tissue

Six plant samples were randomly selected per plot by detaching the two uppermost fully developed leaves at 50% flowering. The samples were placed in khaki paper bags and oven-dried at a temperature of 65ºC for 48 hours. The samples were ground in an electric miller to pass through less 1mm. 0.1g of the sample were weighed ashed in a muffle furnace at a temperature of 500℃ then dissolved into a mixed acid (hydrochloric acid and nitric acid) and hydrogen peroxide solution as digestion mixture. After ashing the samples were placed in the hot plate to near dryness, desorption was done using 25 ml of 0.05N hydrochloric acid. The samples was the taken from solution and analysed for phosphorous, calcium and magnesium using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP – AES) (Kalra *et al.*, 1997).

3.6.3 Aboveground biomass determination

Aboveground biomass was determined because it is an important parameter in determining the crop performance with respect to nutrient uptake especially in acidic soil where most of the nutrient are deficient. It was determined at 50% flowering stage by randomly selecting six common bean plants and cutting them at ground level in each plot. The plant materials were then placed in a brown paper bag and oven-dried at 65ºC for 48 hours after which dry weight was determined. The biomass was expressed on a dry weight basis in kilograms per hectare.

3.6.4 Belowground biomass determination

Belowground biomass was determined because of the effect of aluminium toxicity which affects root growth hence was an important parameter in predicting the effect of the treatment in relationship with the root growth. Belowground biomass was determined at 50% flowering by randomly selecting and carefully excavating six bean plants per plot. The roots were washed with a stream of tap water to remove the attached soil. The root samples were detached and placed in brown paper bags, oven-dried at 65ºC for 48 hours after which dry weight was determined. The biomass was expressed on a dry weight basis in kilograms per hectare.

3.6.5 Common bean grain yield determination

After attaining physiological maturity, the pods in the three middle rows were harvested, threshed and winnowed to obtain the grain in each plot. The grain moisture was determined using an electric moisture meter and used to adjust the grain yield to t ha^{-1} at 12% moisture content using the formula below (Mulvaney & Devkota, 2020).

$$\frac{Harvested\ yield\ \times \left[\frac{100 - Harvested\ Moisture\ (\%)}{100}\right]}{\left[\frac{100 - Standard\ moisture\ (\%)}{100}\right]}$$

3.7 Data analyses

The nutrient uptake, above and belowground biomass, and grain yield data were subjected to analysis of variance (ANOVA) using general linear model and difference in means determined using the Least Significant Difference Test at ($p<0.05$) using SAS statistical package (Version 8.2). Statistical model:

$Y_{ijklm} = \mu + S_h + \beta_i + \tau_j + \iota_k + \delta_l + \alpha_m + \tau\alpha_{jm} + \iota\alpha_{km} + \delta\alpha_{lm} + \varepsilon_{ijklm}$

Y_{ijklm} = overall observation

μ = overall mean

S_h = effect due to the hth site

βi = effect due to the ith block

τ_j = effect due to the jth level of *Sympal* fertilizer

ι_k = effect due to the kth level of *Mavuno* fertilizer

δ_l = effect due to the lth level of DAP

α_m = effect due to the mth level of lime

$\tau\alpha_{jm}$ = effect due to the interaction of jth level of *Sympal* fertilizer and mth level of lime

$\iota\alpha_{km}$ = effect due to the interaction of kth level of *Mavuno* fertilizer and mth level of lime

$\delta\alpha_{lm}$ = effect due to the interaction of lth level of DAP and mth level of lime

$\varepsilon ijklm$ = error term component

3.8 Results and discussions

3.8.1 Chemical properties of the study sites

The selected soil chemical properties for the two sites are as given in (Table 3.3). The soil pH for Kapkerer farm was 5.53, which falls under moderately acidic soil, while for Kiptaruswo farm, the pH was 4.49, categorized as strongly acidic (Kanyanjua *et al*., 2002). Available phosphorous for Kiptaruswo and Kapkerer were 50 mg kg^{-1} and 48 mg kg^{-1}, respectively, which was medium (31 - 50 mg kg^{-1}) in both sites (Jones, 2001). Potassium content in Kapkerer and Kiptaruswo was 826 mg kg^{-1}, and 1170 mg kg^{-1}, respectively, which was high in both sites (>300 mg kg^{-1}), the calcium content at Kapkerer site was 1250 mg kg^{-1} which was medium in the range of (1000 – 1600 mg kg^{-1}) while for Kiptaruswo site was 1640 mg kg^{-1} which fall under high in the range of 1600 -2400 mg kg^{-1}), magnesium content in Kapkerer site was 30 mg kg^{-1} which fall under low (20 – 40 mg kg^{-1}) while for Kiptaruswo site was 373 mg kg^{-1} which fall under high level (> 30 mg kg^{-1}) (Okalebo *et al*., 2002). Total Zn content in Kapkerer and Kiptaruswo was 27 mg kg^{-1} and 37 mg kg^{-1} which was low the average total Zn in the soil is 50 mg kg^{-1} (Alloway, 2008). Boron content in both Kapkerer and Kiptaruswo were 31 mg kg^{-}1, which was medium the total boron in soil is (30 mg kg^{-1}) (Whetstone *et al*., 1942).

Table 3.3 Some selected chemical properties of soil used in the experiment.

Parameter	Site Kapkerer	 Kiptaruswo
Depth (cm)	0-20	0-20
Soil type	*Humic Acrisol*	*Humic Acrisol*
pH	5.53	4.49
Available P (mg kg^{-1})	50	48
K (mg kg^{-1})	826	1170
Ca (mg kg^{-1})	1250	1640
Mg (mg kg^{-1})	30	373
Mn (mg kg^{-1})	108	213
Zn (mg kg^{-1})	27	37
Cu (mg kg^{-1})	17	17
Fe (mg kg^{-1})	107	107
Al (mg kg^{-1})	576	541
B (mg kg^{-1})	31	31

3.8.2 Effect of *Mavuno*, DAP, *Sympal* and lime application on soil pH, above and below-ground biomass, phosphorous uptake, magnesium uptake, and bean yield.

Application DAP and *Sympal* fertilizers did not have a significant effect on soil pH over both negative and positive controls at ($p<0.05$) (Table 3.4). However, the application of *Mavuno* and lime significantly increased soil pH over negative and positive controls at ($p<0.05$) *Mavuno* by between 3.2% and 3.7% and lime over both positive and negative controls at *($p<0.001$)* by between 11% and 20% (Table 3.4). The non-significant effect is attributed to the high concentration of aluminium and hydrogen ions in the soil since the application of fertilizers did not have a significant effect on soil pH, and the acidifying effect of DAP. An increase in soil pH is attributed to the presence of Ca^{2+} and CO_3^{-2} in lime and the presence of basic cations in *Mavuno* fertilizer which displaces H+. A study done by Opala *et al*. (2018) in acid soil of Western Kenya reported that the application of lime in maize significantly increased soil pH by 27%. Similar results were reported by Buni (2014), who reported that the application of lime in haricot bean significantly increased soil pH by 34% in *Nitisols*. In terms of site there was a significant increase in soil pH at Kapkerer compared to Kiptaruswo at ($p<0.001$) (Table 3.5). This is attributed to the slightly acidic soil in Kapkerer of pH 5.53 compared with strongly acidic soil of Kiptaruswo of pH 4.49.

Table 3.4 Main effect of *Mavuno*, DAP, *Sympal* and lime application on calcium, magnesium and phosphorous uptake, above and below-ground biomass, and bean yield

Treatment	Soil pH	Ca uptake (%)	Mg uptake (%)	P uptake (%)	ABG (t ha^{-1})	BGB (t ha^{-1})	Yield (t ha^{-1})
L1	6.14a	1.93a	0.48a	0.453a	1.90a	0.20a	1.34a
L0	4.90b	1.85b	0.44b	0.446b	1.51b	0.17b	0.94b
M1	5.66a	1.94a	0.48a	0.453a	2.04a	0.19a	1.35a
M0	5.48b	1.87b	0.46b	0.448a	1.59b	0.19a	1.07b
D1	5.45a	1.89a	0.47a	0.453a	1.67a	0.19a	1.08a
D0	5.55a	1.89a	0.46a	0.448a	1.71a	0.19a	1.16a
S1	5.54a	1.95a	0.48a	0.446a	1.60b	0.20a	1.03b
S0	5.51a	1.70b	0.46b	0.451a	1.74a	0.18b	1.08a
CV %	3.01	2.98	3.14	1.64	3.44	6.85	7.65
LSD	0.17	0.05	0.01	0.006	0.1	0.01	0.1

Means with the same letter within a column are not significantly different ($p<0.05$) using the Least Significant Difference (LSD) test.

Key: L1 = 1.6 t Lime ha^{-1} for Kapkerer and 2 t Lime ha^{-1} for Kiptaruswo, L0 = 0 t lime ha^{-1}, M1 = 185 kg *Mavuno* fertilizer ha^{-1}, M0 = 0 kg *Mavuno* fertilizer ha^{-1}, D1 = 62.5 kg DAP fertilizer ha^{-1}, D0 = 0 kg DAP fertilizer ha^{-1}, S1 = 125kg *Sympal* fertilizer ha^{-1}, S0 = 0 kg *Sympal* fertilizer ha^{-1}, ABG = Aboveground biomass and BGB = Belowground biomass.

Table 3.5 Site effect on soil pH, above and belowground biomass, phosphorous, calcium, magnesium uptake and yields

Site	pH	AGB t ha^{-1}	BGB t ha^{-1}	P uptake (%)	Ca uptake (%)	Mg uptake (%)	Yield t ha^{-1}
Kiptaruswo	4.95b	2.36a	0.23a	0.51a	1.92a	0.37a	2.02a
Kapkerer	6.08a	1.04b	0.14b	0.38b	1.84a	0.54b	0.23b
LSD	0.15	0.14	0.01	0.009	0.10	0.02	0.13

Means with same letters are not significantly different at ($p<0.05$) using Least Significant Deference (LSD) test.

Key: ABG = Aboveground biomass, BGB = Belowground biomass.

The application of *Mavuno* and lime significantly increased aboveground biomass over positive and negative controls at ($p<0.001$) *Mavuno* by between 18% and 22% and for lime by between 12% and 21% (Table 3.4). The application of *Sympal*, however, significantly decreased aboveground biomass by 8% over both positive and negative controls at ($p<0.05$) (Table 3.4). However, application DAP did not significantly differ in the aboveground biomass compared to the control at ($p<0.05$). The decrease in the aboveground biomass following the application of *Sympal* is attributed to soil acidity and lack of micronutrients Mo, B, Fe and Cu in *Sympal* fertilizer. *Mavuno* fertilizer contains NPK + Ca + Mg + Fe + S + Cu + Mo + B which are essential nutrients for common bean growth and development. Therefore, the increase in aboveground biomass is attributed to the supply of essential nutrients, which improved the growth of common bean. A study done by Shumi *et al*. (2018) in Ethiopia on *Nitisols* showed that blended fertilizer NPK + S significantly increased aboveground biomass. Ca and Mg play a significant role in increasing plant biomass by converting solar energy into carbohydrates (Castro and Crusciol, 2015). Aboveground biomass was significantly increased at the Kiptaruswo site at ($p<0.001$) by 55% compared to Kapkerer (Table 3.5). An increase in the aboveground biomass is attributed to high fertility gradient in the region compared to Kapkerer low fertility gradient; Kiptaruswo is considered to be under the medium-fertility zone because it had not been in habitat for long like Kapkerer where it is the oldest site to be in habitat over 80 years ago. Therefore, the increases in aboveground biomass is attributed to higher soil fertility at Kiptaruswo (Odundo *et al*., 2014)

The application of *Mavuno* and DAP fertilizers did not have significant effects on the belowground biomass over both positive and negative controls at ($p<0.05$) (Table 3.4). However, application of *Sympal* and lime significantly increased belowground biomass over positive and negative controls at ($p<0.01$) *Sympal* by between 5% and 10% and for lime by between 5% and15% (Table 3.4). Increase in belowground biomass is attributed the availability of phosphorous availability which stimulates root development. Lime application enhances the availability of phosphorous by counteracting the effect of aluminium toxicity which fixes phosphorous in the soil. A Study by Lambers *et al.* (2006) showed that application of phosphorous increases root growth by stimulating its growth. A study done by Jamieson *et al*. (2012) reported that plants tend to allocate more energy to aboveground and reduce investment in the belowground root system. There was a significant increase of the belowground biomass at Kiptaruswo compared with Kapkerer at ($p<0.001$) by 39% (Table 3.5). This is attributed high soil fertility gradient in Kiptaruswo compared with Kapkerer.

