EFFECT OF PHOSPHORUS APPLICATION ON GROWTH, YIELD AND QUALITY OF SEED POTATO (*Solanum tuberosum* L.*)* VARIETIES PROPAGATED FROM ROOTED APICAL CUTTINGS IN KENYA

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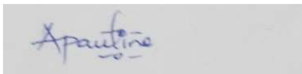
DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been previously published or presented for the award of any degree in any University**.**

Signature:  Date: 7th March 2021

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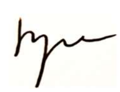
Signature:  Date: 7th March 2021

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DEDICATION

This thesis is dedicated to my parents, Mr. Vincent Ongura and Mrs. Leah Malinga for the emotional and spiritual support. To my brothers and sisters, relatives and friends.

In a special way, I dedicate this thesis to my uncle Mr. Gabriel Omongot and my aunt Ms. Mary Francis Akiteng. Thank you for all the sacrifices you made towards my studies.

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ABSTRACT

Potato (*Solanum tuberosum* L.) is the world's fourth most important food crop after maize, rice and wheat. In Kenya, it is the second most consumed crop after maize and mainly produced by small-scale farmers. Potato production in Kenya is limited by a number of constraints for example pest and diseases, climatic changes, lack of quality seed and low soil fertility. Farmers plant seeds saved from previous harvest, which are degenerated due to pest infestation and disease infection. Management of fertilizer phosphorus is a critical component of potato production systems. Studies on effect of phosphorus on growth, yield and quality of potato propagated from rooted apical cuttings in Kenya have not been done. The objective was to determine the effect of phosphorus rates on growth, yield and quality of seed potato varieties propagated from rooted apical cuttings. The study was done at Egerton University demonstration field, the Kenya Agricultural and Livestock Research organization (KALRO) research field in Molo and a farmers' field in Mauche, Njoro. The field experiments were conducted using randomized complete block design (RCBD) with split plot arrangement and replicated three times. Main plot factors were potato varieties (*Shangi, Dutch Robyjn, Unica* and *Wanjiku*) and the sub plot factors were phosphorus levels (0, 30, 60, 90 kg P ha^{-1}). Data on growth and yield parameters were collected and subjected to analysis of variance (ANOVA) using SAS version 9.3. Phosphorus rates had significant effect ($P< 0.05$) on plant survival and number of stems and marketable tuber yield. The interaction effects of phosphorus rates and varieties on plant survival, plant height, plant biomass, number of eyes and tuber size was significant ($P< 0.05$). The rates of 60, 90, and 30 kg P ha^{-1} recorded 16.12, 15.54 and 14.62 tubers per hill, respectively, which were not significantly different but higher than control. The interaction of Wanjiku and 30 kg P ha^{-1} gave the highest biomass weight of 0.42g and the highest number of large sized tubers of 15.67 per plant. The main effects of variety ($P<0.01$) and phosphorus rates ($P<0.05$) significantly affected days to physiological maturity and marketable tuber yield. The application of phosphorus had significant effect on starch content, dry matter and specific gravity of tubers. Unica variety recorded higher phosphorus use efficiency at both study sites. Application rate of 30 kg P ha^{-1} was optimum for the development and yield of potato under the study conditions. The rooted apical cuttings of Wanjiku, Shangi and Unica varieties can be used by the farmers for potato propagation in order to obtain high yield of potato in the study areas and other areas of similar agro ecological zones. Further studies on effect of phosphorus on the growth of rooted apical cuttings in comparison with the conventional tubers are recommended.

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LIST OF ABBREVIATIONS AND ACRONYMS

ADC	Agricultural Development Corporation
ANOVA	Analysis of Variance
CEC	Cation Exchange Capacity
CIP	International Potato Center
CV	Coefficient of Variation
FAO	Food and Agricultural Organization of the United Nations
FAOSTAT	Food and Agriculture Organization of the United Nations (Statistics division)
KALRO	Kenya Agricultural and Livestock Research Organization
KEPHIS	Kenya Plant Health Inspectorate Services
LSD	Least Significant Difference
MOP	Muriate of Potash
NPCK	National Potato Council of Kenya
NPK	Nitrogen Phosphorus Potassium
PUE	Phosphorus use efficiency
SAS	Statistical Analysis System
TSP	Triple Super Phosphate

CHAPTER ONE
INTRODUCTION

1.1 Background information

Potato (*Solanum tuberosum* L.) is the world's fourth most important food crop after maize (*Zea mays* L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.). The area under production is 19,302,642 ha with annual production of 38,819,067 tonnes (FAO, 2017). In Kenya potato is mainly grown by small scale farmers and is the second most consumed crop after maize (Janssens *et al*., 2013). The area under potato production is 192,341 ha with average yield of 79,020 tonnes per ha (FAO, 2017). It is the cheapest source of carbohydrates, vitamins B and C, proteins and minerals thus is important in food and nutritional security (Islam & Nahar, 2012).

Potato is mainly cultivated in the highland areas of Kenya at altitudes ranging from 1200 to 3000 metres above sea level where it is a major staple food crop. The main potato producing areas in Kenya are Embu, Nyandarua, Meru, Kirinyanga, Laikipia, Mau Narok, Molo, Tinderet, Nandi Escarpment and Cherangani hills. Other minor potato producing areas in Kenya are Kericho Kisii and Taita (Muthoni & Nyamongo, 2009).

Potato yields and quality in smallholder farms is affected by shortage of clean planting materials. Farmers use farm saved seed potato tubers from the previous seasons' harvest without taking phytosanitary measures against diseases (Muthoni *et al.*, 2013; Tsoka *et al*., 2012). Potato diseases occur at any stage of plant development and are caused by an array of pathogens, including viruses, bacteria, phytoplasmas, and fungi. Potatoes are propagated from vegetative parts like tubers, meristem tips and stems and thus it is important to have control measures on seed borne diseases (Nolte *et al*., 2020). Clean potato planting materials can be produced through the use of tissue culture techniques or rooting apical cuttings. Plant tissue culture involves culturing of the plant cells or tissues under controlled hygienic environments on a solid or liquid medium. It increases production of disease free and true to type planting materials of crops like bananas, potatoes and even trees (Mohapatra & Batra, 2017). In potato, various tissues can be used as explants for shoot generation directly (Anjum & Ali, 2004). There is need to ensure quality control during the production process of tissue culture planting materials. This starts with selection of the explants that are disease free and varieties that are high yielding (Suman, 2017). The environment, culture vessels, explant, media and instruments used in handling tissues must be sterilized to kill all germs that may cause contamination (Chawla, 2003; Mohapatra & Batra, 2017). It however, takes long for the seeds produced from tissue culture plants to reach the farmer because of the long certification process involved (CIP, 2017).

The alternative to tissue culture planting materials are the rooted apical cuttings which are similar to nursery grown seedlings except that they are produced from vegetative parts and not seed tubers. The apical cuttings originate from the tissue culture materials. They are produced from plantlets by taking single or double node cuts from the lateral shoots. They are planted in to coco plugs media for hardening process in the screen house for a period of three weeks until they are ready for transplanting to the field (Personal communication from Stokman Rozen Company Limited, Naivasha Kenya; CIP, 2017). The plant medium contains macronutrients, micro nutrients and vitamins that are necessary for plant growth (George *et al.*, 2008; Suman, 2017). The hardening process of the rooted apical cuttings is done gradually from high to low humidity and from low to high light intensity to acclimatize the plants to environmental conditions.

The production of rooted apical cuttings also involves *in vitro* procedures from selection of explants, sterilization, and establishment and shoot proliferation. They are derived from the apical meristem tips that are effective for propagation of virus free planting materials. The plantlets are rooted in hormones and plant regulators to initiate roots and shoot growth. After the shoots and roots had established the plantlets were transferred into pots containing sterilized soil for hardening process. Once the plantlets are acclimatized to the environmental conditions, they are ready for transplanting to the fields (Badoni & Chauhan, 2010; Hoque, 2010; Yasmin *et al.,* 2011). The experiments conducted in the warm tropical sites of Philippines used fine sand and clay soil mixed with rice husks for rooting of the cuttings without any hormones. They also used volcanic soils or compost that were rich in nitrogen. They also used rooting hormones but they had no statistical increase on root length and plant survival of the cuttings (Vanderzaag & Escobar, 1990). The daily average temperature of 26°C reduced the root length and shoot dry weight as compared to cool site with average daily temperature of 21°C.

The rooted apical cuttings have rapid regeneration ability and therefore increase production throughout the year irrespective of the seasons since the multiplication is done inside a controlled environment (Hossain & Nahar, 2014). Due to their ability to regenerate rapidly, rooted apical cuttings are ideal for conservation of potato seed**,** storage and distribution of the potato germplasm through breeding lines and varieties (Yasmin *et al*., 2012)**.**

Phosphorus (P) is important for early crop growth; vine growth, tuber formation and tuber bulking in potato (Hopkins *et al*., 2014; Margenot *et al.*, 2016; Nyiraneza *et al.*, 2017; Van de Wiel *et al.,* 2016;). The macronutrient is also important for tuber starch synthesis (Atkinson *et al*., 2003). In Sub Saharan Africa, there is increase decline in P availability in the soils due to soil degradation and poor agronomic practices (Margeno *et al*., 2016; Mikkelsen *et al*., 2011).
Soil pH affects the availability of essential nutrients like nitrogen, potassium, phosphorus calcium, magnesium and sulfur. These nutrients are readily available at pH range of 5.5 to 8 (Margeno *et al*., 2018). Another factor that makes P unavailable to the crops is the phosphate binding capacity of some soils with about 30% of the soils in Sub Saharan Africa (Kochian, 2012; Syers *et al*., 2008). Among crops, potato is sensitive to low phosphorus in soils due to shallow rooting system that indicates low P uptake capacity by the crop and consequently affects the phosphorus use efficiency (Gebru *et al*., 2017; Hopkins *et al.,* 2014; Thornton et al., 2014).

Increasing phosphorus use efficiency of potato genotypes is very important because there is rising demand and increased prices for phosphorus in the world (Jiang *et al*., 2019), increased environmental regulations to minimize effects of P in water quality and the problems about depletion of P mineral sources (Gebru *et al*., 2017; Thornton *et al.,* 2014). The potato varieties commonly grown in Kenya include Kenya karibu, Tigoni, Shangi, Wanjiku, Unica and Dutch Robyjn (Kaguongo, 2008; Lung'aho *et al.,* 2006). The application of optimal P rates during planting plays key role in nutrient use and it improves yield and minimizes risks of losses that potentially harm the environment (Fernandes *et al.*, 2014; Gebru *et al.*, 2017; Nyiraneza *et al*., 2017). Therefore, to increase P uptake and use efficiency by the potato crop, high rates of phosphorus applied at the root zones and as foliar fertilizer (Westerman & Kleinkopf,, 1985).

1.2 Statement of the problem

Potato production is declining in Kenya due to limited supply of quality seed and low soil fertility. Farmers plant seeds saved from previous harvests. These planting materials are degenerated due to pest and disease infestation subsequently giving low yields when planted. Rooted apical cuttings can be used as an alternative to conventional potato seeds. They produce disease free hence high quality seeds. Apart from the need to use high quality potato seeds, fertilization with optimum rates of recommended nutrients is important. Phosphorus application rates for potato growing areas of Kenya is specifically for tuber generated seed potato. Thus, there is need to establish whether the same recommendation is appropriate for increasing production of potato varieties derived from rooted apical cuttings. This has not been established for potato producing sub-counties of Molo and Njoro located in the Kenyan highlands. This study sought to determine the optimal phosphorus rates for growth, tuber yield and quality potato varieties by using seed produced from rooted apical cuttings.

1.3 Objectives

1.3.1 General Objective

To contribute to food security in Kenya by improving potato (*Solanum tuberosum* L.) production through use of rooted apical cuttings and appropriate phosphorus application rates.

1.3.2 Specific Objectives

i. To determine the effects of phosphorus application rates on growth of seed potato varieties derived from rooted apical cuttings.

ii. To determine the effects of phosphorus application rates on the yield of seed potato varieties derived from rooted apical cuttings.

iii. To evaluate the effects of phosphorus application rates on quality of potato varieties derived from rooted apical cuttings.

1.4 Hypotheses

i. Phosphorus application rate has no significant effect on the growth of seed potato varieties derived from rooted apical cuttings.

ii. Phosphorus application rate has no significant effect on the yield of seed potato varieties derived from rooted apical cuttings.

iii. Phosphorus application rate has no significant effect on the quality of potato varieties derived from rooted apical cuttings.