DAP, *Mavuno* and *Sympal* fertilizers did not have a significant effect on P uptake over the controls at ($p<0.05$) (Table 3.4). However, the application of lime significantly increased P uptake over negative control at ($p<0.05$) by 2% (Table 3.4). The non-significant effect is attributed to toxicity which affects the availability of phosphorous. Soluble inorganic phosphorous is fixed in acidic soil hence not available to plants (Ch'ng *et al*., 2014). An increase in P uptake is attributed to improved soil pH, which enhances the availability of fixed phosphorous. Application of lime reduce hydrogen concentration therefore, releasing fixed phosphorous, making it available for plant uptake. A study by Kassa *et al*. (2014) in Ethiopia showed that application of lime in haricot bean contributes to the availability of fixed phosphorous for plant uptake in *Nitisols*. Similar results were reported by Seng *et al*. (2006), who showed that the application of lime in a lowland acidic soil significantly increased phosphorous uptake in rice. At Kiptaruswo there was a significant increase in P uptake compared with Kapkerer at ($p<0.001$) by 25% (Table 3.5). Enhanced uptake of P is attributed to the high fertility gradient of Kapkerer and availability of P through the fertilizers and lime application.

DAP application did not have a significant effect on Ca uptake over control at ($p<0.05$) (Table 3.4). However, application of lime, *Mavuno* and *Sympal* fertilizers significantly increased Ca uptake over positive and negative controls at ($p<0.01$) lime by between 2% and 4%, *Mavuno* by between 3% and 4% and *Sympal* by between 3% and 13% (Table 3.4). Increase in Ca uptake is attributed to the availability of Ca in both *Mavuno* and *Sympal* fertilizer, and at the same time, application of lime improved soil pH hence the availability of Ca for plant uptake. Application of lime containing Ca or Mg increases the concentration of Ca and Mg in soil solution and reduces Al^{3+}, H^{+} Mn^{2+} and Fe^{2+} concentration in the soil solution therefore improving the uptake of other nutrients including Ca and Mg (Bekele *et al*., 2018). Study done by Wamalwa *et al*. (2019) on acidic soil of Western Kenya reported that application of blended NPK + Ca + Mg fertilizer significantly increased Ca uptake in finger millet due to the availability of Ca in the fertilizer. A study done by Fekadu *et al.* (2019) in acid soil of Ethiopia showed that application of lime increased Ca and Mg levels in the soil, and therefore, availability for plant uptake. There was no significant effect on Ca uptake at Kapkerer and Kiptaruswo (Table 3.5)

The application of DAP did not have a significant effect on Mg uptake over control at ($p<0.05$) (Table 3.4). However, lime, *Mavuno* and *Sympal* fertilizers application significantly increased Mg uptake over positive and negative controls at ($p<0.01$) lime by between 2% and 8%, of *Mavuno* by between 2% and 4% and of *Sympal* by between 2% and 4% (Table 3.4). Increase in Mg uptake was similar to that of Ca uptake and may be attributed to the same reasons above. There was a significant increase in Mg uptake at Kapkerer compared to Kiptaruswo at ($p<0.001$) by 45% (Table 3.5) this is attributed to the enhanced supply of Mg in the fertilizers and improved soil pH.

The application of DAP did not have a significant effect on grain yield over control at ($p<0.05$) (Table 3.4). However, the application of *Sympal* fertilizer significantly decreased yield over positive and negative controls by 4.9% at ($p<0.05$) (Table 3.4). The decrease in yields is attributed to soil acidity, which affects the availability of nutrients and nitrogen fixation by rhizobium, therefore, affecting common bean growth and development. Under acidic conditions, rhizobium will not be able to fix nitrogen in the roots leading to deficiency of nitrogen; as a result, poor plant growth and decreased yields (Lapinskas, 2007). The application of *Mavuno* and lime fertilizer significantly increased yields over positive and negative controls at ($p<0.01$) *Mavuno* by between 20% and 21% and lime by between 19% and 29% (Table 3.4). An increase in yield may be attributed to the availability of both macro and micronutrients in the *Mavuno* fertilizer and improved soil pH, which leads to improved growth and yield. A study done by Shumi *et al*. (2018) in *Nitisols* of Ethiopia showed that the application of blended fertilizer NP + S significantly increased common bean yield by 31%. As explained above, the increase in yield may be related to the role of Ca and Mg in energy conversion into carbohydrates. A study done by Fageria *et al*. (2007) in Brazil on *Oxisols* reported that application of lime significantly increased common bean yield by 32% due to availability of nutrients which enhanced common bean growth. At Kiptaruswo site there was a significant increase in yield compared with Kapkerer at ($p<0.001$) by 88% (Table 3.5). This is attributed to high fertility gradient in the region, therefore the availability of nutrients for plant growth resulting to improved yields at Kapkerer.

3.8.3 Interaction of *Sympal, Mavuno* and DAP fertilizers with lime application on soil pH

The application of *Sympal* and DAP did not show any significant interaction effect with lime on soil pH at ($p<0.05$) (Appendix A). However, a significant effect between *Mavuno* and lime was observed. Combined application of *Mavuno* and lime significantly increased soil pH over both positive and negative controls at ($p<0.05$) by between 25% and 27% (Figure 3.2). The non-significant interaction between lime, DAP and *Sympal* fertilizers may be attributed acidifying effect of DAP and NPK fertilizer. Increase in soil pH following application of lime and *Mavuno* is attributed to displacement of H^+ and Al^{3+} in the soil solution which was enhanced by Ca both in lime and the *Mavuno* fertilizer, and Mg contained in *Mavuno* fertilizer. Application of lime raises soil pH, while Ca^{2+} ions contained in lime displace the adsorbed H^+ Al^{3+} Fe^{3+} and Mn^{4+} in the soil solution, increasing soil pH (Kisinyo *et al*., 2015).

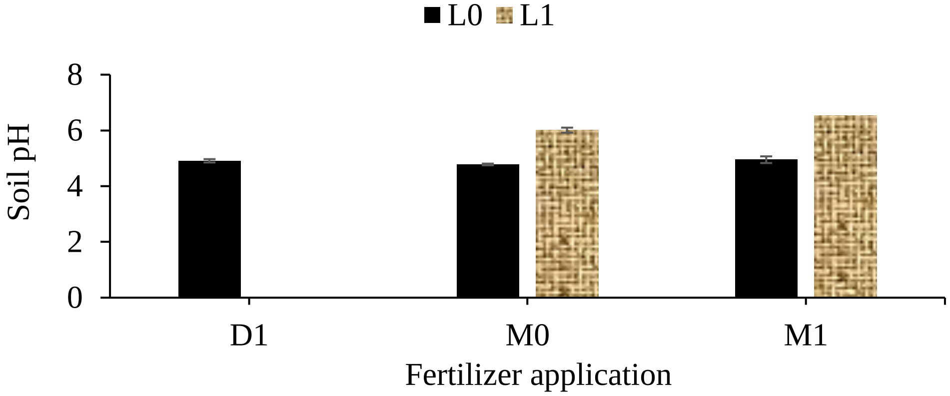

Figure 3.2 Interaction effect of application of *Mavuno* Fertilizer with lime on soil pH

Key: D1 = 62.5 kg DAP fertilizer ha^{-1} (positive control) M0 = 0 kg *Mavuno* fertilizer ha^{-1} M1 = 185 kg ^{1} *Mavuno* fertilizer ha^{-1}, L0 = 0 t lime ha^{-1} and L1 = 1.6 t lime $ha^{-1}$for Kapkerer and 2 t lime ha^{-1} for Kiptaruswo.

3.8.4 Interaction of *Sympal, Mavuno* and DAP fertilizers with lime application on aboveground biomass

The application of DAP, in combination with lime, did not have a significant effect on aboveground biomass over the controls at ($p < 0.05$) (Appendix A). However, the application of *Mavuno* and *Sympal* fertilizers in combination with lime significantly increased the aboveground biomass over positive and negative controls at ($p < 0.001$) of *Mavuno* fertilizer in combination with lime by between 39% and 40%, and negative and positive controls of *Sympal* in combination with lime by between 16% and 22% (Figure 3.3a and b). The increase in the aboveground biomass may be attributed to the availability of both macro and micronutrients contained in the customized fertilizer further enhanced by improved soil pH with the lime application. A study done by Arega and Zenebe (2019) in slightly acidic soils of Ethiopia reported that the application of blended fertilizer NPK + S + B significantly increased the aboveground biomass of common bean due to integration of nutrients in the blended fertilizer.

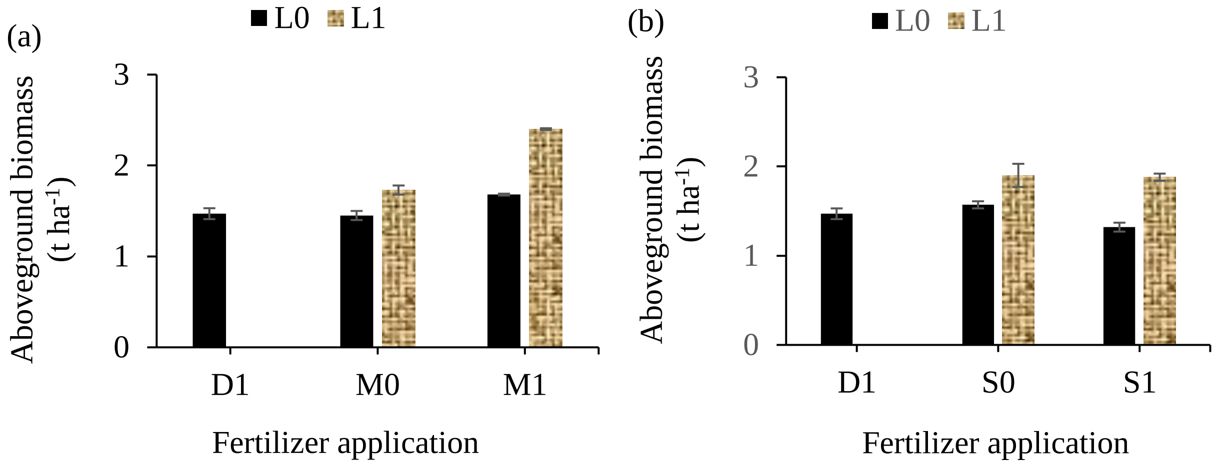

Figure 3.3 Interaction effect of application of *Mavuno* (a) and *Sympal* (b) fertilizer with lime on aboveground biomass

Key: D1 = 62.5 kg DAP fertilizer ha^{-1} (positive control), L0 = 0 t Lime ha^{-1}, L1 = 1.6 t lime ha^{-1} for Kapkerer and 2 t lime ha^{-1} for Kiptaruswo. S0 = 0 kg *Sympal* fertilizer ha^{-1}, S1 = 125 kg *Sympal* fertilizer ha^{-1}, M0 = 0 kg *Mavuno* fertilizer ha^{-1} and M1 = 185 kg *Mavuno* fertilizer ha^{-1}.

3.8.5 Interaction effect of *Sympal, Mavuno* and DAP fertilizers with lime application on belowground biomass

The application of DAP with lime did not have a significant effect on belowground biomass over the controls at (p<0.05) (Appendix A). However, application of *Mavuno* and *Sympal* fertilizers in combination with lime significantly increased the belowground biomass over negative and positive controls at (p<0.01) of *Mavuno* fertilizer in combination with lime by between 18% and 27%, and of *Sympal* in combination with lime by between 26% and 30% (Figures 3.4a and b). Effects on the belowground biomass were similar to the interaction of customized fertilizer in combination with lime on aboveground biomass. This is attributed to the enhanced availability of nutrients through application of lime. Application of lime improves the availability of essential nutrients especially phosphorous which plays a key role in root development; it also improves the soil condition for nitrogen fixation by nitrogen fixing organism hence improving common bean growth (Dida & Etisa, 2019)

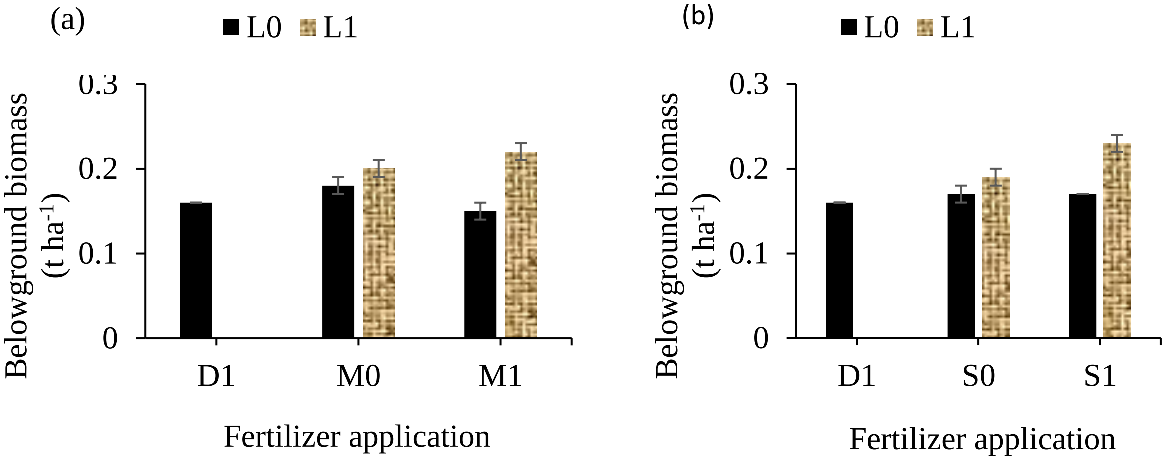

Figure 3 4 Interaction effect of application of fertilizer *Mavuno* (a) and *Sympal* (b) with lime on belowground biomass

Key: D1 = 62.5 kg DAP fertilizer ha^{-1} (positive control), L0 = 0 t Lime ha^{-1}, L1 = 1.6 t Lime ha^{-1} for Kapkerer and 2 t lime ha^{-1} for Kiptaruswo, S0 = 0 kg *Sympal* fertilizer ha^{-1}, S1 = 125 kg *Sympal* fertilizer ha^{-1}, M0 = 0 kg *Mavuno* fertilizer ha^{-1} and M1 = 185 kg *Mavuno* fertilizer ha^{-1}.