1.5 Justification

The use of farm saved seed tubers contributes to low potato yields as these seeds may be infested by pests and may habour disease pathogens. There is need therefore to shift from the use of conventional tubers to use of rooted apical cuttings. They are derived from the apical meristem tips that are effective for propagation of virus free planting materials. The plantlets are rooted in plant growth hormones to initiate roots and shoot growth. After the shoots and roots have established the plantlets are transferred in to pots containing sterilized soil for hardening process. Once the plantlets are acclimatized to the environmental conditions, they are ready for transplanting to the fields (Badoni & Chauhan, 2010; Hoque, 2010; Yasmin *et al.,* 2011). The cuttings can also be rooted in sand fine soils, clay soils mixed with rice husks, compost and volcanic soils that are rich in nitrogen (Vanderzaag & Escobar, 1990). The rooted apical cuttings are free from pests and diseases thus they are efficient for production of clean planting materials. The rooted apical cuttings are true to type and produce uniform planting materials thus farmers are assured of uniformity of their plants in terms of growth, yields and quality of the potato.

Low soil fertility and poor quality seed among other factors limit potato production. The application of phosphorus at the required amount and at the right time for utilization by the potato crop is key to increasing P use efficiency. Potatoes require phosphorus for optimizing tuber formation and tuber starch synthesis, thus needed to increase on the productivity. Potato is a major source of proteins, carbohydrates, vitamins and minerals and therefore important for human nutrition. They also mature fast hence important for food security. However, there is continued use of applied mineral fertilizers to boost soil fertility, blanket recommendations have been in play for a long period. This results in either excess or limited application, leading to nutrient depletion, soil degradation and risks to environmental quality. This study contributes knowledge, which may be used to increase potato production through use of rooted apical cuttings and proper nutrient management.

CHAPTER TWO
LITERATURE REVIEW

2.1 Botany of potato

Potato (*Solanum tuberosum* L.) is a herbaceous plant. It is an annual plant that belongs to the solanaceae family which also includes crops like tomatoes (*Lycopersicon esculentum*) and peppers (*Capsicum annuum*) and eggplant (*Solanum melogena*) (Belachew, 2016). Potato was first domesticated in the modern day southern Peru and northwestern Bolivia in South America (Navarre & Pavek, 2014). It was introduced in to Kenya during the 1880s and up to date is widely grown in the highland areas between 1200 – 3000 metres above sea level. The current potato production occupies 217,315 ha in Kenya, yielding 1,870,375 tonnes per year (FAO, 2018).

It is an annual dicotyledonous plant with erect stems, pinnately compound alternate leaves; stolons, roots and with specialized storage underground tubers (Navarre & Pavek, 2014). Potato is three carbon cycle (C_3) plant with ability to absorb sunlight energy and maximize photosynthesis despite the cold weather (Kumar *et al.,* 2017). Drought affects plant growth, shortens the life cycle of the plant and reduces the size and number of tubers formed (Monneveux *et al*., 2013). Other factors that affect the photosynthesis rate of the potato plants are; light intensity, day length, water and soil fertility. The effect of water stress majorly affects emergence and tuberization process of potato growth (Monneveux *et al*., 2013). Potato has five different growth stages; sprout emergence, vegetative development, tuber formation, tuber bulking and tuber maturation (Belachew, 2016). Plants have the ability to express genes that help in drought resistance and response to environmental conditions for example genes that directly protect against environmental stress and genes that regulate other genes involved in drought response (Monneveux *et al*., 2013).

Potato tubers are modified stems containing 70 to75% water content and 25 to 30% dry matter content, and have buds in the eyes of the tubers from which sprouts emerge to form new plants (Merga, 2018). These sprouts grow after a period of dormancy, which varies according to the cultivars. The main stems emerge from the potato buds and consist of other stems, stolons and tubers. Stolons are lateral stems that grow horizontally from the underground part of the stems. Stolons enlarge to form tubers at their terminal ends; however, not all of them form tubers. Stolons that are not covered by soil grow in to vertical stems and form leaves.

2.2 Importance of potato

Potato consumption is steadily increasing in the developing countries where it is widely used for human consumption, a source of income, employment and animal feed (Lutaladio & Castaldi, 2009; Toroitich, 2017). The fresh potato tubers contain about 80% water and 20% dry matter content. It contains about 18% starch as a good source of energy, 2% protein and 1% vitamins A, B, C, D and E (Lutaladio & Castaldi, 2009; Zewide *et al*., 2016). It is low in fat and rich in several micronutrients (Riungu, 2011). Potato has high vitamin C that increases iron absorption. It has vitamins like vitamin B1, B3 and B6, and minerals like potassium, phosphorus and magnesium. Potato is considered a medicinal herb for stomach ulcers and stomach acidity. It is also rich in plant polyphenols that offer protection against development of cancers, cardiovascular diseases, diabetes, osteoporosis and neurodegenerative diseases thus their consumption is beneficial to human health (Pandey & Rizvi, 2009). It also contains folate pantothenic acid, riboflavin and dietary oxidants that help the body to fight chronic diseases (Burlingame *et al*., 2009). The potato is used in a variety of ways as food; such as chips, crisps, fried or boiled. It can be processed in to potato powder and alcohol brewing (Ekin, 2011; Toroitich, 2017).

2.3 Overview of potato production in Kenya

Potato is the second most important crop after maize in Kenya (Janssens *et al.,* 2013) and is important for national food and nutritional security. It is cultivated mostly by small scale farmers totaling up to 800,000 on acreage of 158,000 hectares, with potato production yields between 7-10 tonnes ha^{-1} as compared to attainable 20 tonnes ha^{-1} in Egypt and 40 tonnes ha^{-1} in the Netherlands (Muthoni *et al*., 2013; Rosen *et al*., 2014). The potato industry provides employment, income, contributes to poverty alleviation and facilitates economic growth (Abong *et al*., 2015). Many Kenyans are employed in the potato value chain that acts as a source of livelihood for small scale-farmers (Kaguongo *et al*., 2010; Lung'aho *et al*., 2006).

The potato varieties commonly grown in Kenya are varied in numbers but farmers select them according to disease resistance, tuber dormancy, soil types, maturity period, yield potential and taste (Kaguongo, 2017). The commonly grown varieties are Shangi, Jelly, Kenya karibu, Kenya sifa, Annet, Wanjiku, Unica, Dutch Robyjn, because they are easy to cook and good for making chips and crisps (Kaguongo *et al*., 2008). According to Kaguongo (2017), the classification of potato varieties based on maturity gives three types of varieties. These include early, medium and late maturing varieties. Among the early maturing varieties that take, less than 90 days include Dutch Robyjn, Unica and Shangi. Among the medium maturing varieties that take between 90 to 120 days include, Kenya Baraka, Kenya karibu, Kenya mpya, Sherekea and Wanjiku. The late maturing varieties that take more than 4 months include Tigoni, Jelly, Kenya mavuno and Markies. Currently, there are 56 potato varieties of different maturity periods, disease resistance grown in different areas of Kenya.

Small-scale farmers with less than 1 hectare of land (Toroitich, 2017) mainly carry out potato production. The following diseases affect it; bacterial wilt (*Ralstonia solanacearum*), late blight (*Phytopthora infestans*), early blight (*Alternaria solani*), soft rot and potato leaf roll virus (Champoiseau *et al.,* 2010; Muthoni *et al*., 2013; Toroitich, 2017). Integrated methods are employed to control the diseases including use of resistant varieties, intercropping, crop rotation, use of clean planting materials, field sanitization, certified seeds and application of preventive fungicides to control the pathogens and vectors of diseases. Late blight is seed borne and air borne disease that affects the tubers when fungus is washed off the leaves and zoospores are carried down in to the soil (Toroitich, 2017). Late blight and bacterial wilt have drastic effect on the crop yields and can cause between 50 -100% yield losses if not properly managed (Champoiseau *et al.,* 2010).

2.4 Overview of potato propagation methods

Currently, the common method for propagation of potato in Kenya is use of tubers. The main source of seed is from recycled or own seed from previous harvest due to limited supply of the certified seed (Kaguongo *et al*., 2010). Kenya produces less than 1% of the certified potato seed and this shortage of clean planting materials leads to use of uncertified seed that result in buildup of pests and diseases that lead to low yields (Tsoka *et al*., 2012). Quality seed is the key to increasing the productivity of the potato crop, thus various methods and technologies are introduced to increase multiplication and production of clean quality seed. They include rapid multiplication techniques, tissue culture techniques and minituber production using aeroponics (Chindi *et al*., 2013). The new technologies give extensive production of healthy planting materials in a very short time. The rooted apical cuttings are the easiest and cheapest means to propagate potato crop. They regenerate faster which gives them great potential for conservation of potato clones and production of seed, true to type and free from pathogens (Tsoka *et al*., 2012). The rooted apical cuttings serve as the basic means for production of basic seed under strict management like aeroponics.

2.5 Environmental requirements of potato

Genotype x environment interactions are conditions in which environmental factors affect characters differently depending on the genotype. The genotypes respond to diseases, temperature changes, solar radiation and rainfall and soil moisture differently (Hassanpanah, *et al*., 2009). Researchers in Sub Saharan Africa have focused on identifying genotypes that are high yielding, disease resistant and highly adaptive to the environment (Abalo *et al*., 2003; Asfaw *et al*., 2015; Ewell, 2002). Genotype and environment interactions show important variations in crop yields. The ability of the genotype to give relatively constant yield irrespective of the environmental changes are termed as stability genotypes (Hassanpanah *et al*., 2009).

2.5.1 Temperature and altitude

In Kenya, potato cultivation is carried out in the highland areas with temperature range of 15 to 25°C (Toroitich, 2017). It grows well with mean day temperatures ranging between 20°C to 25°C conducive for vegetative growth and night temperatures between 15°C to 20°C good for tuber initiation (Kooman & Haverkort, 1995; FarmLink Kenya). Tuber initiation and development is inhibited when temperatures go below 10°C and above 30°C. Tuber initiation is delayed by high temperatures. The optimum temperatures of 15-25°C increase the number of tubers as compared to high temperatures of 34°C that hinder growth of tubers (Belachew, 2016).

The ideal areas for production of potato are the Kenyan highlands at altitudes of 1500 to 3000 meters above sea level that have favourable climate and soils for the growth and development of potatoes (Janssens *et al.,* 2013). The high altitude areas have cool temperatures that make potatoes to emerge rapidly as compared to the warmer temperatures in the low altitude areas (Komen *et al.,* 2018). Temperature also affect the rate of emergence, shoot and root growth, tuber initiation and tuber growth (Kooman & Haverkort, 1995).

2.5.2 Rainfall

The Kenyan highland areas receive bimodal rainfall system that makes it possible for farmers to produce potato crop twice a year. The long rainy season lasts from March/April to June/July and the short rainy seasons from October to December (Janssens *et al*., 2013). The potato crop grows well at areas that receive regular rainfall of 850mm to 1400mm per annum. The potato plant is predominantly rain fed and thus susceptible to climatic hazards like drought, frost, excessive rainfall and hailstorms (Horton, 1988). The growth of potato is favoured by high rainfall amounts and can be supplemented by use of irrigation. However most farmers use irrigation for high value crops like vegetables and flowers and depend entirely on rainfall for production of potato and surplus production would occur during seasons with high rainfall (Janssens *et al*., 2013; Kaguongo *et al.,* 2010; Lung'aho *et al*., 2006).

2.5.3 Soils

The loose loamy soils and sandy soils that are well aerated, good drainage and contain organic matter with pH range of 5- 6.5 are ideal for production of potato crop (Janssens *et al*., 2013). The potato crop requires permeable soil layers that allow proper growth of the roots. Soil moisture, soil temperature and type of variety influence the time for emergence and the establishment of the plants in the field. The major constraint in potato production in Kenya is low soil fertility characterized by application of fertilizers with blanket recommendations that increases soil acidity. The continued use of Diammonium phosphate (DAP) fertilizer by potato farmers at low recommended rates increases the acidity levels and this is compounded by the volcanic origin of the soils in the highland areas (Janssens *et al*., 2013). The soils of volcanic acidic rocks are heavily leached by rainfall and have low soil pH that affects the availability of nutrients like potassium, phosphorus, nitrogen, Sulphur, calcium and magnesium and makes aluminium, manganese, boron, iron and zinc readily available to the crops. The low soil pH causes nutrient imbalance in the soil and subsequently affects the growth of crops and yields (Janssens *et al*., 2013; Stewart *et al*., 2020).

2.6 Role of nutrients in potato production

The supply of the right nutrients, at the right time, at the right place and at the right amounts is important in improving crop yields and protecting the environment from contamination and soil degradation (Fixen & Bruulsema, 2014; Margenot *et al*., 2016; Thornton *et al.,* 2014; Westermann, 2005). There are 16 nutrients that are essential for proper growth of the potato crop. These nutrients are characterized by: ability to be present during the life cycle of the crop, the metabolic role of the element should be replaced by another nutrient and ability to be involved directly in the metabolic processes of plants or act as compound components involved in the process. The 13 nutrients can be supplied to the plants through soil and fertilizer sources, while carbon, hydrogen and oxygen plants can access from air and water (Westermann, 2005). Therefore, to increase crop yields and soil health it is important to maintain soil fertility levels (Stewart *et al*., 2020).