3.8.6 Interaction effect of *Sympal, Mavuno* and DAP fertilizers with lime application on Ca, Mg and P uptake

The application of *Mavuno* and *Sympal* fertilizers in combination with lime did not have a significant effect on Ca and Mg uptake over the controls at ($p<0.05$). The non- significant effect may be attributed to leaching of both Ca and Mg due to heavy rainfall during the trial period in the area. The application of DAP and *Sympal* fertilizer in combination with lime did not have a significant effect on P uptake over control at ($p<0.05$) (Appendix A). However, the application of *Mavuno*, in combination with lime showed a significant increase in P uptake over both the positive and negative controls at ($p<0.05$) by 2.2% (Figure 3.5). An increase in P uptake with *Mavuno* and lime application is attributed to improved soil pH. Ca contained in both lime and *Mavuno* fertilizer counteract the effect of phosphorous fixation hence enhancing its availability for plant uptake. Liming acidic soil precipitate Al^{3+} as$(OH)_3$ which fixes phosphorous in acidic soil, thus increasing the availability of P for plant uptake (Barasa *et al*., 2013).

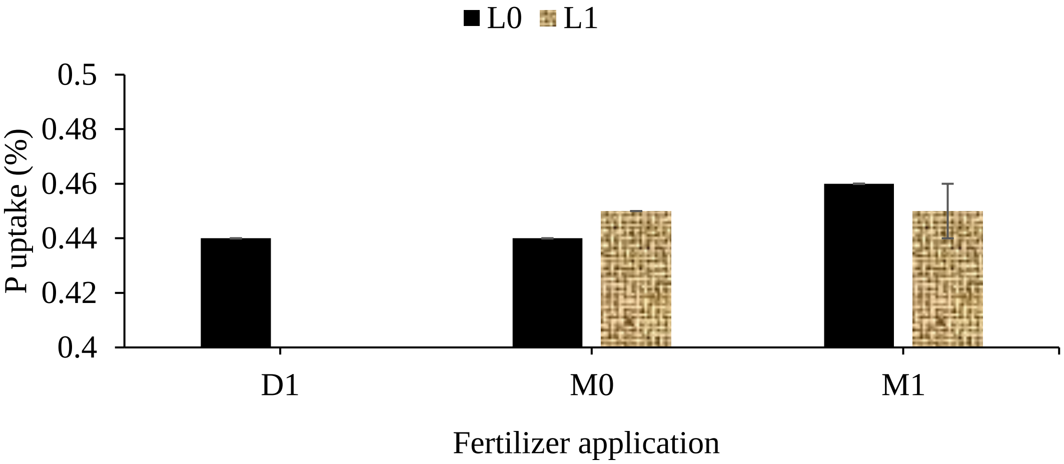

Figure 3.5 Interaction effect of application of *Sympal* with lime on P uptake

Key: D1 = 62.5 DAP fertilizer ha^{-1} (positive control S0 = 0 kg *Sympal* fertilizer ha^{-1}, S1 = 125 kg *Sympal* fertilizer ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t Lime ha^{-1} for Kapkerer and 2 t lime ha^{-1} for Kiptaruswo.

3.8.7 Interaction of *Sympal, Mavuno* and DAP fertilizers with lime application on yield

The application of DAP and *Sympal* fertilizer in combination with lime did not have a significant effect on grain yield over the controls at (p<0.05) (Appendix A). However, the application of *Mavuno* fertilizer in combination with lime significantly increased grain yield over positive and negative controls at ($p<0.05$) by between 34% and 42% (Figure 3.6). The non-significant effect following the application of DAP and *Sympal* fertilizer with lime may be attributed to the deficiency of micronutrient Mo and B which are important in common bean production. The increase in yield with the application of *Mavuno* and lime is attributed to improved soil pH and supply of essential nutrients NPK + Ca +Mg + S + B + Mo + Fe + Cu through *Mavuno* fertilizer. Unlike *Sympal* fertilizer which has Zn but lacks B, Mo, Fe and Cu micronutrients. A study done by Keino *et al*. (2015), working on acidic *Acrisols* and *Ferralsols* in Western Kenya reported that the combined application of lime and customized fertilizer significantly increased soybean (*Glycine max* L.) yield. Similar results were reported by Kumar *et al*. (2016a), working on acid *Alfisols* in North India, who reported that integrated application of lime and fertilizer significantly increased yield of French Beans. A study done by Kahira *et al*. (2020) showed that application of blended fertilizer containing NPK 10:26:10 and secondary micronutrients Ca, Mg and S and micronutrients Zn, Cu, Mn, B and Mo significantly increased phosphorous use efficiency and improved yields compared to local fertilizers.

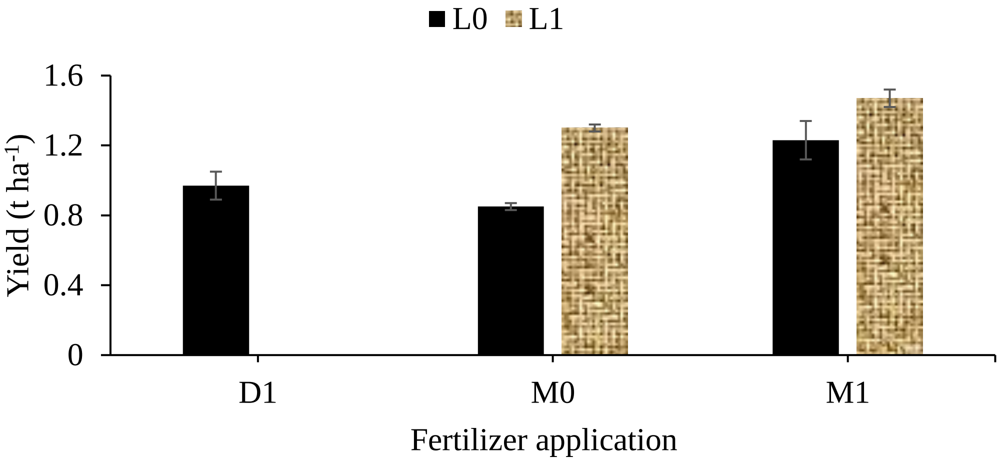

Figure 3.6 Interaction effect of application of *Mavuno* fertilizer with lime on yield

Key: D1 = 62.5 kg DAP fertilizer ha^{-1} (positive control) M0 = 0 kg *Mavuno* fertilizer ha^{-1}, M1 = 185 kg *Mavuno* fertilizer ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t lime ha^{-1} for Kapkerer and 2 t Lime ha^{-1} for Kiptaruswo.

3.9 Conclusion

i. The application of *Mavuno* fertilizer significantly improved common bean production in *Acrisols* of Western Kenya. Common bean production was further enhanced by the application of *Mavuno* fertilizer in combination with lime. The *Mavuno* fertilizer performed better probably because of its high nitrogen and supply of B, Mo, Fe and Cu micronutrients compared with *Sympal* which had only Zn and DAP which had no micronutrients. Therefore, in order to improve common bean production in *Acrisols* of Western Kenya, application of fertilizers containing Nitrogen and micronutrients boron, molybdenum, iron and copper and liming is essential.

ii. Application of *Sympal* fertilizer with or without lime did not show any significant effect on common bean production in *Acrisols* of Western Kenya. The fertilizer does not supply nitrogen, it is applied with biofix, a nitrogen fixing bacteria containing rhizobium strain, and therefore the non-significant effect on yield could be attributed to poor nodulation in the acidic soils. This results demonstrates the importance of formulating and applying the right type of fertilizer in the region

iii. The results of this study indicate that low common bean production among smallholder farmers in Western Kenya could be attributed to soil acidity, application of customized fertilizers which are formulated with nitrogen and the dependency of NPK based fertilizer without micronutrients boron, molybdenum copper and iron.

CHAPTER FOUR

EFFECT OF BORON, ZINC, MOLYBDENUM AND LIME ON COMMON BEAN GROWTH

Abstract

Micronutrient deficiency is a constraint limiting common bean production, most importantly boron, zinc and molybdenum, yet these micronutrients are not included in fertilizer recommendation. Therefore, a greenhouse experiment was conducted on acid *Acrisols* of Nandi County, Western Kenya, to determine the effects of boron, zinc, molybdenum and lime on their uptake and common bean growth. A 2^4factorial experiment was set up in a completely randomized design consisting of three micronutrients and lime treatments applied at two levels (0 and recommended rate). The treatments were, Boron (0, 1.5 kg B ha^{-1}), Zinc (0, 3 kg Zn ha^{-1}), Molybdenum (0, 0.6 kg Mo ha^{-1}) and lime 0, 1.6 t ha^{-1}) with three replicates. The experiment was conducted between March and July 2019. The finding showed that the application of B, Zn, Mo and Lime significantly increased aboveground biomass over control by 8%, 3.1%, 16% and 3.8%, respectively. The application of Mo significantly increased belowground biomass over control by 19%. In terms of micronutrient uptake, the application of B and lime significantly increased B uptake over control by 4% and 17%. Application of B, Mo and lime significantly increased Zn uptake over control by 13%, 13% and 2.7%, respectively, While B, Mo and lime significantly increased Mo uptake over control by 26%, 36% and 131%, respectively. On the other hand, Mo + B, B + L and Zn + L significantly increased aboveground biomass over control by 24%, 11% and 10%. Application of B + Mo, Mo + L significantly increased belowground biomass over control by 47% and 30%. Application of Mo + L and B + L significantly increased Mo uptake over control by 173% and 91%. Application of B + L, Mo + L and B + Mo significantly increased Zn uptake over control by 15%, 16% and 26%, respectively. In contrast, application of Zn + L, B + L and B + Zn significantly increased B uptake over control by 21%, 11%, and 5% respectively. This result showed that poor growth of beans was due to B, Zn and Mo deficiency and soil acidity. It also signifies the necessity of formulation of blended fertilizer for legumes, especially with B, Zn, Mo and application of lime towards increasing common bean in *Acrisols* of Aldai Sub-County.

4.1 Introduction

Micronutrient deficiencies in sub-Sahara Africa are widespread; however, limited research has been done, which focuses on the extent of the impact of the deficiencies on crop production (Van Der Waals & Laker, 2008). About 75% of the Sub-Saharan arable land has serious soil fertility problems, with farmers losing 8 million tons of nutrients each year due to continuous cropping without macronutrients and trace element applications, growing of high yielding crops associated with a high rate of nutrient removal and high analyses fertilizers use causing deficiency in the soil, hence low common bean crop production (Gupta *et al*., 2008; Toenniessen *et al*., 2008)

Boron zinc and molybdenum deficiency is a significant constraint affecting common bean production yield and reducing the availability of protein folate and other nutrients, especially in acidic soil due to leaching in highly weathered soil leading to low common bean production (Andersen, 2007; Kumar *et al*., 2016a). Highly weathered soil, especially acidic soil in the tropics, are deficient of most essential nutrients, strongly leached acidic soil are low in most of the micronutrients because their parent are deficient in nutrients and as a result of leaching micronutrients initially present in the soil (Choudhary *et al*., 2014).