Soil P deficiency is widely reported in the Sub Saharan African soils of smallholder farmers caused by soil acidity and degradation. A study conducted in western Kenya reported that 92% of the soils are deficient in P (<20ppm) (Mikkelsen, 2015). Phosphorus deficiency in potato plants is manifested by elongation of the leaflets associated with deformation of the leaf margins, brownish spots, and dark green appearance of the leaf nodes. It can also lead to stunted growth of the plants characterized with thin stems and curling of the leaves (Koch *et al*., 2020). It is important to carry out soil testing and tissue analysis using Mehlich method to determine phosphorus requirements during the season (Rosen *et al.*, 2014). Determination of nutrient requirements is important because it influences yield maximization in potato production and other crops (Singh & Lallawmkima, 2018).

2.6.1 Role of phosphorus in potato establishment and plant growth

Phosphorus is a second limiting nutrient in potato growth and important in cells of living organisms (Hopkins *et al*. 2014; Mikkelsen *et al*., 2014; Rosen *et al.* 2014). It plays prominent role in cellular energy transfer process in the form of phosphorylated sugars, alcohols and lipids (Westermann, 2005). It aids conversion of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) (Koch *et al*., 2020). Adequate phosphorus is important for early root and shoot development (Hopkins *et al*., 2014; Jenkins & Ali, 2000). Phosphorus increases growth rate of all plant parts for some weeks after emergence and improves on canopy development and leaf size though the leaf number may not be affected (Shunka *et al*., 2017). Appropriate amounts of phosphorus will provide energy for ion uptake and transport during the early stages of growth to facilitate proper crop growth and reproduction (Hopkins *et al.,* 2014). Adequate supply of phosphorus during early stages of growth is important because it plays a role in formation of structural components of phospholipids, nucleic acids, coenzymes and phosphoproteins that store nutrients in seeds in the form of phytic acid (Rosen *et al*., 2014).

2.6.2 Role of phosphorus in tuberization and yield

Potato yields can be increased through timely application and proper management of macro nutrients (Shunka *et al.,* 2017). Timely application of phosphorus (P) promotes early tuber development, increases tuber number and tuber size (Jenkins & Ali, 2000; Koch *et al*., 2020). P applied at later growth stages improves tuber maturity (Rosen *et al*., 2014). Having adequate knowledge of plant mineral requirement is important for best practices in application and management in order to achieve better yields and increase plant resistances to diseases (Singh & Lallawmkima, 2018).

2.6.3 Role of phosphorus in nutritional composition of tubers

The highest percentage dry matter of potato tuber is composed of 75% carbohydrates and starch has the highest ratio (Nauman *et al*., 2020). Increase for phosphorus in the soil leads to high concentration amount of P in the potato tubers that contributes to accumulation of amylose content and starch pasting properties like viscosity (Leonel *et al*., 2017). According to Leonel *et al*. (2017), the increase in the application of P led to increase in the dry matter content, lower total sugar content and high contents of starch and proteins. Thus, phosphorus contributes to the high nutritional content and quality of ware potato tubers.

2.7 Phosphorus use efficiency by potatoes

Phosphorus efficiency is defined as yield increase as per kilogram amount of phosphorus fertilizer applied. Phosphorus use efficiency (PUE) is the ability of the plants to produce biomass or economic product for example tubers (Hopkins *et al*., 2014; Nyiraneza *et al*., 2017; Soratto *et al.,* 2015; Thornton *et al*., 2014). P uptake is the ability of the plants to take up P in the soil (Soratto *et al*., 2015). Potato plants have shallow roots as compared to cereals and legumes and thus they are sensitive to soils with deficient phosphorus (Fixen & Bruulsema, 2014; Hopkins *et al.,* 2014; Thornton *et al*., 2014). Phosphorus is a limited mineral with high demand for crop production therefore its use efficiency must be improved to minimize wastage (Jiang *et al*., 2019; Mikkelsen, 2015; Mikkelsen *et al*., 2014). The differences in phosphorus utilization efficiency have been reported to be influenced by cultivar characteristics such as root weight, root length and diameter (Bayuelo & Ochoa, 2014; Fernandes *et al*., 2014; Wishart *et al*., 2013).

In order to improve phosphorus use efficiency, several practices have been undertaken. The rhizosphere modifications such as raising the bulk pH of acid soils from 5.5 to 6.5 to reduce acidity levels (Nyiraneza *et al*., 2017), the placement of fertilizer in the rhizosphere by broad cast incorporation, use of slow and controlled release of phosphorus fertilizer (Hopkins *et al*., 2014). Organic acids and acid polymers can be used to increase phosphorus solubility in alkaline soils through extending the effective rhizosphere zone that fosters root growth through promotion of mycorrhiza development (Nyiraneza *et al*., 2017).

Cultural practices were improving on the availability of the nutrient to the plant, application of the right rate of phosphorus basing on the environmental conditions and requirements of the soil (Islam & Nahar, 2012; Mikkelsen, 2015; Stewart *et al.*, 2020), And right timing to ensure peak nutrient availability during the time of greatest uptake by plants (Fixen & Bruulsema, 2014). Applying nutrients at the root zones to provide high concentration around the roots for easy absorption by the plant roots and the use of products that are soluble and have slow release patterns that are conducive for plant uptake (Hopkins *et al*., 2014; Westermann, 2005).

2.8 Effect of phosphorus application rates on growth of potato

The balanced application of macronutrients is important in improving crop growth and development (Stewart *et al*., 2020). Nitrogen, phosphorus, potassium, magnesium, manganese, calcium, zinc and iron are all reported to have influence on the rate of crop growth (Margenot *et al*., 2016). Potato crop requires adequate phosphorus for optimum growth and yield. It is essential for early crop establishment (Balemi, 2009; Chala *et al.,* 2017; Gaur *et al*., 2018; Jenkins & Ali, 2000).

Plant biomass production increases with application of phosphorus (Alvarez-Sanchez *et al*., 1999; Balemi, 2009). Adequate application of P influences total leaf area that increases light interception by the crops and this contributes directly to biomass accumulation (Alvarez-Sanchez *et al*., 1999; Jenkins & Ali, 2000; Zelalem *et al*., 2009). According to Zewide *et al*. (2012), adequate application of P_2O_5 significantly increased the above ground biomass by 8.78% and underground biomass by 61.4%. The accumulation of biomass varies amongst the varieties that are grown for example Jalene variety that was grown in this experiment showed the highest accumulation of biomass with application of nitrogen and phosphorus (Misgina, 2016; Zelalem *et al*., 2009). The amount of radiation intercepted by the plants alters canopy development and photosynthesis rate. The potato is sensitive to light energy in order to increase normal stem elongation and leaf expansion that contribute to biomass (Moorby, 1978).

2.8.1 Number of stems

Potato plants are made up of more than one stem and each stem has potential to increase on the number of tubers obtained from the plant (Belachew, 2016). Phosphorus is essential for canopy formation and through increase in the number of stems leads to formation of thick canopy cover. This enables the plant to intercept radiation optimally resulting in high productivity. The increase in phosphorus levels increases on the number of stems (Chala *et al*., 2017). There was positive response of number of stems per plant on P application (Baishya *et al*., 2012; Kumar *et al*., 2017; Misgina, 2016) reported same results.

Rooted apical cuttings regenerate faster therefore they increase the number of stems on each plant which directly corresponds with tuber yield (CIP, 2017; Tsoka *et al*., 2012). The low P amounts led to reduced number of stems that affects light interception thus limited plant growth (Balemi, 2009). However, limited research is done on the growth response of rooted apical cuttings to phosphorus rates grown in the fields.

2.8.2 Plant height

The plant height increases with age of the plants. Application of P increases the growth of plants (Balemi, 2009; Powon *et al*., 2006). Apical cuttings reported significantly high plant height as compared to the tissue culture plantlets (Tsoka *et al*., 2012). According to Gaur *et al.* (2017), they reported that the rate of plant height increase was high at 30 days after planting as compared to 60 days after planting until maturity of the plants. After maturity, the plants have reached senescence and their height declined. This study agrees with the findings of Zelalem *et al*., 2009, who reported that increase in the amount of P_2O_5 applied on potato plants increased the plant height. In a study at Holleta research center in Ethiopia by Shunka *et al*. (2017) that used nitrogen and potassium nutrients, they reported that the interaction of nitrogen and potassium significantly affected the plant height and marketable tuber numbers. Phosphorus availability is vital in early development of plants and thus its application increases on the growth of plants and thus plant height is increased (Baishya *et al.,* 2012; Israel *et al*., 2012; Kumar *et al*., 2012).

2.8.3 Days to 50% flowering

A study by Zewide *et al*. (2012), reported that the application of 60 kg P ha^{-1} significantly increased days to flowering by 3 days while application of 165kgNO^{-}_{3} ha^{-1} significantly increased days to flowering by 6 days. The application of phosphorus fastens the growth of the plants by availing the nutrient required for the physiological growth and this makes the plants to flower at faster rate. The application of potassium and phosphorus in study by Misgina, (2016), showed that P application prolonged the days to 50 % flowering of the plants. And the interaction of potassium and phosphorus did not significantly influence the days to 50% flowering of the plants. However, research by Zelalem *et al*. (2009), reported that P application increased the days to 50% flowering of the potato plants.

2.8.4 Days to 50% physiological maturity

The physiological maturity in potato is attained when the leaves of the plants turn yellow. The varieties with early maturity are important for food security and generate incomes early to meet the financial needs. In places with limited rainfall, the early maturing varieties reach maturity faster before the onset of drought (Kaguongo *et al.,* 2010). According to Chala *et al*. (2017), the control treatment that had no treatment showed the highest number of days taken by the plants to reach flowering and physiological maturity. Phosphorus fertilizer prolonged the days to physiological maturity of the plants (Misgina, 2016).

2.9 Effects of phosphorus application rates on the yield of potato varieties

The potato plant requires optimum nutrients to maximize growth to attain the optimum yield, thus study by Belachew, (2016) reported that application of 60kg phosphorus increased tuber yield by 43.5% over the control treatment. Potato yields can be increased through timely application of phosphorus because it promotes early tuber development, increases tuber number and tuber size

(Jenkins & Ali, 2000; Koch *et al*., 2020; Shunka *et al.,* 2017). Phosphorus applied at later growth stages improves tuber maturity and internal quality traits (Rosen *et al*., 2014; Singh & Lallawmkima, 2018).

The yield of potato is dependent on the variety and growth conditions that prevail during the season. Chala *et al*. (2017) also added that the increase in phosphorus rates up to 115kg P_2O_5 ha^{-1} led to increase on total tuber yield, marketable yield and tuber weight. However, Shunka *et al.,* 2017) observed that season and location has a major effect on the total tuber number and weight of potatoes.

2.9.1 Number of tubers per plant

Tuberization is controlled by both environmental and endogenous factors; it is highly favoured by cool temperatures, short photoperiods, and low levels of nitrogen fertilizer. It is reported that short days and long nights enhance the formation of tubers (Johansen *et al*., 2002). Phosphorus deficiency delays tuber initiation and tuber formation, however the number of tubers obtained per plant depends on the other environmental factors are constant (Alvarez-Sanchez *et al*., 1999; Westermann and Kleinkorf, 1985). The number of stems per plant increase the light interception and biomass accumulation which contribute to the tuber yield at the end of the season (Belachew, 2016; Jenkins & Ali, 2000). Increasing the application of phosphorus increases on the number of tubers per hill (Gaur *et al*., 2017; Powon *et al*., 2006). According to Kawakami *et al.* (2012), the availability of phosphorus to the roots of the plant shortens the tuber formation process and many tubers are formed. According Tsoka *et al*. (2012), apical cuttings gave less number of tubers as compared to the in-vitro plantlets.

2.9.2 Tuber weight

The tuber weight significantly increased with increase in P (Gaur *et al*., 2017; Zelalem *et al.,* 2009). The increase in tuber weight due to P application over the control treatment is because of improved growth and physiological parameters. These favourable conditions lead to increased accumulation of carbohydrates, proteins and they are translocated from source to the sink hence increase in tuber weight (Chala *et al*., 2017; Gaur *et al.,* 2017). Increase in tuber weight is also associated with greater portioning of the metabolites and adequate translocation of the photosynthates to the reproductive plant structures (Gaur *et al*., 2017). The rainfall received in the area and quality of seeds planted also contribute to the size and weight of the tubers that will be harvested (Rosen *et al*., 2014). The study by Eleiwa *et al*. (2012) that used NPK fertilizer reported that there was increased tuber weight.

2.9.3 Tuber size

Tuber size is also affected by variety, soil fertility and environmental factors. The ideal tuber size should be moderate and uniform (Merga, 2018). There is increased formation of medium sized tubers due to increase in phosphorus application (Gitari *et al.,* 2018). Phosphorus is known for increasing number of tubers that are formed by the plant but have minimum effect on the size of tubers. Grading of potato seeds to grades of large size, medium size, small size and chants is important because it's reported to affect the seedling growth vigor, emergence and the yield of the crop. The small size tubers are considered good quality seed (Lung'aho *et al*., 2006). The size of tubers is dependent on the amount of nutrients that are utilized by the crop and synthesized to form tubers (Gaur *et al*., 2017; Rosen *et al.,* 2014).

2.9.4 Marketable tuber yield

Increasing phosphorus rate increases total tuber number, marketable tuber number and average tuber weight apart from unmarketable tuber numbers, this is because of the ability of potato to take up more nutrients as compared to other tuber crops (Chala *et al.,* 2017). They also added that increase in average tuber number is due to the increased photosynthetic activity and translocation of photosynthetic to the root, which might have helped in the initiation of more stolons in potato. The interaction effect of 165kg of N and 60kg P_2O_5 increased marketable tuber yield to 36 tonnes ha^{-1} by 122% as compared to control that recorded 16.2 tonnes ha^{-1}. Availability of conducive environmental conditions and adequate nutrients influence formation of marketable tuber yields (Chala *et al*., 2017; Gaur *et al.,* 2017).

2.9.5 Number of eyes

The selection of seed potato depends on the number of eyes per tuber and this determines the germination ability and growth vigor of the potato plants (Lung'aho *et al*., 2006). The higher the number of sprouts in the tubers and the deeper the sprouts the higher the germination rate of the potato in the field (Kaguongo *et al*., 2008). Number of eyes in the potato tuber is one of the factors considered in selection of good quality seed (Chindi *et al*., 2013). The tubers with manynumber of eyes are considered high quality seed with high germination ability (Kaguongo *et al*., 2010).

2.10 Effect of phosphorus rates on dry matter content, starch content and specific gravity of potato varieties

The internal quality traits of potato are influenced by variety, environmental conditions, cultural practices and fertilizer application (Abong *et al*., 2015; Mohammed, 2016; Öztürk *et al*., 2010). Temperature and day length influence the dry matter content through growth of the plants (Kooman & Haverkort, 1995). Other researchers reported significant differences in tuber internal traits due to varieties (Abebe *et al*., 2013; Hassanpanah *et al*., 2011). Fresh harvested potatoes contain about 80% water and 20% dry matter (Belachew, 2016). Dry matter contents help to determine the quality of potatoes both for cooking and for processing.

The study by Misgina, (2016) reported that with increase in the P rates, the dry matter content of the potato tubers reduced significantly had no significant effect on the starch content of potato tubers, however the combination of PK increased the starch content. Application of phosphorus in deficient soils improves on the tuber specific gravity and dry matter because it increases starch synthesis and fastens maturity (Laboski & Kelling, 2007).

In this study of Kingori *et al.* (2015), application of nitrogen and phosphorus beyond 112.5kg NO_3 ha^{-1} and 75.9kgP ha^{-1} respectively reduced the starch contents. The tuber specific gravity is affected by soil factors like salinity; the soils that have high indices of salt lower the specific gravity of tubers (Zelalem *et al.,* 2009). The potato tubers with low specific gravity are used for canning process (Khan *et al*., 2010).

In conclusion, it is evident that potato requires macro and micro nutrients to achieve proper growth and development. While previous studies have been on use of conventional tubers and phosphorus fertilizer on growth of potato, this study looked at growth, yield and quality response of potato varieties propagated from rooted apical cuttings to different phosphorus rates. To achieve maximum yield of potato and to get good quality seed potato it requires proper application of the essential nutrients because excessive or limited plant nutrition can reduce tuber bulking and quality of potatoes (Nand *et al.,* 2011).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental site

The study was conducted concurrently at three study sites (Fig.1) between the months of September 2019 and January 2020. The first study site was Egerton University agricultural experimental field (35° 35' E; 0° 23’ S) which is located in Njoro, Nakuru County, Kenya, at an altitude of 2200 m above sea level (masl). The University experiences a tropical climate and the annual mean temperatures range between 15℃ to 21℃ (Climatic data.org, 2019). The area receives an annual rainfall of 1132.2 mm and soils are predominantly sandy loam, well drained and dark brown in colour (Jaetzold *et al*., 2012).

The second study site was at Mathangauta farm, in Mauche, Njoro, Nakuru County Kenya (-0.50022^{O}S, 35.97389^{O}E). Its altitude ranges from 2100 to 2800m above sea level and receives an annual rainfall of 985mm with annual mean temperature range between 11 to 16℃ (Climatic data.org, 2019). The site is characterized by loam soil which are moderately well drained, reddish brown with low fertility (Jaetzold *et al*., 2012).

The third study site was at the Kenya Agricultural Livestock and Research Organization (KALRO), located in Molo (35.7373° E; 0.2472° S), Nakuru County, Kenya. The area receives an average rainfall of 1100mm to 1500mm annually and is located at an altitude of 2500masl. The annual mean temperatures range between 15℃ to 25℃ (Climatic data.org, 2019). The site is characterized by loam soils which are moderately well drained, reddish brown with low fertility (Jaetzold *et al.,* 2012).

3.2 Soil sample collection and analysis

Soil samples were collected before experimental setup from the three sites for initial characterization of chemical and physical properties. The soils were collected using a soil auger from six locations in a zigzag pattern, from three depths (0-15, 15-30, 30-45cm) and composited. The soil was subjected to chemical analysis to determine pH, organic carbon, available phosphorus, cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K) and total nitrogen.

The physical properties determined were texture and bulk density. Soil analysis was done at KALRO Kabete, laboratories using the following methods:

3.2.1 Determination of soil pH

Soil pH was determined using the electrometric method with 1:2.5 ratio of soil: water (Mehlich *et al.,* 1962). The soil sample was air dried and passed through 2mm sieve then 20gms of the soil was weighed and put in clean plastic bottles. Distilled water (50ml) was added into each bottle and solution shaken for 1 hour. The solution was allowed to settle for 30 minutes and the reading on the pH meter was taken. The pH meter is make of Jenway UK, mode 3510 pH meter.

3.2.2 Determination of soil organic carbon

Soil organic carbon was determined using the Walkley Black method (Anderson and Ingram, 1993). The air dried soil sample was passed through < 0.5 mm sieve. It was oxidized by acidified dichromate at 150^0 C for 30 minutes to ensure complete oxidation. Barium chloride was added to the cool digest. After mixing thoroughly digest was allowed to stand overnight. The carbon concentration was determined using the spectrophotometer made by Analytik Jena, Germany mode SPEKOL 1500 at 600 nm.

3.2.3 Determination of available phosphorus

The Mehlich method also known as the dilute double acid method was used for determining the amount of available phosphorus in the soil (Mehlich *et al.,* 1962). The air dried soil samples were passed through 2mm sieve. The 0.5gms sample was extracted in a 1:5 ratios (w/v) with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. The mixture was put on the rotary shaker for 30 minutes at 180 rpm and at room temperature. After that time the mixtures were filtered using filter papers to get the filtrate which was analyzed for phosphorus using the blank and P standard prepared from the Mehlich solution and absorbance was read from the spectrophotometer made by Analytik Jena, Germany mode SPEKOL 1500 at wavelength of 882nm.

3.2.4 Determination of cation exchange capacity (CEC)

The CEC of the soil samples was determined using Metson method which uses normal ammonium acetate as the exchange solution at pH 7 (Page *et al*., 1982). The exchange solution leaches out all the cations in a soil. Excess NH_4^+ was removed with an organic solvent (alcohol). A potassium (K^+) salt solution was used to replace and leach out adsorbed NH_4^+ ions. The CEC was determined by distillation followed by titration with 0.01 *N* HCl.

3.2.5 Determination of K, Ca and Mg

The Mehlich extraction method was used to determine available K, Ca, Mg (Mehlich *et al.,* 1962). The air dried soil samples were passed through 2mm sieve. The 0.5gms sample was extracted in a 1:5 ratios (w/v) with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. Ca and K were determined using a flame photometer made by corning 400 UK mode M400, and Mg was determined using a spectrophotometer made by Analytik Jena, Germany mode SPEKOL 1500.

3.2.6 Determination of total Nitrogen

The Kjeldahl method was used in the determination of the total nitrogen in the soil samples (Page *et al*., 1982). The air dried soil samples (< 0.5 mm) were digested with concentrated sulphuric acid containing potassium sulphate, selenium and copper sulphate hydrated at approximately 350^0 C. Total N is determined by distillation followed by titration with diluted standardized H_2SO_4.

3.2.7 Determination of soil texture

The air dried soil sample was passed through 2mm sieve to get fine soil. The 50g of soil sample was passed through < 2 mm sieve, weighed and transferred into a 500-ml plastic shaking bottle. 300 ml of distilled water and 50 ml of dispersion agent (Calgon) were added and shaken overnight. After shaking the soil suspension was transferred into sedimentation cylinder and topped up to the 1 L mark. It was then mixed thoroughly with a plunger to bring the soil particles into suspension. The temperature of the suspension was observed and recorded. A hydrometer was lowered into the solution and a reading taken and recorded 40 seconds after stirring ceased. After 2 hours a second reading was taken. The first hydrometer reading gives percentage for silt and clay. The second reading gives the density of clay particles and was calculated. After getting the percentage sand, silt and clay, a textural classification chart was used to classify the soil (Fig. 2).

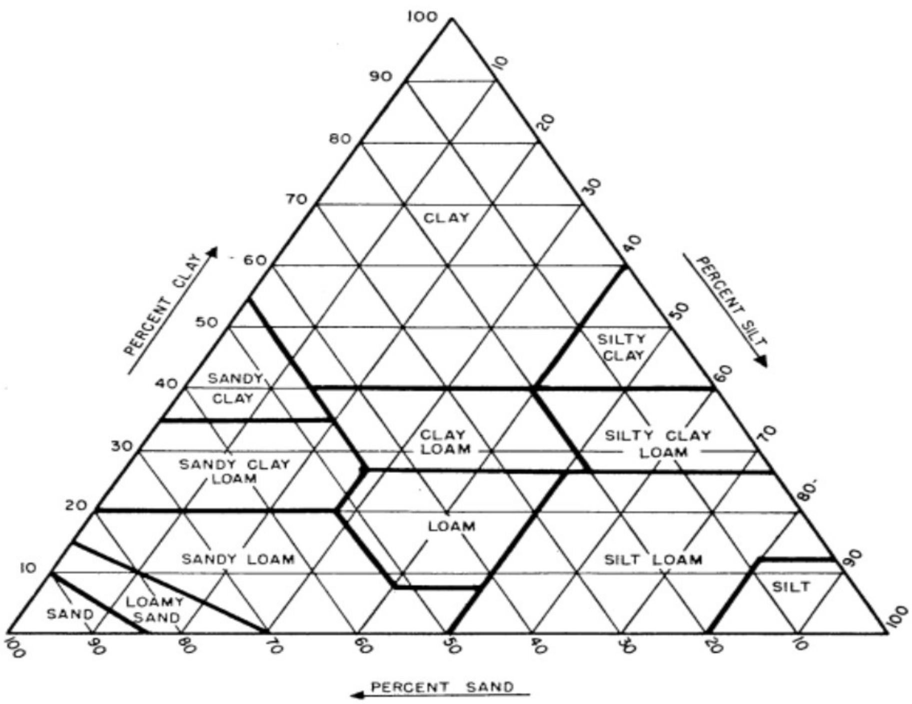

Figure 1: Soil textural classification chart

3.2.8 Determination of bulk density

Soil bulk density was determined using the core ring method (Anderson *et al*., 1988). This involved driving the core metals in to the soil at the desired depth. The samples were dried in an oven and weighed. Soil bulk density is inversely related to soil porosity. The more the pore spaces in the soil the less the value of the bulk density.

The bulk density was calculated as:

$$\rho b = \frac{Ms}{Vt} \text{ ....Equation 1}$$

Where, ρb is the soil bulk density, Ms is the mass of the soil and Vt is the volume of the core used.

3.3 Germplasm

The potato rooted apical cuttings were obtained from Stokman Rozen Company located in Naivasha, Kenya. The study used four varieties: Shangi, Dutch Robyjn, Unica and Wanjiku (Fig 3). Shangi attains maturity within three months and is moderately susceptible to late blight. It is table variety and good for making chips. The tubers are oval shaped with smooth cream skin, white flesh and medium to deep eyes.