The application of micronutrients in adequate amounts enhances optimal productivity (Tripathi *et al*., 2015); these micronutrients play a crucial role in the growth and yield of plants of common bean, molybdenum play is essential in common bean production; it is an essential nutrient in biological nitrogen fixation as it simulates nodulation, living in symbiosis with them (Głowacka *et al*., 2019; Naqib & Jahan, 2017). On the other hand, zinc plays an essential process in synthesizing tryptophan, a precursor of growth hormone iodine acetic acid (IAA) and activation of enzymes responsible for protein synthesis (Kryvoruchko, 2017). An adequate amount of boron is required for effective nitrogen fixation and nodulation in legumes, cell wall formation, movement of sugar into the growing parts of the plant, pollination, and seed setting (Bellaloui *et al*., 2014).

Research on crop response to secondary and micronutrients is scarce in SSA. Therefore, there is a need to quantify potential response under different soil conditions, crop type and crop variety, understanding the residual effects during subsequent seasons, and effectiveness and use efficiency of different secondary and micronutrients and their interactions. This will determine whether applying these nutrients is required and guiding the blending of fertilizers targeting specific crops and determining the best practices to be adopted by smallholder farmers (Kihara *et al*., 2017).

In Nandi County, Western region of Kenya, common bean production is the second crop grown after maize (*Zea mays*) as a staple food (Jaetzold *et al*., 2010. It is mainly grown by small scale farmers with not more than one hectare; it plays an important role as food security and income-generating crop (Mutai *et al*., 2019). However, its production has remained low in the region due to widespread soil degradation, nutrient depletion, inadequate fertilizer application, and dependence on one type of fertilizer (Stoorvogel *et al*., 1993). Most of the research done in the region has mainly focused on addressing the deficiency of Nitrogen and Phosphorous. As a result, most farmers continuously use DAP fertilizer as a general recommendation for a crop without considering micronutrients fertilizers. Despite this focus, the yield has stagnated at 0.7 t ha-1 against the potential yield of 3 t ha^{-1} (Onyango *et al*., 2016); therefore, smallholder farmers need to shift to the use of micronutrients to close the yield gap, a single application of macronutrients may be a significant cause of low production in micronutrient crops, especially legumes (Keino *et al*., 2015; Kumar *et al*., 2016a). There is an indication that micronutrients deficiency is the main reason there is declining common bean production in Western Kenya (Kihara *et al*., 2017). Therefore, the objective of this study was to determine the effect of boron, zinc, molybdenum, and lime on common bean growth.

4.2 Materials and methods

An exploratory greenhouse experiment was carried out to determine the effect of selected micronutrients, namely boron, zinc, molybdenum and lime on common bean production. The greenhouse experiment was conducted at Egerton University Njoro, using soil samples from the upper 0-30 cm in the Kapkerer experimental site Aldai Sub-County, Nandi County. This site was selected because it had been cultivated for over 80 years hence most of this micronutrient are depleted and due to financial constraint we could do for Kiptaruswo site. The soil pH of the study site was 5.53 slightly acidic soil, Total Zn was 27 mg kg^{-1} which was low, the average total Zn in the soil is 50 mg kg^{-1} (Alloway, 2008). Boron content was 31 mg kg^{-}1, which was medium, the total boron in soil is (30 mg kg^{-1}) (Whetstone *et al*., 1942). The field sampled had previously been under crops with minimal DAP fertilizer. Egerton lies between longitude 00°22′ South and latitude

35°35′ East and 2250 meters above sea level with an annual mean temperature of 15.9°C, mean maximum of 27°C and minimum temperature of 11°C.

4.3 Experimental design and treatments

The experimental set-up was 2 × 2 × 2× 2 factorial in completely randomized design (CRD) and replicated three times. The treatments were, boron (0, 3 kg B ha^{-1}), molybdenum (0, 0.6 kg Mo ha^{-1} zinc (0, 1.5 kg Zn ha^{-1}) and lime (0, 1.6 t ha^{-1}) as shown in (Table 4.1).

Table 4.1 Greenhouse treatment combinations

Treatment	B (Kg ha^{-1})	Mo (Kg ha^{-1})	Zn (Kg ha^{-1})	Lime (t ha^{-1})
$B_0Mo_0Zn_0L_0$	0	0	0	0
$B_0Mo_0Zn_0L_1$	0	0	0	1
$B_0Mo_0Zn_1L_0$	0	1	0	0
$B_0Mo_1Zn_0L_0$	0	0	1	0
$B_1Mo_0Zn_0L_0$	1	0	0	0
$B_0Mo_0Zn_1L_0$	0	0	1	1
$B_0Mo_1Zn_0L_1$	0	1	0	1
$B_1Mo_0Zn_0L_1$	1	0	0	1
$B_0Mo_1Zn_1L_0$	0	1	1	0
B1M0Z1L0	1	0	1	0
$B_1Mo_1Zn_0L_0$	1	1	0	0
$B_0Mo_1Zn_1L_1$	0	1	1	1
$B_1Mo_1Zn_0L_1$	1	1	0	1
$B_1Mo_0Zn_1L_1$	1	0	1	1
$B_1Mo_1Zn_1L_0$	1	1	1	0
$B_1Mo_1Zn_1L_1$	1	1	1	1

Key: B0 = 0 kg Boron ha^{-1}, M0 = 0 kg Molybdenum ha^{-1}, Z0 = 0 kg Zinc ha^{-1}, L0 = 0 t Lime ha^{-1}, B1 = 3kg Boron ha^{-1}, M1 = 0.6 kg Molybdenum ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, L1 = 1.6 t lime ha^{-1}.

4.4 Planting and thinning

Soils were thoroughly mixed while removing weeds and stones. Then 4 kg soils were placed in all pots measuring (17cm at the top, 13cm at the bottom diameters and height of 22cm). NPK 17:17:17 fertilizer was added at an equivalent rate of 200 kg ha^{-1} in all pots and micronutrients were applied at recommended rate in each pot. Three seeds of *KK Red 13* variety were planted per pot and selectively thinned to one per seedling pot of equal vigour and height two weeks after emergence. Plants were watered daily and twice a day during the later stage of growth to avoid water stress and maintain soil moisture at field capacity. Pests mainly aphids were controlled using *Duduthrin*® and diseases control was carried out on a need basis using *Ridomil*®

4.5 Data collection

4.5.1 Plant tissue analysis for determination of micronutrient uptake

Plant samples were collected by detaching the plant at 50% flowering stage. The samples were placed in paper bags and oven-dried at a temperature of 65ºC for 48 hours. The samples were ground in an electric mill to pass through 1 mm sieve. It was ashed in the muffle furnace at a temperature of 500℃ for two hours. The ash was then dissolved in a mixed acid (hydrochloric acid and nitric acid), and hydrogen peroxide, it was paced in the hot plate and remove at near dryness. 25mls of 0.05N hydrochloric acid then added and the content of boron, zinc and molybdenum in the solvent were analysed using Induced Coupled Plasma Spectroscopy (ICP – AES) at Tea Research Institute laboratory Kericho using protocol described by Kalra *et al*. (1997). Dry ashing was used as a standard procedure for nutrient determination hence the values were absolute.

4.5.2 Aboveground biomass

Aboveground biomass was determined by cutting the bean plant of each pot at ground level at the 50 % flowering stage. The plant materials were placed in brown paper bags and oven-dried at a constant temperature of 65ºC for 48 hours after which dry weight was determined. The aboveground biomass was expressed on a dry weight basis in grams per pot.

4.5.3 Belowground biomass

Belowground biomass was determined by cutting the plant at the ground level of each pot at 50% flowering stage. The roots were carefully excavated then washed with a stream of tap water to remove the attached soil. The root samples were placed in brown paper bags oven, dried at 65ºC for 48 hours after which dry weight was determined. The biomass was expressed on a dry weight basis in grams per pot.

4.6 Data analyses

The nutrient uptake, above and belowground biomass data were subjected to analysis of variance (ANOVA) using the general linear model and difference in means determined using the Least Significant Difference Test at ($p<0.05$) using SAS statistical package (Version 8.2).

Statistical model:

$Yijklm = \mu + \beta i + \tau j + ak + \delta l + Rm + \beta\tau ij + \beta\alpha ik + \beta\delta il + \tau\delta jl + \tau\alpha jk + \alpha\delta kj + \beta\tau\alpha ijk + \beta\tau\delta ijl + \beta\alpha\delta ikl + \tau\alpha\delta jkl + \beta\tau\alpha\delta ijkl + \varepsilon ijklm$

$Yijklm$ = overall observation

μ = overall mean

βi = effect due to the i^{th} level of boron

τj = effect due to the j^{th} level of zinc

αk = effect due to the k^{th} level of molybdenum

δl = effect due to the l^{th} level of lime

Rm= effect due to the m^{th} replicate

$\beta\tau ij$ = effect due to interaction of the i^{th} level of boron and j^{th} level of zinc

$\beta\alpha ik$ = effect due to the interaction of i^{th} level of boron and k^{th} level of molybdenum

$\beta\delta il$ = effect due to the interaction of i^{th} level of boron and l^{th} level of lime

$\tau\delta jl$ = effect due to the interaction of j^{th} level of zinc and l^{th} level of lime

$\tau\alpha jk$ = effect due to the interaction of j^{th} level of zinc and k^{th} level of molybdenum

$\alpha\delta kl$ = effect due to the interaction of k^{th} level of molybdenum and l^{th} level of lime

$\beta\tau\alpha ijk$ = effect due to the interaction of i^{th} level of boron j^{th} level of zinc and k^{th} level of molybdenum

$\beta\tau\delta ijl$ = effect due to the interaction of i^{th} level of boron, j^{th} level of zinc and lth level of lime

$\beta\alpha\delta ikl$ = effect due to the interaction of i^{th} level of boron, k^{th} level of molybdenum and l^{th} level of lime

$\tau\alpha\delta jkl$ = effect due to the interaction of j^{th} level of zinc, k^{th} level of molybdenum and l^{th} level of lime

$\beta\tau\alpha\delta ijkl$ = effect due to the interaction of i^{th} level of boron, j^{th} level of zinc, k^{th} level of molybdenum and l^{th} level of lime

$\varepsilon ijklm$ = random experimental error

4.7 Results and discussion

4.7.1 Effect of boron, zinc, molybdenum and lime application on above and below-ground biomass, boron, zinc and molybdenum uptake

The application of Boron (B) significantly increased the aboveground bean biomass over the control at ($p<0.001$) by 8%. However, B application did not have a significant effect on the belowground biomass at ($p<0.05$) (Table 4.2). The increase in aboveground biomass is attributed to the role of B in enhancing cell elongation and differentiation, hence the improved growth. A Study done by Flores *et al*. (2017) using slightly acidic soil in Brazil showed that the application of B linearly increased the aboveground biomass in common bean by 63% compared with the control. Similar results were reported by Abebe *et al*. (2017) working on *Andosol* in Ethiopia, who showed that the application of B significantly increased the aboveground biomass at ($p<0.05$). Boron stimulates the meristematic activity of the cell, hence cell elongation and differentiation (Rasheed, 2009. It further improves the quality of vegetative growth (El-Dahshouri, 2018). The non-significant effect with B application on belowground biomass is attributed to the critical role of B in physiological functions. A study done by Breys *et al*. (2001) in slightly acidic soil showed that the application of B did not have a significant effect on alfalfa belowground biomass. Boron is essential in enhancing plant physiology and not necessarily increasing biomass (Bardhan *et al*., 2017).

Boron application significantly increased B and Zn uptake over the control at ($p<0.001$) by 4.3% and 14%, respectively. However, the application of boron significantly decreased Mo uptake over control at ($p<0.001$) by 26% (Table 4.2). The increase in B uptake with B application is attributed to B solubility and availability for uptake. A Study done by Byers *et al*. (2001)

working on slightly acidic soil showed that the application of B significantly increased B concentration in plant tissue. The increase in Zn uptake with B application is attributed to the synergistic effect of the two micronutrients. A Study by Sinha and Chatterjee (2000) working on mustard reported that the application of B increased Zn concentration with an increase in B supply. The decrease in Mo uptake following the application of B may be attributed to low Mo content in the soil, further lowered by low soil pH. The availability of Mo is pH-dependent (López *et al.*, 2007). A Study done by Nasar *et al*. (2018) on groundnuts showed that the application of B increases Mo uptake in groundnuts. A decrease in Mo uptake in the current study may thus be attributed to a low Mo level associated with low soil pH.