Dutch Robyjn takes three to four months to attain maturity. It is moderately resistant to late blight and good for crisping. The tubers are round shaped with rough red skin, pale yellow flesh and medium deep eyes.

Unica is medium tall variety with strong semi erect stems and dark green medium sized leaves. It has pink flowers which bloom profusely. It takes three months to attain maturity. It is moderately resistant to late blight and highly tolerant to the potato virus X and potato leaf roll virus. Its table variety and good for making chips with good combining flavour, texture and appearance. They are oblong tubers with a red skin, cream flesh and shallow eyes.

Wanjiku takes three to four months to attain maturity. It is tolerant to late blight, potato virus X and potato virus Y. It is good for crisps and chips. The tubers are oblong shaped with white cream skin, cream flesh and shallow pinkish eyes (Fig 3) (Kaguongo *et al*., 2017)**.**

Plate A: Potato variety Shangi

Plate B: Potato variety Dutch Robyjn

 Plate C: Potato variety Unica	 Plate D: Potato variety Wanjiku

Figure 2: Potato varieties used in the study

3.4 Experimental design and treatments

The experiment was conducted using randomized complete block design (RCBD) in split plot arrangement, with three replicates. The main plots consisted of four potato varieties (Shangi, Dutch Robyjn, Unica and Wanjiku*)* and the subplots were four levels of phosphorus (0, 30, 60, 90 kg P ha^{-1}) giving 16 treatment combinations (Fig 4). The treatments were randomly assigned to main plots and subplots.

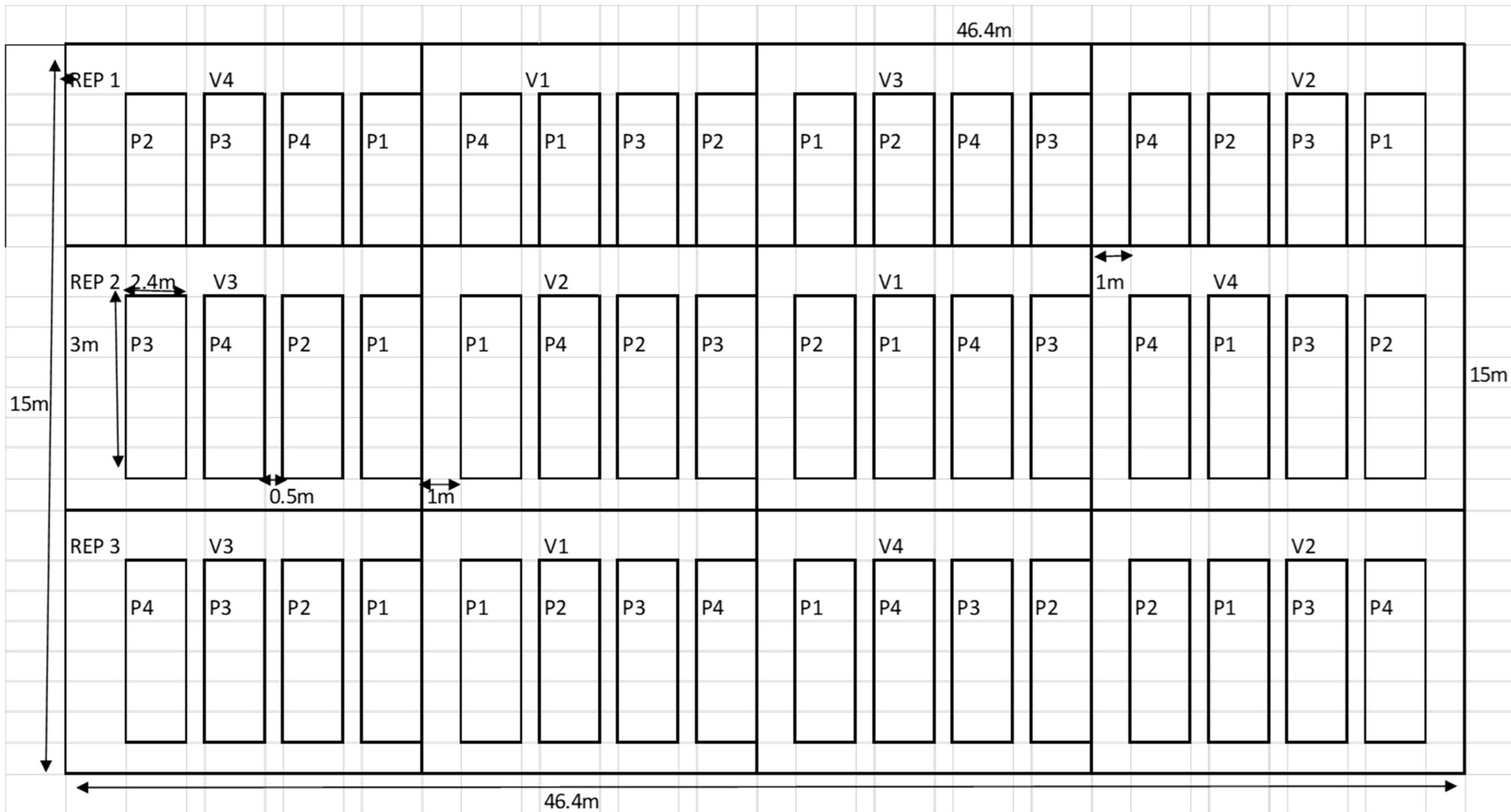

Figure 3. Experimental lay out

Key: V1 Shangi, V2 Dutch Robyjn, V3 Unica, and V4 Wanjiku P1 0 kg P ha^{-1}, P2 30kg P ha^{-1}, P3 60kg P ha^{-1}, P4 90k

3.4.1 Land preparation and planting

Land preparation was carried out in September 2019. This involved ploughing and harrowing to obtain fine tilth for planting of the rooted apical cuttings. The rooted apical cuttings were planted at spacing of 75cm between plants and 35cm between rows giving 24 plants per plot to obtain the maximum plant population for proper sampling (Lung'aho *et al*., 2006). The plot size was 3m by 2.4m between blocks with a footpath of 1m between plots. There were 4 rows of plants and random plants in the two middle rows were tagged for sampling measurements. Data collection was non-destructive. The guard rows were made up of five lines of potato plants on all sides around the experimental plot.

3.4.2 Experimental management

Triple super phosphate fertilizer was applied to the soil by banding, according to the treatments (0, 30, 60, 90 kg P ha^{-1}) and thoroughly mixed with the soil. Urea (46% N) fertilizer was applied in all plots two splits; during the vegetative stage and tuber initiation, thus supplying 50 kg N ha^{-1}. Muriate of Potash (30 kg K ha^{-1}) was applied during planting of potatoes in all plots to supply potassium.

After two weeks of planting, mounding was done to cover the roots and to conserve moisture around the rooted apical cuttings. Weeding was carried out by hand twice during the vegetative stage of the plants to reduce weeds competition with the plants for nutrients and remove alternative hosts for pests. Earthing up was done at stage three prior to tuber initiation or early flowering to promote moisture conservation to encourage tuberization and to prevent exposure of the tubers to direct light. Pests like cut worms (*Agrotis segetum*) were controlled by application of Alpha Cypermethrin (Tata Alpha 10 EC-15ml/20 litres water) which is systematically translocated. It was applied immediately after planting. Diseases like late blight (*Phytopthora infestans*) were controlled by spraying with protective fungicide Ridomil gold ^{R} (Metalaxyl 40g/kg + Mancozeb 640g/kg) at a dose of 40gms per 20 litres water every fortnight until plants attained 50% physiological maturity.

3.4.3 Data collection

a. Growth parameters

Plant survival was counted fourteen days after planting (DAP). Number of stems per plant were counted from five plants in the middle rows of each plot. Plant height was measured using a ruler from the base of the main plant to the apex of the shoot. These measurements were started at 14 DAP and repeated every fortnightly up to 56 DAP. Days to 50% flowering were determined by counting the number of plants in each plot that had attained 50 % flowering. Days to 50% physiological maturity was noted when the leaves started to yellow.

b. Yield components

Data on plant shoot biomass were determined by obtaining the mean fresh weight of five plants in the middle rows during harvesting. After harvesting the number of tubers obtained from each hill of the sampled plants was counted. The tubers from the five plants were weighed and graded according to sizes to determine the marketable tuber yield. Tubers were classified into three size grades; large at >60mm, medium at 30-60mm and small <30mm in diameter. Tubers were randomly picked from each plot and number of sprouts/eyes in each tuber were counted.

c. Quality parameters

Tubers were randomly picked and washed. A sample of 500gm was taken and dried in an oven at 105°C for 72 hours to determine the dry matter content (Bewell, 1937). The dry matter was then calculated as follows:

$$\text{Dry matter} = \frac{\text{weight of sample after drying}}{\text{Initial weight of sample}}\ x\ 100 \text{.......Equation 2}$$

The specific gravity of tubers was determined by weighing potatoes in air and when immersed in water (Lulai and Orr, 1979).

$$\text{Specific gravity} = \frac{\text{weight in air}}{\text{Weight in air} - \text{weight in water}}\ \text{..............................Equation 3}$$

Starch content of tubers was determined by iodine reaction and spectrophotometer (McGrance *et al*., 1998). The potato tuber samples were grated and dried in an oven for 72 hours at 85°C until constant weight. The tubers were milled and flour sample weight of approximately 50g were used for analysis (Moorthy *et al.,* 2006). The standard soluble starch solution (0.1 to 0.8%) was prepared and 1ml of each standard was pipetted into clean test tubes. Two drops of iodine solution were added to each test tube and absorbance for each standard was read at 620 nanometers wavelength in APEL- PD 3000 UV - Vis spectrophotometer.

d. Phosphorus uptake

Analysis of total phosphorus in the leaves and tubers was done to determine phosphorus uptake by the potato varieties. The third to sixth leaf from the growing tip was sampled at 42 days after planting and at 84 days after planting. The total nutrient uptake was calculated by the following formula (Badr *et al*., 2012).

Total nutrient uptake = Nutrient concentration % × Dry matter content………… Equation 5

e. Phosphorus use efficiency (PUE)

The following formula was used for determining phosphorus use efficiency;

$$\text{PUE (kg kg}^{-1}\text{)} = \frac{\text{Yield of fertilized plot} - \text{Yield of unfertilized plot}}{\text{total amount of P applied}} \text{…………………....Equation 6}$$

3.5 Data analysis

The data collected on growth, yield and quality parameters were subjected to analysis using general linear model procedure SAS version 9.3 statistical software to generate analysis of variance (ANOVA) (Gomez and Gomez, 1984).

The field data was fitted on this statistical model:

$$Y_{ijkl} = \mu + R_i + S_j + V_k + SV_{jk} + P_l + VP_{kl} + SP_{jl} + SVP_{jkl} + \mathcal{E}_{ijklm} \text{ .... (Equation 7)}$$

Where; Y_{ijkl} is the response; μ is the overall mean; R_i is the replicate effect; E_j is the site effect; V_k is the main plot factor variety; V_{jk} is the main plot error (error a); P_l is the sub plot factor phosphorus; SV_{jk}, VP_{kl}, SP_{jl}, EVP_{jkl} are the interaction factors; $\mathcal{E}_{ijklm}$ is the sub plot error (error b) All pairs of treatment means were separated using least significant difference (LSD) at 5% level of significance.

$$\text{LSD} = t\ \alpha_{\underset{df}{error}} \times \sqrt{\frac{2MSE}{r}}$$

Where t is the t value from the table, α is the level of significance

df is the degrees of freedom, $2MSE$ is the mean square errors and r is the replicate

Correlation analysis was used to determine simple correlation coefficient between growth, yield and quality parameters as affected by phosphorus application and varieties.

CHAPTER FOUR
RESULTS

4.1 Initial soil analysis results

The initial properties of study soils are presented in Table 1. The pH of the soils in all sites was moderately acidic. The available P concentration was low in top soil layers (0-15cm) at Egerton site and 15-30 and 30-45 cm depths at KARLO Molo. The levels were adequate in Mauche. Total N was adequate and organic C moderate in the three sites (1).