Table 4.2 Effect of boron, zinc, molybdenum and lime application on above and below-ground biomass, boron, zinc and molybdenum uptake

Treatments	Aboveground biomass (g/pot)	Belowground biomass g/pot)	Boron leaf concentration (%)	Zinc leaf concentration (%)	Molybdenum leaf concentration (mg/l)
Boron					
B1	4.15a	2.50a	0.96a	38.22a	3.68b
B0	3.85b	2.54a	0.92b	33.65b	4.95a
Zinc					
Z1	4.06a	2.25b	0.94a	29.68b	3.84b
Z0	3.94b	2.79a	0.93b	42.20a	4.80a
Molybdenum					
M1	4.29a	2.80a	0.84b	38.24a	4.98a
M0	3.70b	2.24b	1.04a	33.64b	3.66b
Lime					
L1	4.07a	2.50a	1.01a	36.42a	6.02a
L0	3.92b	2.54a	0.86b	35.45b	2.61b
%CV	4.9	9.8	1.14	1.90	10.45
LSD	0.117	0.08	0.006	0.313	0.023

Means with the same letter within a column are not significantly different ($p<0.05$) using the Least Significant Difference (LSD) test

Key: B1 = 0.3 kg Boron ha^{-1}, B0 = 0 kg Boron ha^{-1}, Z1 = 1.5kg Zinc ha^{-1}, Z0 = 0 kg Zinc ha^{-1}, M1 = 0.6kg Molybdenum ha^{-1}, M0 = 0 kg Molybdenum ha^{-1}, L1 = 1.6 t Lime ha^{-1} and L0 = 0 t Lime ha^{-1}.

Zinc application significantly increased the aboveground biomass over the control at ($p<0.05$) by 3%. However, it significantly decreased belowground biomass at ($p<0.001$) by 19% (Table 4.2). The increase in aboveground biomass with zinc application is attributed to improved growth because of increased synthesis of growth hormones due to Zinc application. Zinc plays a vital role in the synthesis of tryptophan and IAA hence increasing the leaf area (Nadergoli *et al*., 2011). A Study by Hidoto *et al*. (2017) in Ethiopia on chickpea reported that the application of zinc significantly increased the aboveground biomass. A decrease in the belowground biomass is attributed to the role of Zn in flowering. Zinc application plays a crucial role in flowering (Hafeez *et al*., 2013).

The application of Zn significantly increased B uptake over the control at ($p<0.05$) by 1%. However, it significantly decreased Zn and Mo uptake over the control at ($p<0.001$) by 30% and 20%, respectively (Table 4.2). The increase in B uptake is attributed to the synergistic effect between boron and zinc. A study by Hosseini *et al*. (2007) showed that irrespective of Zn supply, B concentration in the shoot increased in corn and does so by increasing B concentration in leaves and branches. A decrease in zinc uptake might be attributed to soil pH and the low solubility of Zn which affects the availability of zinc for plant uptake. A Study by Fageria *et al*. (2004) on acidic soil reported a decrease in zinc uptake with zinc application in rice due to low soil pH. Contrary results to the current study were reported by Ayalew *et al*. (2016) showed that the use of Zn fertilizer significantly increases Zn concentration in haricot bean. Similar results were also reported by Kumar and Babel (2011) who reported that the application of Zn fertilizer increased Zn uptake in plant tissue. The decrease in Mo uptake with Zn application is attributed to low soil pH, as availability of Mo is pH dependant and may be attributed to low Mo content in the soil. Mo uptake is affected by soil pH (Zakikhani *et al*., 2014). A Study by Ndakidemi *et al*. (2011) on acidic soil showed that the application of Mo significantly reduced Zn uptake in common bean.

Molybdenum application significantly increased above and below-ground biomass over the control at ($p<0.001$) by 16% and 25%, respectively. (Table 4.2). An increase in aboveground biomass because of Mo application is ascribed to improve growth such as leaf area index due to enhanced nitrogen fixation. A study done by Almeida *et al*. (2013) in Brazil reported that the application of Mo in common bean increased leaf area and shoot mass by 26%, it further accelerates the reproductive development of common bean and advancing flowering. An increase in the belowground biomass is attributed to improved nodulation and nitrogen fixation hence improving root growth. A study by Liu *et al*. (2005) showed that the application of Mo enhanced root growth, root system volume and dry root weight in soybean. A study by Tahir *et al*. (2016) also showed that the application of Mo increased belowground biomass due to increased nodulation, enhances the availability of micronutrient and improved root system in common bean.

Molybdenum application significantly increased Mo and Zn uptake over the control at ($p<0.001$) by 36% and 15% respectively. However, it significantly decreased B uptake at ($p<0.001$) by 19% (Table 4.2). An Increase in Mo uptake with Mo application is attributed to increased concentration of Mo in the soil, therefore available for common bean uptake. A Study done by Ndakidemi *et al*. (2011) showed a significant increase in Mo uptake with Mo application in common bean. Similar results were reported by Zakikhani *et al*. (2014), who reported an increase in Mo uptake with Mo application in rice. An increase in Zinc uptake may be attributed to the availability of zinc in soil, right soil moisture conditions which enhance availability for Zn uptake. Contrary results to the current study were reported by Ndakidemi *et al*. (2011), who reported that the application of Mo decreased Zn uptake in common bean. A decrease in B uptake with Mo application is attributed to competition for the exchange site because they are both anions. A study by Ndakidemi *et al*. (2011) in field and greenhouse experiment on *Leptosols* showed a decrease in B uptake following the application of Mo in common bean, and it significantly reduced B uptake with an increase in the supply of Mo.

The application of lime significantly increased the aboveground biomass over the control at ($p<0.05$) by 4% (Table 4.2) However, it did not have a significant effect on belowground biomass over control at ($p<0.05$) (Table 4.2). An increase in the aboveground biomass with the lime application is attributed to enhanced availability of nutrients, especially phosphorous, which improved the growth of common bean. A study done by Shanka *et al*. (2017) on slightly acidic soil showed that the application of lime significantly increased aboveground biomass in common bean. Calcium deficiency in soil is associated with low levels of nitrogen in plant tissue which is associated with reduced plant growth, liming, therefore, significantly increases plant productivity in common bean through the enhanced condition for seedling growth and nodulation (Bambara & Ndakidemi, 2010). A study done by Lunze *et al*. (2012) demonstrated that the application of lime improved aboveground biomass by 8% in common bean.

The lime application significantly increased B, Zn and Mo uptake over the control at (p<0.001) by 17%, 3% and 131%, respectively (Table 4.2). An increase in B, Zn and Mo uptake with the lime application is attributed to reduced Al^{3+} and H^+ toxicity and improved soil pH, hence enhancing the availability of B, Zn and Mo for plant uptake. A study done by Barman *et al*. (2014) showed that the application of lime significantly affected B uptake, liming at 1/3 lime recommendation increased B uptake, but at 2/3 lime recommendation significantly decreased B uptake. Application of lime increases B uptake in plants (Souza *et al*., 1997). A study done by Do Nascimento *et al*. (2007) on acidic soil showed an increase in soil pH due to lime application in Zn treated soil resulted in the redistribution of Zn into sparingly available forms. Contrary results were reported by Shahram *et al*. (2017), they showed that Zn concentration in plant tissue of rice increased with an increase in Zn levels and decreased with the lime application, the leave Zn concertation decreased by 35.5% due to lime application in comparison with non-limed pots. A study done by López *et al*. (2007) showed that the application of lime in legumes increased Mo concentration in plant tissues. Similar results were reported by Ndakidemi *et al*. (2011), who showed that the application of lime on slightly acidic significantly increased Mo uptake in common bean.

4.7.2 Interactive effect of Zn, B, Mo and lime application on aboveground biomass

The application of B in combination with lime and Zn in combination with lime significantly increase aboveground biomass over the control at (p<0.001) by 11% and 8%, respectively (Figure 4.1a). On the other hand application of Mo in combination with B significantly increased aboveground biomass by 24% over control at (p<0.01) (Figure 4.1b). An increase in the aboveground biomass with boron and lime is attributed to enhanced solubility of boron and availability of other essential nutrients like phosphorous and nitrogen due to liming. A study by Chowdhury *et al*. (2019) in acidic soil of India reported that the application of B and lime significantly increased plant height and number of leaves by 18% in broccoli. Application of lime increase B solubility in the soil hence increases the number of leaves (Chowdhury *et al*., 2019). An increase in the aboveground biomass with Zn and lime application is attributed to improved soil pH and availability of Zn, which plays an essential role in auxin formation, which is essential for plant growth. An increase in aboveground biomass with B and Mo application is attributed to active nitrogen fixation due to B and Mo, therefore enhancing the availability of nitrogen for common bean growth. A study by Liu *et al*. (2005) on alluvial soils showed that the application of B and Mo increased leaf area; he further showed that B and Mo combination increased aboveground biomass in soybean compared with the application of B and Mo alone. Increase in the aboveground biomass is also attributed to B and Mo co-supplementary effect since they are weak anion Liu *et al*. (2010). It could also be because of B function, which resulted in precipitation of excess cations, buffer action, maintenance of conducting tissues which helped in the absorption of nitrogen; Mo activates physiological process by stimulating factors in metabolism and growth of the plant (Singh *et al*., 2017).

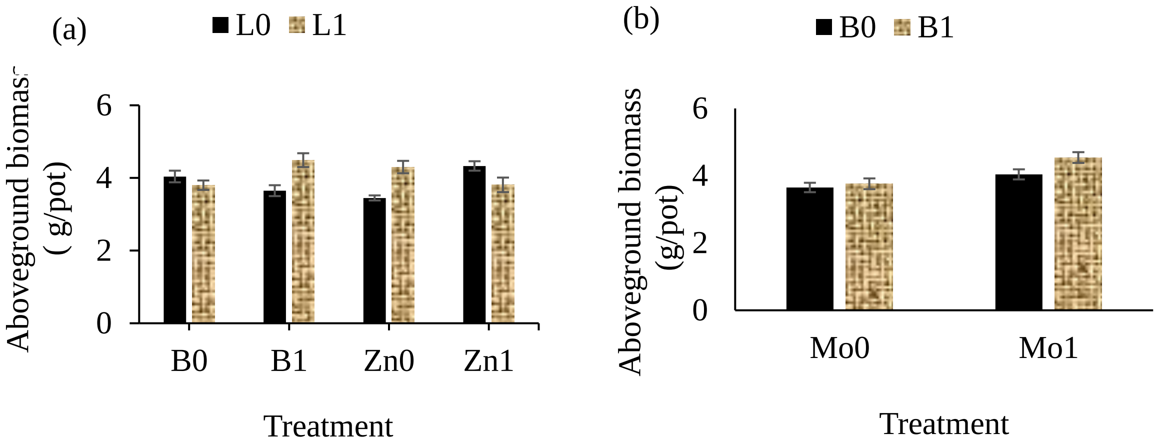

Figure 4.1 Interaction effect of Zn, B, Mo and lime on aboveground biomass

Key: Mo0 = 0kg Molybdenum ha^{-1}, Mo1 = 0.6 kg Molybdenum ha^{-1}, B0 = 0 kg Boron ha^{-1}, B1 = 3kg Boron ha^{-1}, Zn0 – 0 kg Zinc ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t Lime ha^{-1}.

4.7.3 Interactive effect of Zn, B, Mo and lime application on belowground biomass

The application of Mo in combination with lime, Zn in combination with Mo and B in combination with Mo significantly increased the belowground biomass over control at (p<0.001) by 29%, 1.2% and 32%, respectively (Figure 4.2a). However, the application of B in combination with Zn significantly decreased belowground biomass over control at (p<0.001) by 20% (Figure 4.2b). An increase in the belowground biomass with Mo and lime application is attributed to enhanced nodulation, further enhanced by the availability of nutrients such as nitrogen and phosphorous due to liming, which improved root growth. The application of lime and Mo increases nodulation and plant growth (Bambara & Ndakidemi, 2010). A study done by Almeida *et al*., (2013) in *Ultisols* showed that the application of lime and Mo increased the number of effective nodules which enhances the availability of macro and micronutrients, therefore, improved root growth.

An increase in the belowground biomass with Zn and Mo application is attributed to the role of Zn and Mo in nodule formation. Zinc plays a vital role in metabolism and is involved in N-fixation through nodule formation (Patel *et al*., 2011). On the other hand, boron is an essential micronutrient in enhancing effective nodulation and N-fixation in legumes (Shil *et al*., 2007). A study done by Quddus *et al*. (2018) on the effect of boron and zinc on pea in Bangladesh reported that the application of both zinc and boron significantly increased the number of nodules. An increase in the belowground biomass with B and Mo is attributed to improved nodulation and root elongation due to the combined effect of B and Mo. A study by Liu *et al*. (2005) showed that combined application of B and Mo increased belowground biomass in soybean due to the role of B and Mo in root elongation, root volume enlargement and increasing root dry weight. A decrease in the belowground biomass with Zn and B application may be attributed to low soil pH, which affected availability of other essential nutrients. A study by Montenegro *et al*. (2010) reported that the application of B and Zn did not affect root dry weight. Contrary results to the current study were reported by Khan and Prakash (2014) who reported that the application of B and Zn significantly improved belowground biomass in summer urdbean (*Vigna mungo* L) due to improved nodulation.