Table 1. Initial soil physical and chemical properties of experimental site

Sites	**Egerton site**			**KALRO Molo Site**			**Mauche site**		
Soil depth (cm)	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
Soil chemical properties									
Soil **pH**	5.78	5.90	6.06	5.69	5.05	5.00	5.81	6.15	6.21
Total nitrogen (%)	0.29	0.21	0.18	0.22	0.16	0.15	0.23	0.23	0.22
Total organic C (%)	2.99	2.27	1.89	2.36	1.79	1.66	2.52	2.53	2.50
CEC (meq/100g)	40.0	43.2	28.0	34.0	24.0	30.8	20	37.2	31.2
Available P (ppm)	25	25	30	30	25	25	35	35	35
Potassium (me %)	1.94	1.70	1.64	1.50	0.96	0.92	1.30	1.16	1.32
Calcium (me %)	10.4	9.8	8.4	7.0	1.2	1.4	12.4	13.0	11.2
Magnesium (me %)	2.65	2.67	2.58	2.44	1.18	1.24	2.91	3.0	3.31
Sodium (me %)	0.66	0.54	0.62	0.64	0.56	0.54	0.60	0.60	0.66
Soil physical properties									
Soil textural class	SCL	SCL	SCL	SCL	SCL	SC	SCL	SCL	SCL
Sand %	56	56	54	54	52	52	54	52	54
Silt %	16	16	14	14	14	12	18	18	16
Clay %	28	28	32	32	34	36	30	30	30
Soil bulk density (g/m^3)	0.91	0.89	0.89	0.87	0.86	0.86	0.86	0.87	0.86

Key: SCL= sandy clay loam, SC= sandy clay

4.2 Effect of phosphorus rates on growth of potato varieties propagated from rooted apical cuttings

4.2.1 Plant survival of rooted apical cuttings

Plant survival was generally higher at 14 to 28 days after planting (DAP) as compared to 42 and 56 DAP (Fig 5). The main effects of P rates on plant survival was significant (P<0.05) at 14 and 28 DAP. Treatments 0, 30 and 60 kg P ha^{-1} recorded the highest survival during these periods.

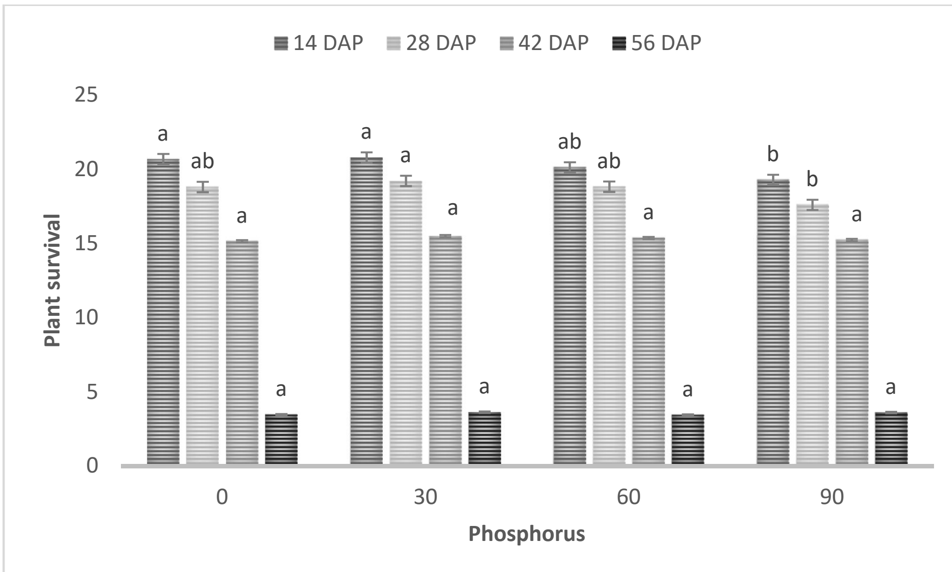

Figure 4. Main effect of phosphorus rates on plant survival of rooted apical cuttings

The interaction effect of study sites and variety on plant survival of rooted apical cuttings was highly significant (P<0.001) at all sampling periods. At 14, 28 and 42 DAP, all varieties at Egerton site had highest survival (Table 2). Plant survival of the cuttings was significantly (P<0.05) lower at Mauche study site than at Egerton and KALRO Molo during these periods. 90% of the plants at Mauche had died by 56 DAP.

Table 2. Interaction effect of study sites and varieties on survival of rooted apical cuttings

		Plant survival of rooted apical cuttings			
Study sites	**Variety**	14 DAP	28 DAP	42 DAP	56 DAP
Egerton	Shangi	$22.92±0.57^{ab}$	$22.42 ±0.70^{a}$	$22.08 ± 0.73^{a}$	$22.08±0.86^{ab}$
	Dutch R	$23.17 ± 0.51^{a}$	$22.17±0.78^{ab}$	$21.42±0.78^{ab}$	$21.42±0.84^{ab}$
	Unica	$23.50 ± 0.19^{a}$	$22.92 ± 0.42^{a}$	$22.50 ± 0.34^{a}$	$22.67 ±0.26^{a}$
	Wanjiku	$22.33±0.53^{ab}$	$21.58±0.63^{ab}$	$19.92±0.84^{bc}$	$19.67±0.86^{bc}$
KALRO M	Shangi	$21.08±0.50^{bc}$	$18.75±0.83^{cd}$	$17.00± 0.90^{d}$	$16.50±0.73^{d}$
	Dutch R	$13.42 ± 0.86^{f}$	$13.67 ± 0.87^{f}$	$13.33 ± 0.89^{e}$	$13.17±0.86^{e}$
	Unica	$20.25±0.55^{cd}$	$18.67±1.01^{cd}$	$18.83±0.94^{cd}$	$18.58±0.92^{cd}$
	Wanjiku	$20.17±0.86^{cd}$	$19.92±1.15^{bc}$	$18.00±1.00^{cd}$	$17.50±0.95^{cd}$
Mauche field	Shangi	$20.00±0.46^{cd}$	$15.42 ±0.71^{ef}$	$7.25 ± 0.55^{f}$	$4.08±0.98^{f}$
	Dutch R	$17.50 ± 0.93^{e}$	$14.00 ± 0.83^{f}$	$7.00 ± 0.41^{f}$	$1.08±0.43^{g}$
	Unica	$20.00±1.16^{cd}$	$16.92±1.32^{de}$	$9.00 ± 0.85^{f}$	$4.92±1.49^{f}$
	Wanjiku	$18.50±0.65^{de}$	$17.00±0.88^{de}$	$7.58 ± 0.67^{f}$	$4.83±1.15^{f}$
P Value		<.0001	0.0136	0.0044	0.0222
Mean		20.23	18.61	15.32	3.53
CV		11.57	16.35	16.90	15.47

Means within a column followed by the same letter are not significantly different at P<0.05, ± values indicate the standard deviation, CV= Coefficient of variation, DAP= Days after planting

4.2.2 Number of stems

The number of stems per plant increased with plant growth (Fig 6). The main effect of phosphorus rates on number of stems was highly significant (P<0.001) at 28, 42 and 56 DAP. The plots in which P was applied at 30, 60, 90 kg P ha^{-1} recorded significantly higher number of stems per plant compared to the control treatment (Fig 6).

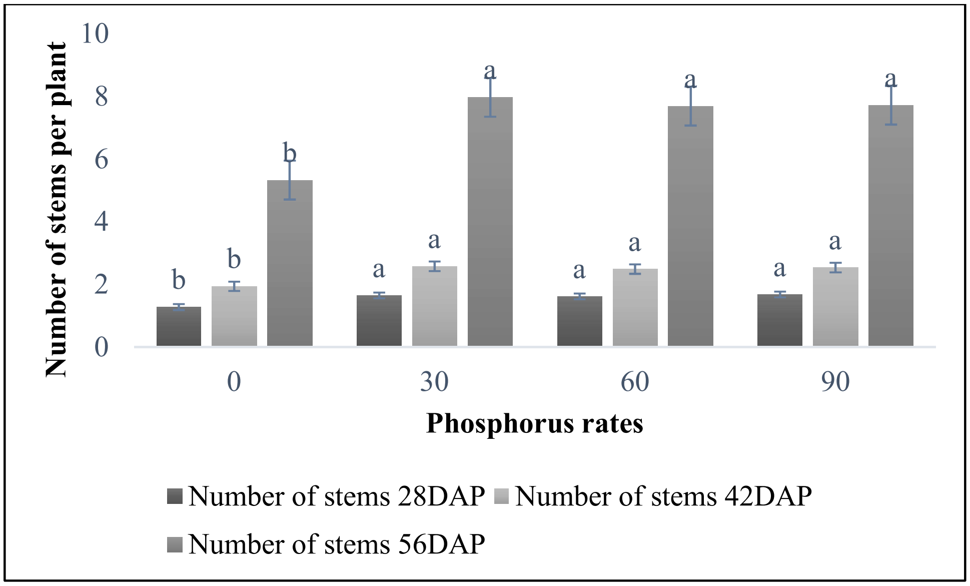

Figure 5. Effect of phosphorus rates on number of stems per potato plant

The interaction effect of study sites and potato varieties on the number of stems per plant was highly significant ($P<0.001$) at 28, 42 and 56 DAP (Table 3). At 28 DAP, Shangi and Unica varieties at Egerton had significantly higher number of stems than Dutch Robyjn and Wanjiku. This differed from Molo and Mauche where no difference among varieties was observed. At 42 DAP, at Egerton Shangi and Dutch Robyjn had significantly greater number of stems compared to Unica and Wanjiku. By 56 DAP there were no significant differences among the four varieties at Egerton. However, compared to Molo and Mauche, Shangi, Dutch Robyjn, Unica and Wanjiku varieties at Egerton site had greatest number of stems (Table 3). The rate of plant growth at Mauche site was slow. This resulted in the least number of stems from 14 DAP to 56 DAP as compared to Egerton and KALRO Molo sites (Table 3).

The interaction effects of study sites and phosphorus rates on number of stems was significant ($P<0.05$) at 28 days after planting. P rates of 30, 60 and 90 kg P ha^{-1} at Egerton site recorded higher number of stems of 4.25, 4.17 and 4.25 respectively, as compared to KARLO Molo with 3.75, 3.42 and 4.08 respectively. Mauche site recorded the least number of stems.

Table 3. Interaction effect of study sites and varieties on number of stems

		Number of stems		
Study sites	**Variety**	28 DAP	42 DAP	56 DAP
Egerton	Shangi	4.50 ± 0.29^{a}	9.92 ± 0.34^{a}	10.67 ± 0.26^{a}
	Dutch Robyjn	3.67 ± 0.31^{bc}	9.17 ± 0.79^{ab}	10.75 ± 0.76^{a}
	Unica	4.00 ± 0.33^{ab}	8.75 ± 0.41^{ab}	9.17 ± 0.27^{a}
	Wanjiku	3.00 ± 0.28^{c}	8.00 ± 0.54^{bc}	9.42 ± 0.50^{a}
KALRO Molo	Shangi	3.25 ± 0.39^{bc}	6.50 ± 0.84^{cd}	7.67 ± 0.89^{b}
	Dutch Robyjn	3.50 ± 0.29^{bc}	5.17 ± 0.64^{d}	5.25 ± 0.59^{cd}
	Unica	3.25 ± 0.39^{bc}	5.83 ± 0.41^{d}	6.42 ± 0.40^{bc}
	Wanjiku	3.00 ± 0.39^{c}	6.83 ± 0.71^{cd}	7.75 ± 0.70^{b}
Mauche field	Shangi	1.00 ± 0.00^{d}	3.42 ± 0.34^{e}	5.17 ± 0.44^{cd}
	Dutch Robyjn	1.00 ± 0.00^{d}	3.42 ± 0.26^{e}	4.75 ± 0.18^{d}
	Unica	1.00 ± 0.00^{d}	3.33 ± 0.36^{e}	4.58 ± 0.40^{d}
	Wanjiku	1.00 ± 0.00^{d}	3.00 ± 0.39^{e}	4.58 ± 0.31^{cd}
P Value		0.0013	0.0235	0.0002
Mean		1.56	2.38	7.18
CV		10.81	11.95	18.26

Means within a column with the same letter are not significantly different at $P<0.01$, ± values indicates the standard deviation, CV =Coefficient of variation, DAP Days after planting

4.2.3 Plant height

Plant height increased with time (Table 4). The results showed that the interaction effect of study sites and phosphorus rates on plant height was significant (P<0.05) at 28, 42 and 56 days after planting (Table 4). The treatments 30, 60 and 90 kg P ha^{-1} at 28 and 42 DAP in KARLO, Molo and 56 DAP in Egerton resulted in significantly taller (P<0.05) plants.