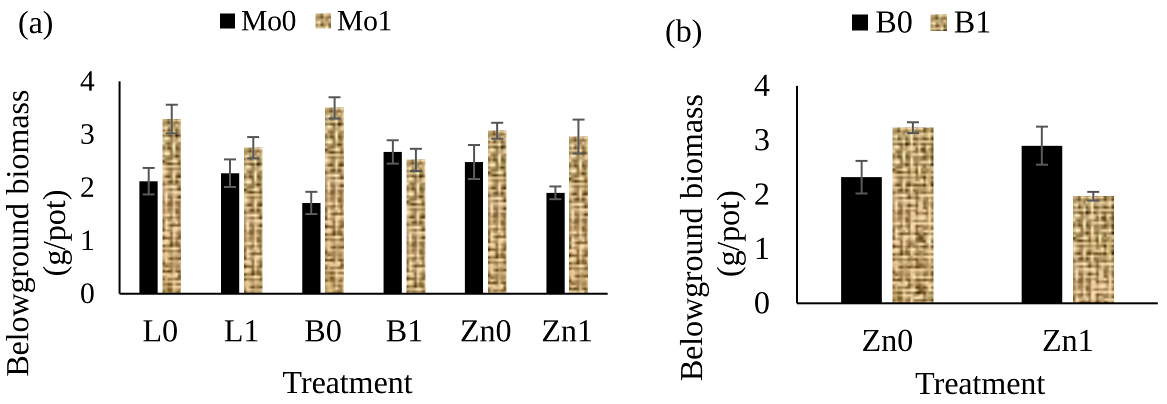

Figure 4. 2 Interaction effect of Zn, B, Mo and lime on belowground biomass

Key: Zn0 = 0 kg Zinc ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, B0 = 0 kg Boron ha^{-1}, B1 = 3kg Boron ha^{-1}, Mo0 = 0 kg Molybdenum ha^{-1}, Mo1 = 0.6 kg Molybdenum ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t Lime ha^{-1}.

4.7.4 Interaction of zinc, boron, molybdenum and lime application on boron uptake

The application of Zn in combination with lime, B in combination with lime and B in combination with Zn significantly increased B uptake over control at ($p<0.001$) by 14%, 28% and 5%, respectively (Figure 4.3a). However, application of Mo in combination with lime, B in combination with Mo and Zn in combination with Mo significantly decreased B uptake over control at ($p<0.001$) by 6%, 18% and 19%, respectively (Figure 4.3b and c). An increase in B uptake with lime and zinc application is attributed to improved soil pH and synergistic effect of zinc and boron. A study done by Shaaban *et al*. (2004) on wheat in Germany reported that the application of zinc and lime significantly increased boron uptake they attributed this to the role of Zn in enhancing the availability of boron. A study by Barman *et al*. (2014) in acidic soil reported that the application of Zn and lime increased B uptake in sunflower by enhancing its availability in soil and concentration in plant tissue. An increase in B uptake with B and lime may be attributed to improved soil pH, further enhanced by B application; hence an increase in B concentration for plant uptake. A study by Souza *et al*. (1997) in acidic soil reported that the application of lime with B fertilization significantly increased B uptake in sunflower.

An increase in B uptake with Zn and boron application is attributed to the synergistic effect of the two micronutrients. A study by Islam *et al*. (2018) on the impact of trace elements addition on lentil showed that the application of B and Zn increased B uptake. Similar results were reported by Quddus *et al*. (2018), who reported that combined application of B and Zn significantly increased B uptake in peas. A study done by Rathod *et al*. (2017) also reported that the application of B and Zn in lateritic soil significantly increased B uptake in soybean. A decrease in B uptake with lime and molybdenum application is attributed to an increase in Mo level with liming; therefore, affecting B uptake due to the antagonistic effect with Mo. A study by Ndakidemi *et al*. (2011) on the effect of rhizobium inoculation and the supply of lime and molybdenum on micronutrient uptake in common bean showed that application of Mo decreased B uptake. Reduction in boron uptake with B and Mo application may be attributed to competition for the exchange site since both are anions. A study done by Ndakidemi *et al*. (2011) on the effect of rhizobium inoculation and the supply of lime and molybdenum on micronutrient uptake in common bean showed that application of Mo decrease B uptake, it significantly decreased B uptake with an increased supply of Mo. A decrease in B uptake with Zn and Mo application may be attributed to competition for exchange site with Mo and antagonistic effect of the two nutrients. A study by Ndakidemi *et al*. (2011) on the effect of rhizobium inoculation and the supply of lime and molybdenum on micronutrient uptake in common bean reported that application of Mo decreased B uptake.

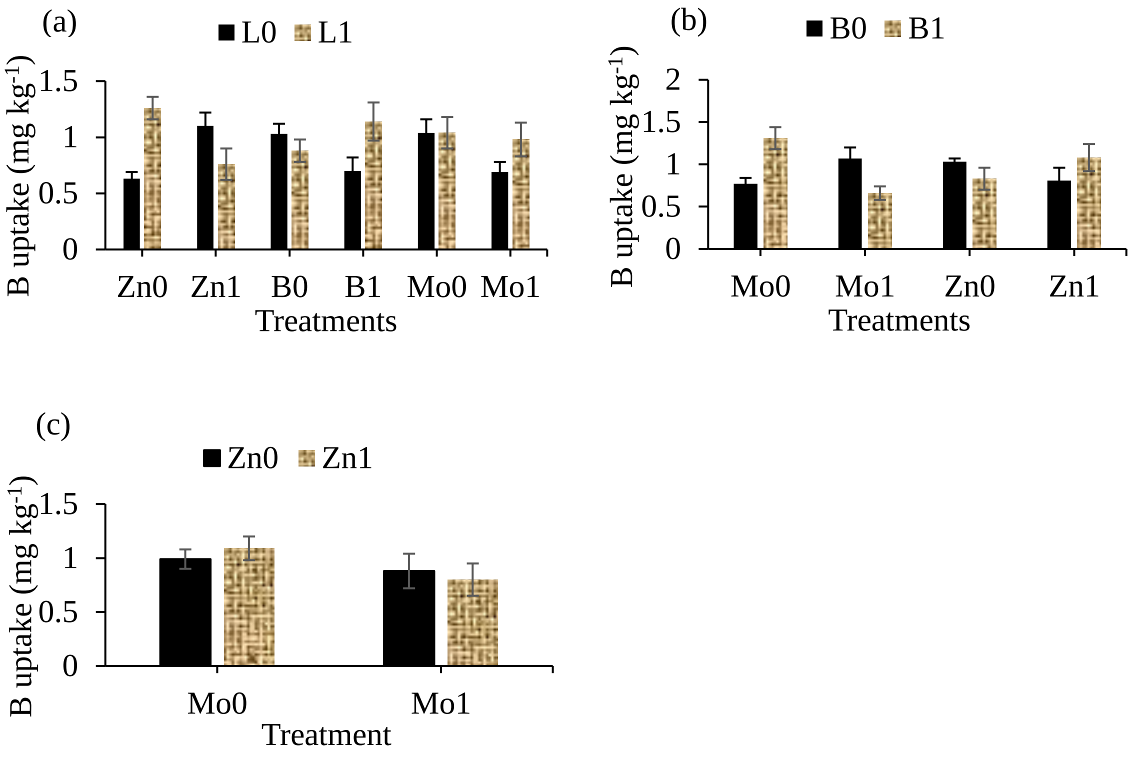

Figure 4.3 Interaction effect of Zn, B, Mo and lime on B Uptake

Key: Zn0 = 0 kg Zinc ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, B0 = 0 kg Boron ha^{-1}, B1 = 3kg Boron ha^{-1}, Mo0 = 0 kg Molybdenum ha^{-1}, Mo1 = 0.6 kg Molybdenum ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t Lime ha^{-1}.

4.7.5 Interaction effect of Zn, B, Mo and lime application on Mo uptake

The application of Zn in combination Mo, Mo in combination with lime, B in combination with Mo and B in combination with lime significantly increased Mo uptake over the control at ($p<0.01$) by 9%, 174%, 0.2%, and 91%, respectively (Figure 4.4a and b). An increase in Mo uptake with Zn application may be attributed to the synergistic effect of the two micronutrients. A study done by Singh *et al*. (2004) showed that the application of Mo and Zn significantly increased Zn uptake in chickpea. An increase in Mo uptake with the lime application is attributed to improved soil pH, which enhanced the availability of Mo for plant uptake. A study done by Quaggio *et al*. (2004) showed that the application of lime and molybdenum significantly increased Mo uptake in peanuts.

An increase in Mo uptake with boron and Mo application may be attributed to the enhanced availability of Mo. A study by Shankhe *et al*. (2004) working on the effect of boron and molybdenum in groundnuts reported that combined application of B and Mo increased Mo uptake. Similar results were reported by (Singh *et al*., 1991), who reported that the application of B significantly increased Mo uptake in chickpea and pigeon pea. An increase in Mo uptake with B and lime applications is attributed to enhanced availability of Mo due to liming. Liming increases the availability of Mo in soil (Ndakidemi *et al*., 2011). A study done by Quaggio *et al*. (2004) on the effect of lime on molybdenum uptake in peanuts in acidic soil reported a significant increase in Mo uptake with the lime application. Similar results were reported by Ndakidemi *et al*. (2011) working on common bean in acidic soil reported a significant increase in Mo with lime application.

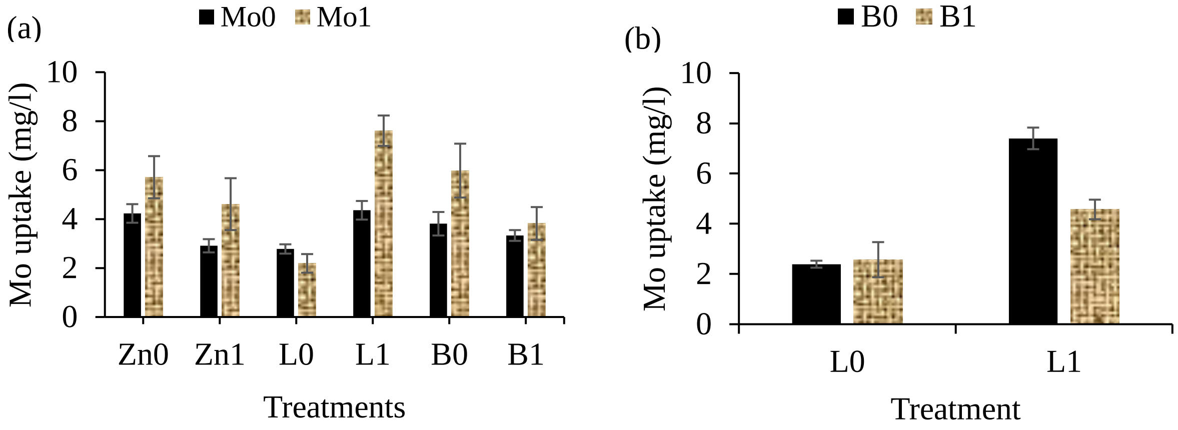

Figure 4.4 Interaction effect of Zn, B, Mo and lime on Mo uptake

Key: B0 = 0 kg Boron ha^{-1}, B1 = 3 kg Boron ha^{-1}, Mo0 – 0 kg Molybdenum ha^{-1}, Mo1 = 0.6 kg Molybdenum ha^{-1}, Zn0 = 0 kg Zinc ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, L0 = 0 t Lime ha^{-1} and L1= 1.6 t Lime ha^{-1}.

4.7.6 Interaction of Zn, B, Mo and lime application on Zn uptake

The application of B in combination with lime and Mo in combination with lime, B in combination with Mo significantly increase Zn uptake over control at (p<0.001) by 15%, 16% and 27% respectively. However, application of Zn in combination with lime, B in combination with Zn and Zn in combination with Mo significantly decreased Zn uptake over control at (p<0.001) by 30%, 32% and 21%, respectively (Figure 4.5a, b and c). An increase in Zn uptake with B and lime combination is attributed to the synergistic effect of B and Zn. A study done by Barman *et al*.

(2014) on the effect of boron and lime application in acidic soil reported that the application of B and lime enhances Zn uptake in sunflower. A study done by Panhwar *et al*. (2011) in acidic soil reported that the application of boron and zinc in maize had a synergistic effect hence enhancing uptake of Zn. An increase in Zn uptake with lime and Mo application is attributed to enhanced availability of nitrogen in the soil, which in turn increased uptake of zinc. A study done by Erenoglu *et al*. (2011) on wheat reported a significant increase in Zn uptake with nitrogen fertilization. A study done by Quaggio *et al*. (2004) reported that the application of lime and molybdenum increase Zn uptake. An increase in zinc uptake with B and Mo application may be attributed to the fact that both B and Mo are ions while Zn is a cation therefore enhancing the uptake of Zn. Study done by Islam *et al*. (2018) reported that application of B and Mo significantly increased Zn uptake in lentils.

Reduced Zn uptake with lime and Zn application may be attributed to changes in soil pH since the availability of Zn in the soil is a pH-dependent and antagonistic effect of phosphorous on Zn uptake. Application of lime enhances the availability of phosphorous which may affect the availability of zinc for plant uptake. A study done by Behera *et al*. (2016) showed that the application of lime significantly reduced Zn concentration. Similar results were reported by Ndakidemi *et al*. (2011), who reported that the application of lime significantly decreases Zn concertation in plant tissue. Contrary results were reported by Barman *et al*. (2014) who reported that the application of lime enhanced availability of Zn, which was observed by an increase in plant uptake. A decrease in the Zn uptake with B and Zn application is attributed to the antagonistic effect of B and Zn at a high concentration of B. A study done by Hossain *et al*. (2001) reported that the application of B and Zn increased Zn uptake. Similar results were reported by Panhwar *et al*. (2011) who reported that the application of B and Zn increases Zn concentration in plant tissue, but antagonistic effect sets in when the level of boron is high. A decrease in Zn uptake with Zn and Mo application may be attributed to increasing phosphorous with Mo application, which might have reduced Zn uptake. A study done by Ndakidemi *et al*. (2011) showed that application of Mo significantly decreased Zn uptake.

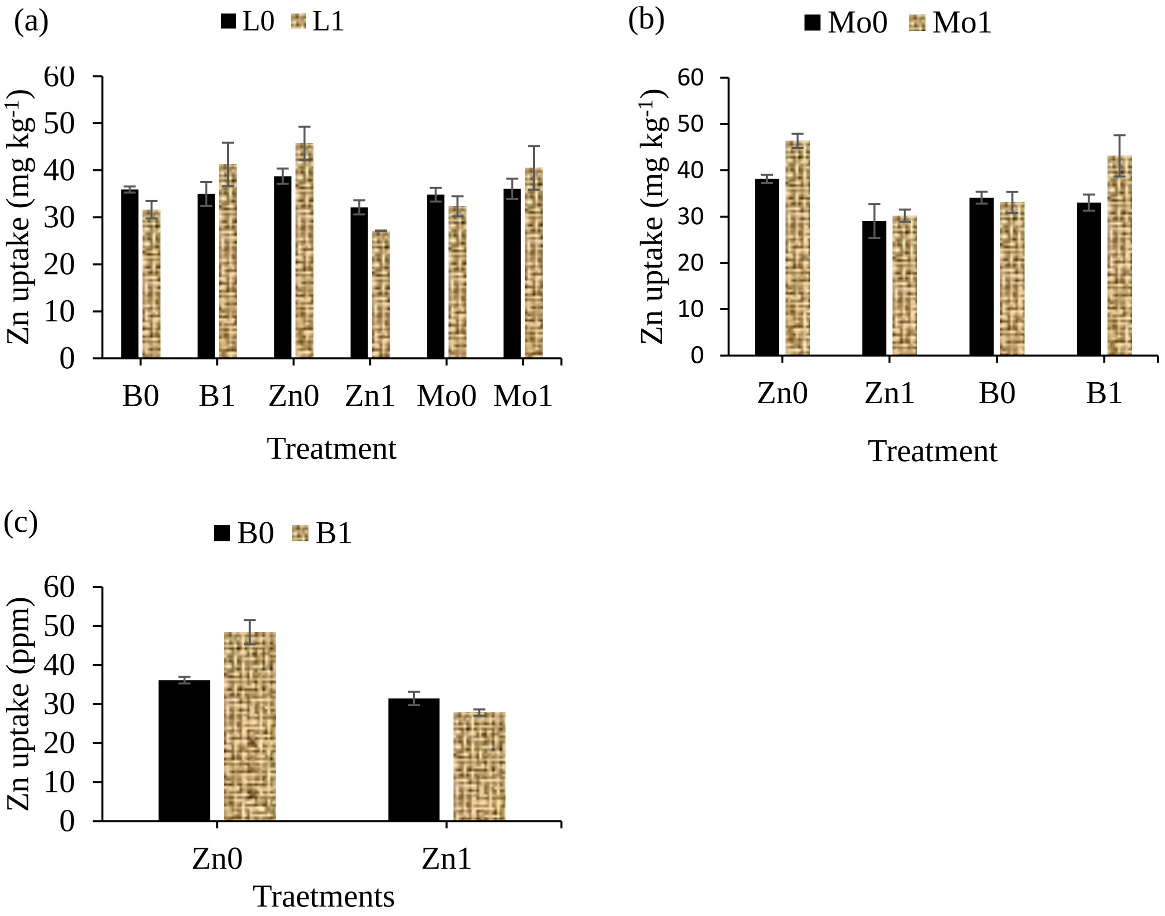

Figure 4.5 Interaction effect of Zn, B, Mo and lime on Zn uptake

Key: Zn0 = 0 kg Zinc ha^{-1}, Zn1 = 1.5 kg Zinc ha^{-1}, B0 = 0 kg Boron ha^{-1}, B1 = 3 kg Boron ha^{-1}, Mo0 = 0 kg Molybdenum ha^{-1} Mo1 = 0.6 kg Molybdenum ha^{-1}, L0 = 0 t Lime ha^{-1} and L1 = 1.6 t Lime ha^{-1}.

4.8 Conclusion

i. Molybdenum application significantly improved above and belowground biomass. This micronutrient plays an essential role in nitrogen fixation, enhancing nitrogen availability for common bean growth and development. Therefore, this micronutrient play an important role in improving common bean in acidic *Acrisols*. Interaction of Mo B Zn with lime improved above and belowground biomass, attributed to the important role of liming in enhancing the availability of other nutrients, zinc in the activation of growth-promoting enzymes, boron in enhancing cell elongation and differentiation and molybdenum role in the improvement of nodulation. Therefore, these results signify the critical role of lime and micronutrient B, Zn and Mo in improving common bean production in acidic *Acrisols* of Western Kenya.

ii. The single application of micronutrient fertilizer may be beneficial, but the interaction effects showed that there might be antagonistic effects on applying a particular combination of micronutrients. Therefore, during the process of fertilizer blending, key consideration put on beneficial interactions.

iii. These results signify the critical role played by B, Zn, Mo and lime in improving common bean growth and development. Therefore, to improve common bean production in *Acrisols* of Western Kenya, there is a need for liming and fertilizer formulation with micronutrients B, Zn and Mo.

CHAPTER FIVE

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 General Discussion

The use of mineral fertilizers by smallholder farmers in Sub- Sahara Africa is essential towards improving crop production, however; various studies have reported that the application of NPK fertilizer without micronutrients has been the norm among smallholder farmers in Western Kenya, which has resulted in non-responsive soils (Keino *et al*., 2015; Njoroge *et al*., 2017). This has resulted in stagnation of yield resulting in reduced farmer's income and food insecurity in the region. A study done by Roobroeck *et al*. (2021) showed that applying NPK fertilizer at the recommended rate does not result in a significant increase in yield. There are indications that micronutrients deficiency and nutrient imbalance could be the main reason for non-responsive soils and stagnation of yields in the region.

This study indicated that customized *Mavuno* fertilizer and lime application significantly improved the common bean yield. *Mavuno* fertilizer contains micronutrient molybdenum, boron, iron, and copper, which has contributed to improved common bean yield in the region and the availability of nutrients through liming. The application of boron, molybdenum, zinc, and lime improved common bean growth attributed to the role of these micronutrients. Molybdenum plays a critical role in nitrogen fixation, while boron is important in cell differentiation, elongation and meristem activities. On the other hand, Zn activates growth enzymes, whereas liming counteracts hydrogen and aluminium toxicity. DAP fertilizer contains nitrogen and phosphorus but lacks micronutrients. Its application did not have a significant effect on common bean yield. The decrease in common bean yield and non-responsiveness of the soils to the application of DAP fertilizer in the acidic soil of Aldai Sub-County is attributed to micronutrient deficiency. Therefore, incorporating these micronutrient fertilizers in blends and liming is essential in improving common bean production in acid *Acrisols* of Western Kenya.

5.2 Conclusions

i. The application of lime and *Mavuno* fertilizer in Aldai Sub-County will significantly improve common bean growth and yield compared with other fertilizers. The fertilizer supplies primary macronutrient NPK, secondary macronutrient Ca, Mg and S and micronutrient B, Mo, Cu and Fe. These micronutrients are essential in common bean growth, hence improving yield. It is further improved by lime application, which improves soil pH and nutrient availability for the growth and development of common bean. The application of lime counteracts the effect of aluminium and hydrogen ions in the soil, enhancing phosphorous, nitrogen, calcium, molybdenum, and magnesium, resulting in improved common bean production.

ii. The application of molybdenum, boron and lime at the rate of 0.6 kg ha^{-1}, 3 kg ha^{-1} and 1.6 t ha^{-1}, respectively, will significantly increase common bean growth (above and belowground biomass) and micronutrient uptake in acidic soil of Aldai Sub-County, Nandi County. Interaction of molybdenum boron with lime plays an essential role in nitrogen fixation and improvement of common bean growth.

5.3 Recommendations

i. Application of *Mavuno* fertilizer and lime is recommended for improved common bean production in acidic *Acrisols* of Western Kenya. The recommended rate of application of lime in Kapkerer is 1.6 t ha^{-1} and Kiptaruswo is 2 t ha^{-1}, while for *Mavuno* fertilizer is 185 kg ha^{-1}.

ii. There is a need for manufacturing companies to include micronutrients, especially boron and molybdenum in their fertilizers to enhance common bean production in *humic Acrisols* of Nandi County.

iii. Further research on micronutrients antagonistic effect and other micronutrients that limit common bean growth and other customized fertilizer key focus being region-specific towards improving common bean production.

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APPENDICES

Appendix A ANOVA table for above and below-ground biomass, and nutrient uptake on application of customized fertilizer and lime

Source of variation	df	pH	AGB (t ha^{-1})	BGD (t ha^{-1})	P uptake (%)	Ca uptake (mg kg^{-1})	Mg uptake (mg kg^{-1})	Yield (t ha^{-1})
Replicates	2	0.024	0.006	0.0002	0.00003	0.003	0.0001	0.006
Site	1	15.42***	20.78***	0.106***	0.183***	0.087^{ns}	0.341***	38.16***
Mavuno	1	0.137*	0.875***	0.00005^{ns}	0.0002^{ns}	0.022*	0.002ns	0.170**
DAP	1	0.0001^{ns}	0.088^{ns}	0.0010^{ns}	0.0001^{ns}	0.056^{ns}	0.002ns	0.004^{ns}
Sympal	1	0.03^{ns}	0.031**	0.0016**	0.0001^{ns}	0.314***	0.003*	0.022*
Lime	1	3.26***	0.516***	0.004**	0.00001**	0.048**	0.007**	0.147**
Mavuno × Lime	1	0.426**	0.208***	0.003**	0.0060*	0.004^{ns}	0.00008^{ns}	0.044*
DAP × Lime	1	0.005^{ns}	0.008^{ns}	0.001^{ns}	0.0004^{ns}	0.0077^{ns}	0.004^{ns}	0.0037^{ns}
Sympal× Lime	1	0.01^{ns}	0.106***	0.001**	0.0003^{ns}	0.0003^{ns}	0.0003^{ns}	0.0003^{ns}
CV%		3.012	3.44	6.849	1.649	2.98	3.14	7.65
R2		0.962	0.980	0.882	0.66	0.917	0.863	0.93

ABG- Aboveground biomass, BGB- Belowground ground biomass, *- significant at 0.05 level, **- significant at 0.01 level, $^{***-}$ significant at 0.001 level ns- not significant

Appendix B ANOVA table for above and below-ground biomass, and nutrient uptake following application of Boron, zinc, molybdenum and lime and their interactions in common bean production