Table 4. Interaction effect of study sites and phosphorus rates on plant height of potato

		Plant height (cm)		
Study sites	P rates	28 DAP	42 DAP	56 DAP
Egerton	0	4.94 ± 0.24^{cd}	8.21 ± 0.55^{de}	17.86 ± 1.66^{c}
	30	6.15 ± 0.38^{b}	13.65 ± 0.90^{b}	28.93 ± 2.01^{a}
	60	5.84 ± 0.28^{bc}	13.04 ± 1.06^{bc}	28.78 ± 2.02^{a}
	90	6.18 ± 0.46^{b}	13.93 ± 0.88^{b}	29.85 ± 1.67^{a}
KALRO Molo	0	4.93 ± 0.36^{cd}	9.84 ± 1.33^{cd}	10.39 ± 1.30^{d}
	30	7.38 ± 0.68^{a}	21.91 ± 2.13^{a}	22.55 ± 2.22^{b}
	60	7.03 ± 0.68^{ab}	21.02 ± 1.87^{a}	21.39 ± 1.94^{bc}
	90	7.70 ± 0.65^{a}	20.27 ± 2.74^{a}	20.52 ± 2.71^{bc}
Mauche field	0	3.80 ± 0.15^{d}	4.80 ± 0.39^{e}	7.23 ± 0.56^{d}
	30	4.45 ± 0.31^{d}	7.17 ± 0.54^{de}	9.01 ± 0.63^{d}
	60	4.27 ± 0.25^{d}	6.69 ± 0.54^{de}	9.01 ± 0.59^{d}
	90	4.36 ± 0.25^{d}	7.59 ± 0.64^{de}	9.39 ± 0.68^{d}
P Value		0.0001	0.0010	0.0003
Mean		5.58	3.37	4.06
CV		13.72	13.42	11.75

Means within column followed by the same letter are not significantly different at P<0.05, ± values indicate the standard deviation, CV= Coefficient of variation, DAP= Days after planting

The interaction between variety and phosphorus rates on plant height at 28 DAP was significant (P<0.05). Shangi variety and P rates of 90 kg P ha^{-1} and 30 kg P ha^{-1} recorded the greatest plant heights of 9.32cm and 9.24cm, respectively. Interaction of Wanjiku variety and 90, 60 and 30 kg

P ha^{-1} recorded plant heights of 7.35cm, 6.77cm, and 6.40cm, respectively. At 28 DAP, Unica and Dutch Robyjn recorded the least plant height across all the P rates.

At 14, 42 and 56 DAP the interaction of varieties and phosphorus rates on plant height were not significant (P<0.05).

The result showed that interaction effect of study sites and variety on plant height was significant (P<0.05) at 14, 28, 42 and 56 DAP (Table 5). Shangi variety at KARLO Molo had significantly (P<0.05) greater height at 14 and 28 DAP (Table 5). At 42 DAP, significantly greater (P<0.05) plant heights were observed for Shangi Unica and Wanjiku varieties at KARLO Molo. At 56 DAP Shangi variety recorded the greatest plant height of 34.82cm at Egerton study site. The plants at Mauche study site showed stunted growth throughout sampling periods.

Table 5. Interaction effect of study sites and varieties on plant height (cm) of potato

		Plant height (cm)			
Study sites	**Variety**	14 DAP	28 DAP	42 DAP	56 DAP
Egerton	Shangi	6.61±0.28^{b}	7.25±0.39^{b}	15.70±1.04^{bc}	34.82±1.90^{a}
	Dutch R	3.71±0.13^{de}	4.58±0.16^{fgh}	11.19±0.92^{d}	23.58±2.08^{b}
	Unica	5.38±0.24^{c}	5.47±0.19^{def}	12.06±0.92^{cd}	24.67±1.67^{b}
	Wanjiku	6.53±0.15^{b}	5.81±0.19^{de}	9.89±0.72^{de}	22.35±1.68^{bc}
KALRO Molo	Shangi	7.17±0.19^{a}	9.25±0.67^{a}	22.09±3.14^{a}	22.76±3.16^{bc}
	Dutch R	3.84±0.18^{de}	4.84±0.22^{fgh}	11.99±1.35^{cd}	12.18±1.30^{d}
	Unica	3.96±0.11^{de}	6.03±0.34^{cd}	18.29±1.61^{ab}	18.70±1.61^{c}
	Wanjiku	5.71±0.11^{c}	6.92±0.57^{bc}	20.67±2.53^{a}	21.22±2.47^{bc}
Mauche field	Shangi	4.20±0.21^{d}	4.54±0.15^{gh}	8.59±0.57^{def}	10.38±0.59^{de}
	Dutch R	2.13±0.06^{f}	3.29±0.10^{i}	4.71±0.25^{f}	6.04±0.31^{e}
Vtut	235\]	3.63±0.27^{e}	3.94±0.19^{hi}	6.03±0.34^{ef}	8.84±0.49^{de}
	Wanjiku	4.08±0.16^{de}	5.11±0.18^{efg}	6.92±0.57^{ef}	9.38±0.38^{de}
P Value		<.0001	<.0001	0.0011	0.0002
Mean		4.74	5.58	3.37	4.06
CV		13.71	13.72	13.42	11.75

Means within a column followed by the same letters are not significantly different at P<0.05, ± values indicate the standard deviation, CV= Coefficient of variation, DAP = Days after planting

4.2.4 Days to 50% flowering of potato

The main effect of phosphorus rates on days to 50% flowering of potato was significant (P<0.001). The days taken by plants from plots with 90 kg P ha^{-1} to flower were not significantly different as compared to plots with 0, 30, 60 kg P ha^{-1} that flowered at 57 DAP.

The interaction of study sites and variety highly influenced (P<0.001) days to 50% flowering (Table 6). Shangi flowered faster at both KALRO Molo site and Egerton site; after 45 days and 49 days, respectively. The days to flower by Unica variety at both study sites were not significantly different. Dutch Robyjn and Wanjiku flowered three days earlier at Egerton site as compared to KALRO Molo study site.

Table 6. Interaction effect of study sites and varieties on days to 50% flowering of potato

Study sites	Variety	Days to 50% flowering
Egerton	Shangi	49.17 ± 0.11^{e}
	Dutch Robyjn	63.67 ± 1.22^{b}
	Unica	58.00 ± 0.54^{d}
	Wanjiku	57.33 ± 0.36^{d}
KALRO Molo	Shangi	45.00 ± 0.25^{f}
	Dutch Robyjn	66.17 ± 0.58^{a}
	Unica	59.83 ± 0.75^{c}
	Wanjiku	60.58 ± 0.77^{c}
P Value		<.0001
Mean		57.46
CV (%)		3.70

Means within a column followed by the same letter are not significantly different at P<0.001, CV =Coefficient of variation, ± values indicate the standard deviation

4.2.5 Days to 50% physiological maturity of potato

The results showed that the main effect of phosphorus rates on days to 50% physiological maturity was not significant ($P<0.05$). The main effects of variety and study sites on days to 50% physiological maturity was highly significant ($P<0.001$). Shangi variety attained 50% physiological maturity earlier followed by Unica then Dutch Robyn and lastly Wanjiku variety (Table 7). Potato plants reached 50% physiological maturity faster at Egerton study site (84.85 days) as compared to KALRO Molo study site at 88.66 days.

Table 7. Main effect of varieties on days to 50% physiological maturity of potato

Varieties	Days to 50% physiological maturity
Shangi	70.29d
Dutch Robyjn	92.42b
Unica	84.21c
Wanjiku	100.12a
P Value	<.0001
LSD	2.75
CV (%)	11.55

Means within a column followed by the same letter are not significantly different at $P<0.001$, CV= Coefficient of variation

4.3 Effect of phosphorus rates on yield of potato varieties propagated from rooted apical cuttings

4.3.1 Biomass yield of potato

The interaction effect of phosphorus and variety on biomass yield was significant ($P<0.01$). Wanjiku variety registered the highest plant shoot biomass across all phosphorus treatments. Dutch Robyjn registered the least plant shoot biomass across all the P treatments (Table 8).

Table 8. Interaction effect of varieties and phosphorus rates on biomass yield of potato

Varieties	Phosphorus rates (kg)	Plant shoot biomass (gm)
Shangi	0	0.30 ± 0.04^{bc}
	30	0.31 ± 0.01^{bc}
	60	0.26 ± 0.01^{cd}
	90	0.28 ± 0.01^{cd}
Dutch Robyjn	0	0.16 ± 0.02^{ef}
	30	0.14 ± 0.01^{ef}
	60	0.11 ± 0.01^{f}
	90	0.10 ± 0.01^{f}
Unica	0	0.21 ± 0.01^{de}
	30	0.26 ± 0.01^{cd}
	60	0.24 ± 0.02^{cd}
	90	0.24 ± 0.02^{cd}
Wanjiku	0	0.36 ± 0.04^{ab}
	30	0.42 ± 0.04^{a}
	60	0.37 ± 0.05^{ab}
	90	0.39 ± 0.04^{a}
P Value		0.0085
Mean		0.25
CV (%)		11.55

Means within a column with the same letter are not significantly different at $P<0.01$, CV= Coefficient of variation, ± values indicates the standard deviation

The interaction effect of study sites and variety on biomass yield of potato was highly significant ($P<0.001$). Wanjiku variety at Egerton study site registered the highest plant biomass followed by Shangi and Wanjiku at Egerton study site and Molo respectively (Table 9). Dutch Robyjn and Unica varieties recorded the lowest plant biomass at both study sites.

Table 9. Interaction effect of study sites and varieties on biomass yield of potato

Study sites	Variety	Plant shoot biomass (gm)
Egerton	Shangi	0.31 ± 0.02^{b}
	Dutch Robyjn	0.14 ± 0.01^{e}
	Unica	0.27 ± 0.01^{c}
	Wanjiku	0.47 ± 0.01^{a}
KALRO Molo	Shangi	0.27 ± 0.01^{c}
	Dutch Robyjn	0.12 ± 0.01^{e}
	Unica	0.21 ± 0.01^{d}
	Wanjiku	0.30 ± 0.01^{b}
P Value		<.0001
Mean		0.25
CV (%)		11.50

Means within a column followed by the same letter are not significantly different at P<0.001, CV =Coefficient of variation, ± values indicate the standard deviation

4.3.2 Number of tubers in potato

The main effects of phosphorus on number of tubers was highly significant (P<0.001). The P rates of 60, 90, and 30 kg P ha^{-1} recorded 16.12, 15.54 and 14.62 tubers per hill, respectively, which were not significantly different but higher than control. The control treatment (0 kg P ha^{-1}) recorded the least number of tubers per hill (12).

The results of the study showed that interaction effect of study sites with potato varieties on number of tubers was highly significant (P<0.01). The highest number of tubers were registered with Wanjiku variety followed by Shangi and Dutch Robyjn at Egerton study site. At KALRO Molo study site Dutch Robyjn and Shangi varieties had least number of tubers (Table 10).

Table 10. Interaction effect of study sites and varieties on number of tubers and tuber weight in potato

Study sites	Varieties	Number of tubers hill^{-1}	Tuber weight (kg) per hill
Egerton	Shangi	19.67 ± 0.87^{b}	1.10 ± 0.05^{c}
	Dutch Robyjn	18.58 ± 0.98^{b}	0.76 ± 0.05^{d}
	Unica	15.50 ± 0.57^{c}	1.30 ± 0.07^{b}
	Wanjiku	25.92 ± 0.79^{a}	1.44 ± 0.05^{a}
KALRO Molo	Shangi	10.25 ± 0.78^{e}	0.32 ± 0.03^{g}
	Dutch Robyjn	7.42 ± 0.66^{f}	0.20 ± 0.02^{h}
	Unica	6.17 ± 0.41^{f}	0.47 ± 0.02^{f}
	Wanjiku	13.08 ± 0.87^{d}	0.63 ± 0.04^{e}
P value		0.01	0.001
Mean		14.57	0.77
CV (%)		12.86	16.68

Means within column followed by the same letter are not significantly different ($P<0.01$), CV =Coefficient of variation, ± values indicates the standard deviation

4.2.3 Tuber weight

The main effect of phosphorus on tuber weight was highly significant ($P<0.001$). The P rates of 30, 60 and 90 kg P ha^{-1} recorded tuber weight of 19.30 kg, 19.84kg and 18.88 kg ha^{-1} respectively. The control treatment (0 kg P ha^{-1}) recorded the lowest tuber weight of 15.55 kg ha^{-1}.

The result of the study showed that interaction of study sites and varieties on tuber weight was highly significant ($P<0.01$). Wanjiku variety recorded heaviest tubers at Egerton study site while Dutch Robyjn variety registered the lowest tuber weight at KALRO Molo. Overall, potato tubers at Egerton University were 64.35% heavier than at KARLO-Molo (Table 10).

4.2.4 Size of tubers

The result of the study showed that the interaction effect of study sites and variety on size of tubers was highly significant (P<0.001). Wanjiku variety at Egerton study site recorded the highest number of large (>60mm diameter) and medium size tubers (30-60mm diameter) (Table 11). Dutch Robyjn at Egerton site registered the highest number of small sized tubers (<30mm diameter) followed by Shangi and Wanjiku. At Molo, Dutch Robyjn and Wanjiku varieties had the highest number of small sized tubers. Unica variety had the least number of small sized tubers at both study sites (Table 11).