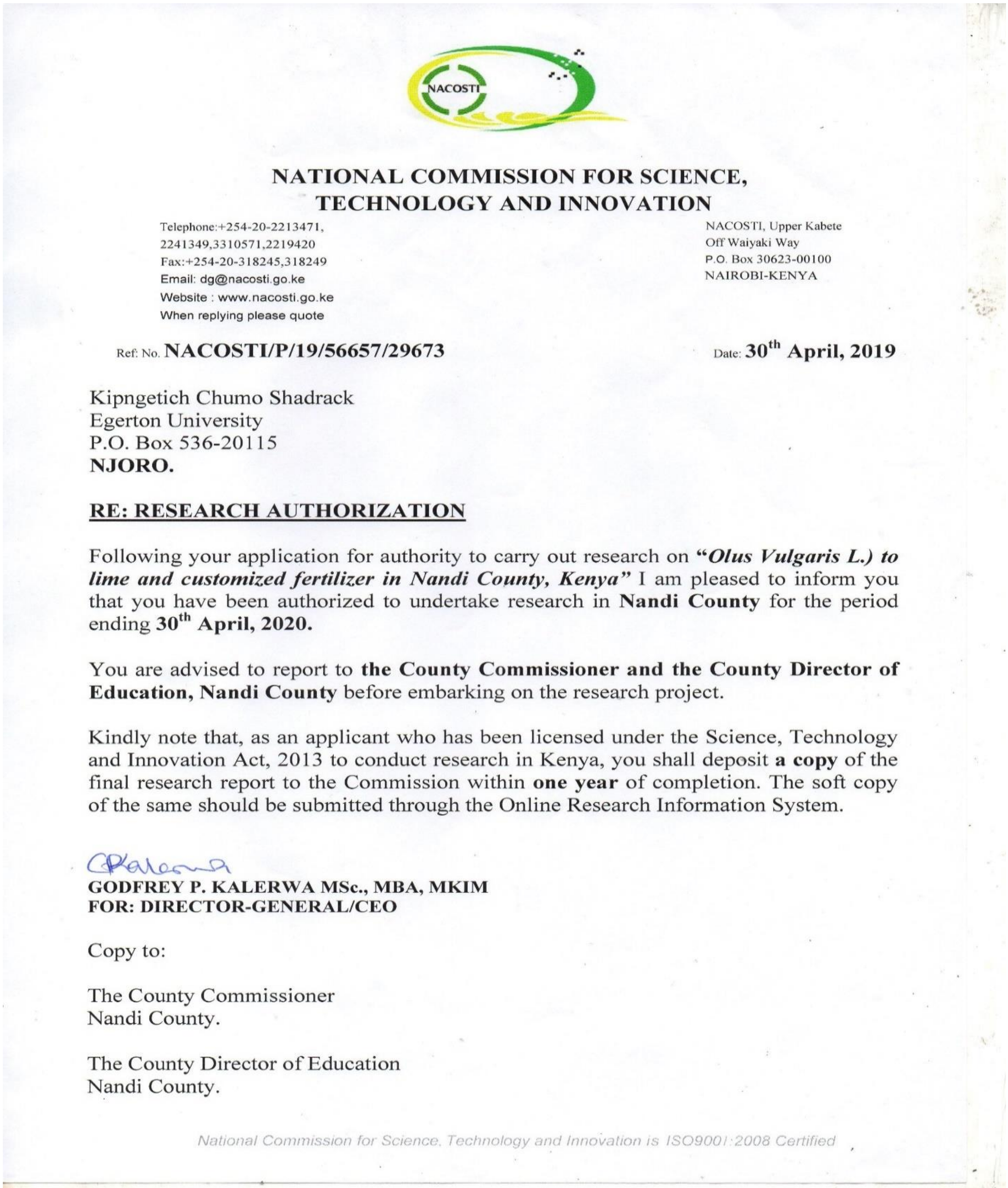
Source of variation	df	AGB (g/pot)	BGB (g/pot)	B uptake (mg kg^{-1})	Zn uptake (mg kg^{-1})	Mo uptake (mg l^{-1})
Rep	2	0.025	0.202	0.00007	0.806	0.753
B	1	1.086***	0.001^{ns}	0.017***	4.087***	21.00***
Zn	1	0.173*	1.408***	0.001**	1912.81***	10.76***
B × Zn	1	0.124^{ns}	1.014***	0.646***	757.71***	0.527^{ns}
Mo	1	4.118***	8.18***	0.478***	265.79***	21.213***
B × Mo	1	0.460**	11.43***	3.035***	348.03***	8.594***
Zn × Mo	1	0.023^{ns}	0.64**	0.089***	147.39***	54**
B × Zn × Mo	1	1.498***	0.147^{ns}	0.439***	66.11***	2.665***
L	1	0.273*	0.452*	0.257***	19***	147.245***
B × L	1	3.424***	0.166^{ns}	1.047***	336.39***	27.105***
Zn × L	1	4.967***	0.279*	2.800***	431.1***	0.502^{ns}
B × Zn × L	1	0.077^{ns}	0.639**	0.144***	8.918***	2.104**
Mo × L	1	0.134^{ns}	1.435***	0.245***	142.93***	43.988***
B × Mo × L	1	0.004^{ns}	0.255^{ns}	0.254***	20.29***	1.425*
Zn × Mo × L	1	0.0003^{ns}	4.118***	0.005***	62.27***	6.475***
B × Zn × Mo × L	1	0.163*	0.452*	0.138***	1.58*	4.496***
%CV		4.94	9.83	1.14	1.90	10.45
R^2		0.93	0.95	0.99	0.99	0.98

ABG- Aboveground biomass, BGB- Belowground ground biomass, *- significant at 0.05 level, **- significant at 0.01 level, ***- significant at 0.001 level ns- not significant.

Appendix C Thesis output

1. Kipngetich, S. C., Mwonga, S. M. and Ojiem, J. O. The effect of multi-component fertilizer and lime application on yield of common bean in Western Kenya. *African Journal of Agricultural Research*, *17*(1), 112-117.– **Manuscript**
2. Kipngetich, S.K., Mwonga, S. M. and Ojiem, J (2020) Effect of boron zinc molybdenum and lime application on common bean growth in acidic *Acrisols* of Nandi County, Kenya – **Under review**

Appendix D Research Permit



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Date: **30th April, 2019**

Kipngetich Chumo Shadrack
Egerton University
P.O. Box 536-20115
NJORO.

RE: RESEARCH AUTHORIZATION

Following your application for authority to carry out research on ***"Olus Vulgaris L.) to lime and customized fertilizer in Nandi County, Kenya"*** I am pleased to inform you that you have been authorized to undertake research in **Nandi County** for the period ending **30th April, 2020.**

You are advised to report to **the County Commissioner and the County Director of Education, Nandi County** before embarking on the research project.

Kindly note that, as an applicant who has been licensed under the Science, Technology and Innovation Act, 2013 to conduct research in Kenya, you shall deposit **a copy** of the final research report to the Commission within **one year** of completion. The soft copy of the same should be submitted through the Online Research Information System.

GODFREY P. KALERWA MSc., MBA, MKIM
FOR: DIRECTOR-GENERAL/CEO

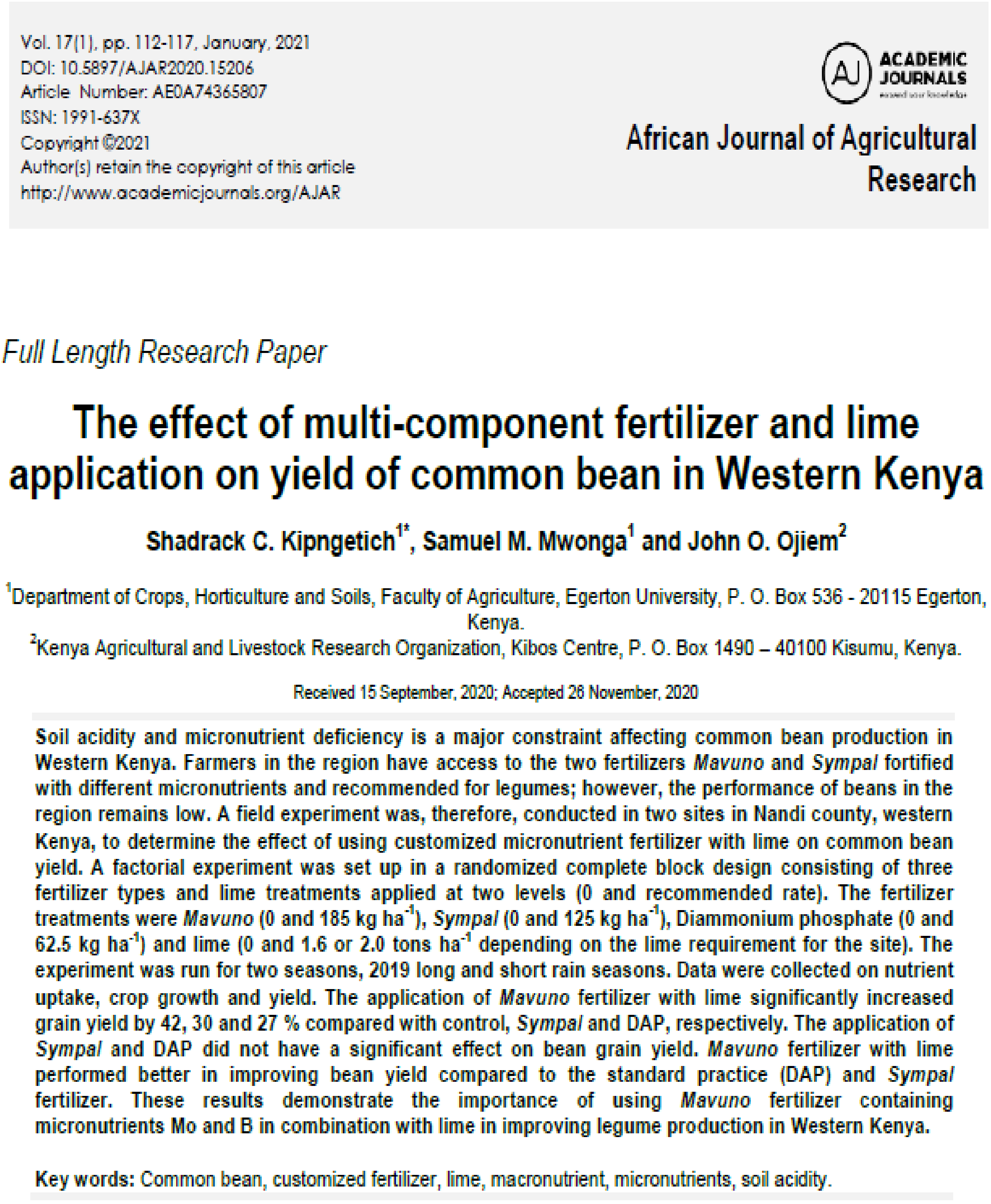
Copy to:

The County Commissioner
Nandi County.

The County Director of Education
Nandi County.

National Commission for Science, Technology and Innovation is ISO9001:2008 Certified

Appendix E Abstract of published paper



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African Journal of Agricultural Research

Full Length Research Paper

The effect of multi-component fertilizer and lime application on yield of common bean in Western Kenya

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Soil acidity and micronutrient deficiency is a major constraint affecting common bean production in Western Kenya. Farmers in the region have access to the two fertilizers *Mavuno* and *Sympal* fortified with different micronutrients and recommended for legumes; however, the performance of beans in the region remains low. A field experiment was, therefore, conducted in two sites in Nandi county, western Kenya, to determine the effect of using customized micronutrient fertilizer with lime on common bean yield. A factorial experiment was set up in a randomized complete block design consisting of three fertilizer types and lime treatments applied at two levels (0 and recommended rate). The fertilizer treatments were *Mavuno* (0 and 185 kg ha^{-1}), *Sympal* (0 and 125 kg ha^{-1}), Diammonium phosphate (0 and 62.5 kg ha^{-1}) and lime (0 and 1.6 or 2.0 tons ha^{-1} depending on the lime requirement for the site). The experiment was run for two seasons, 2019 long and short rain seasons. Data were collected on nutrient uptake, crop growth and yield. The application of *Mavuno* fertilizer with lime significantly increased grain yield by 42, 30 and 27 % compared with control, *Sympal* and DAP, respectively. The application of *Sympal* and DAP did not have a significant effect on bean grain yield. *Mavuno* fertilizer with lime performed better in improving bean yield compared to the standard practice (DAP) and *Sympal* fertilizer. These results demonstrate the importance of using *Mavuno* fertilizer containing micronutrients Mo and B in combination with lime in improving legume production in Western Kenya.

Key words: Common bean, customized fertilizer, lime, macronutrient, micronutrients, soil acidity.