Table 11. Interaction effect of study sites and varieties on tuber size and number of eyes in potato

Study sites	Varieties	Large size	Medium size	Small size	Number of eyes
Egerton	Shangi	11.67±0.31^{b}	12.17± 0.34^{b}	13.50±0.51^{b}	11.42 ± 0.26^{c}
	Dutch R	12.50±0.29^{b}	10.92 ± 0.34^{c}	16.25 ± 0.33^{a}	14.75 ± 0.60^{b}
	Unica	11.58±0.60^{b}	8.58 ± 0.15^{d}	2.92 ± 0.48^{e}	8.75 ± 0.49^{d}
	Wanjiku	18.25±1.10^{a}	14.42 ± 0.57^{a}	11.83 ± 0.83^{c}	19.00 ± 1.14^{a}
KALRO Molo	Shangi	4.75± 0.30^{e}	5.17 ± 0.34^{f}	10.08 ± 0.51^{d}	4.67 ± 0.28^{e}
	Dutch R	0.92± 0.19^{f}	1.00 ± 0.25^{g}	13.67 ± 0.36^{b}	1.58 ± 0.34^{f}
	Unica	9.50± 0.60^{c}	6.58 ± 0.15^{e}	2.00 ± 0.44^{e}	9.25 ± 0.52^{d}
	Wanjiku	7.58 ± 1.00^{d}	9.33 ± 0.56^{d}	13.50 ± 0.84^{b}	7.92 ± 1.13^{d}
P Value		<.0001	<.0001	<.0001	<.0001
Mean		9.59	8.52	10.46	9.66
CV (%)		2.73	3.68	3.05	5.02

Means within column followed by the same letter are not significantly different at P<0.001, CV =Coefficient of variation, ± values indicate the standard deviation

The interaction effect of phosphorus and variety on size of tubers was highly significant (P<0.001). Wanjiku and Unica varieties with 30, 60 and 90 kg P ha^{-1} registered the highest number of large sized tubers (Table 12). Wanjiku registered the highest number of medium sized tubers with phosphorus treatments of 60 and 90 kg P ha^{-1} (Table 12).

The control treatment and Dutch Robyjn variety, 90 kg P ha^{-1} and Dutch Robyjn, 60 kg P ha^{-1} and Wanjiku recorded the highest number of small sized tubers (Table 12). The interaction effect of study sites and phosphorus on large size tubers was significant (P<0.05). Treatment 30 kg P ha^{-1} recorded the highest number of large size tubers at Egerton site. KALRO Molo recorded the lowest number of large size tubers across all the P rates.

Table 12. Interaction effect of varieties and phosphorus rates on tuber size and number of eyes in potato

		Tuber size (mm)			
Varieties	P rates	Large size	Medium size	Small size	Number of eyes
Shangi	0	6.83 ± 1.58^{cd}	7.50 ± 1.57^{cd}	13.00 ± 0.77^{b}	6.67 ± 1.50^{d}
	30	8.83 ± 1.58^{bcd}	9.17 ± 1.58^{bcd}	12.67 ± 0.80^{b}	8.67 ± 1.50^{cd}
	60	8.83 ± 1.58^{bcd}	10.17 ± 1.58^{bc}	12.50 ± 0.85^{b}	8.67 ± 1.50^{cd}
	90	8.33 ± 1.54^{bcd}	7.83 ± 1.58^{cd}	9.00 ± 0.77^{c}	8.17 ± 1.58^{cd}
Dutch Robyjn	0	6.00 ± 2.39^{d}	5.00 ± 2.10^{d}	16.17 ± 0.60^{a}	6.83 ± 2.61^{d}
	30	7.17 ± 2.63^{cd}	7.17 ± 2.32^{cd}	14.00 ± 0.63^{b}	8.33 ± 3.14^{cd}
	60	6.33 ± 2.69^{d}	6.33 ± 2.25^{cd}	14.00 ± 0.63^{b}	7.00 ± 2.84^{d}
	90	7.33 ± 2.69^{bcd}	5.33 ± 2.25^{d}	15.67 ± 0.67^{a}	10.50 ± 3.21^{bcd}
Unica	0	7.33 ± 0.49^{bcd}	7.33 ± 0.49^{cd}	4.67 ± 0.42^{d}	6.50 ± 0.22^{d}
	30	11.17 ± 0.60^{abcd}	8.00 ± 0.45^{cd}	1.33 ± 0.33^{e}	11.00 ± 0.26^{bcd}
	60	11.33 ± 0.49^{abcd}	7.67 ± 0.49^{cd}	1.17 ± 0.31^{e}	9.00 ± 0.26^{cd}
	90	12.33 ± 0.49^{abc}	7.33 ± 0.49^{cd}	2.67 ± 0.33^{e}	9.50 ± 0.22^{cd}
Wanjiku	0	7.33 ± 2.25^{bcd}	10.17 ± 1.14^{bc}	10.50 ± 0.43^{c}	7.50 ± 2.46^{cd}
	30	15.67 ± 2.40^{a}	10.17 ± 1.14^{bc}	12.50 ± 0.43^{b}	17.17 ± 2.47^{a}
	60	15.83 ± 2.47^{a}	12.67 ± 1.20^{ab}	17.17 ± 0.48^{a}	15.83 ± 2.63^{ab}
	90	12.83 ± 2.47^{ab}	14.50 ± 1.12^{a}	10.50 ± 0.43^{c}	13.33 ± 2.43^{abc}
P Value		<.0001	<.0001	<.0001	<.0001
Mean		8.52	10.46	9.66	9.59
CV		2.73	3.68	3.05	5.02

Means within column followed by the same letter are not significantly different at P<0.001, CV =Coefficient of variation, ± values indicates the standard deviation, P rates = Phosphorus rates

4.2.5 Number of eyes

The result of the study showed that interaction effect of study sites and variety on number of eyes was highly significant ($P<0.001$). Wanjiku variety grown at Egerton study site gave the highest number of eyes followed by Dutch Robyjn then Shangi and Unica in that order. However, all the varieties recorded fewer eyes at KALRO Molo, with Dutch Robyjn with the fewest eyes (Table 11).

The result of the study showed that interaction effects of phosphorus rates and variety significantly ($P<0.05$) influenced the number of eyes. The highest number of eyes were obtained from Wanjiku variety under P rates of 30, 60 and 90 kg P ha^{-1} (Table 12).

4.2.6 Marketable tuber yield

The main effect of phosphorus application rates on marketable tuber yield was significant ($P<0.05$). Application rate of 30, 60 90 kg P ha^{-1} recorded the highest marketable tuber yield compared to 0 kg P ha^{-1}. Application of 90 kg P ha^{-1} gave the highest marketable tuber yield followed by 30 and 60 kg P ha^{-1} which were not significantly different from each other. The lowest tuber yield was obtained from the control treatment of 0 kg P ha^{-1} (Table 13).

The main effect of varieties on marketable tuber yield was highly significant ($P<0.001$). Shangi recorded the highest number of marketable tubers followed by Wanjiku and Dutch Robyjn then Unica and were not significantly different (Table 13).

The main effect of study sites on marketable tuber yield was not significant ($P<0.05$). KALRO Molo site produced marketable tuber yield of 9.83 tubers as compared to Egerton study site with 9.5 tubers.

Table 13. Main effects of varieties and phosphorus on marketable tuber yield per hill

Varieties	Marketable tuber yield
Shangi	10.66a
Dutch Robyjn	9.54b
Unica	8.58c
Wanjiku	9.87b
Phosphorus rates (kg ha^{-1})	
0	9.25b
30	9.6ab
60	9.5ab
90	10.25a
LSD	0.72
CV (%)	13.03

Means within a column followed by the same letters are not significantly different at P <0.05, (P rates) P<0.001 (variety) CV= Coefficient of variation

4.3 Effect of phosphorus rates on quality of potato varieties propagated from rooted apical cuttings

4.3.1 Dry matter content

The interaction effect of study sites and phosphorus rates on dry matter content was significant (P<0.05). Treatment 0 and 60 kg P ha^{-1} at KALRO Molo recorded the highest dry matter content of 23.49% and 25.76% (Table 14). At Egerton site, the dry matter content were not different among the treatments.

The interaction effect of varieties and phosphorus rates on dry matter content was not significant (P<0.05).

Table 14. Interaction effect of study sites and P rates on dry matter content, starch content and specific gravity of tubers

Study sites	P rates	Dry matter content (%)	Starch content (%)	Specific gravity
Egerton	0	21.73 ± 0.81^{bc}	15.04 ± 0.89^{ab}	1.06 ± 0.01^{a}
	30	21.71 ± 0.75^{bc}	13.91 ± 0.63^{b}	1.01 ± 0.02^{a}
	60	22.88 ± 1.49^{bc}	17.66 ± 2.02^{a}	1.06 ± 0.02^{a}
	90	21.40 ± 0.63^{bc}	15.28 ± 0.97^{ab}	0.96 ± 0.02^{a}
KALRO Molo	0	23.49 ± 0.55^{ab}	15.41 ± 0.83^{ab}	1.02 ± 0.01^{a}
	30	20.51 ± 0.75^{c}	15.78 ± 0.82^{ab}	1.00 ± 0.02^{a}
	60	25.76 ± 1.41^{a}	18.60 ± 2.16^{a}	1.07 ± 0.02^{a}
	90	20.77 ± 0.76^{c}	13.22 ± 1.16^{b}	0.75 ± 0.12^{b}
P Value		0.001	0.001	0.05
Mean		22.27	15.61	0.99
CV (%)		12.70	21.79	12.43

Means within a column followed by the same letters are not significantly different ($P<0.05$), ($P<0.001$), CV= Coefficient of variation

The interaction effect of study sites with varieties on dry matter was highly significant ($P<0.001$). Unica variety at Egerton site and Dutch Robyjn and Wanjiku at KARLO, Molo site recorded the highest dry matter content of 24.70%, 25.52%, 23.45%, respectively. Wanjiku variety had higher dry matter content at KALRO Molo as compared to Egerton site. Shangi variety at Egerton site recorded higher dry matter content as compared to KALRO Molo (Table 15).

Table 15. Interaction effect of study sites with varieties on dry matter content, starch content and specific gravity of potato tubers

Study sites	Variety	Dry matter content (%)	Starch content (%)	Specific gravity
Egerton	Shangi	21.12 ± 0.87^{bc}	14.52 ± 0.81^{cd}	1.00 ± 0.02^{a}
	Dutch Robyjn	20.72 ± 0.73^{c}	12.17 ± 0.94^{d}	1.00 ± 0.02^{a}
	Unica	24.70 ± 1.14^{a}	20.53 ± 1.29^{a}	1.04 ± 0.02^{a}
	Wanjiku	21.18 ± 0.63^{bc}	14.68 ± 0.44^{cd}	1.05 ± 0.00^{a}
KALRO Molo	Shangi	20.87 ± 0.71^{bc}	14.52 ± 1.16^{cd}	0.93 ± 0.02^{ab}
	Dutch Robyjn	25.52 ± 0.57^{a}	19.16 ± 0.67^{ab}	1.04 ± 0.01^{a}
	Unica	20.69 ± 0.70^{c}	12.79 ± 0.62^{d}	1.03 ± 0.01^{a}
	Wanjiku	23.45 ± 1.53^{ab}	16.54 ± 2.11^{bc}	0.84 ± 0.13^{b}
P Value		<.0001	<.0001	0.0054
Mean		22.27	15.61	0.99
CV (%)		12.70	21.79	12.43

Means within a column with the same letters are not significantly different at ($P<0.05$), CV= Coefficient of variation

4.3.2 Starch content

The interaction effect of study sites and varieties on starch content was highly significant ($P<0.001$). Unica variety at Egerton site and Dutch Robyjn at KALRO Molo recorded the highest starch contents of 20.53% and 19.16%, respectively. Shangi variety recorded the same amount of starch content (14.52%) at both study sites (Table 15). Dutch Robyjn and Wanjiku variety had higher starch content at KALRO Molo as compared to Egerton site (Table 15).

The interaction effect of varieties and phosphorus rates on starch content was significant ($P<0.05$). (Table 16). Wanjiku variety and 60 kg P ha^{-1} gave the highest percentage of starch content of 22.07%. The P rates and Shangi, Dutch Robyjn and Unica had no significant difference on starch content.

Table 16. Interaction effect of varieties and P rates on starch content and specific gravity of potato tubers

Variety	P rates	Starch content	Specific gravity
Shangi	0	16.96 ± 1.10^{bc}	1.00 ± 0.03^{abc}
	30	18.85 ± 1.28^{cd}	0.89 ± 0.01^{c}
	60	15.49 ± 1.30^{bcd}	1.07 ± 0.01^{ab}
	90	11.78 ± 1.16^{d}	0.91 ± 0.02^{bc}
Dutch Robyjn	0	14.32 ± 1.00^{bcd}	1.07 ± 0.02^{a}
	30	16.57 ± 1.06^{bcd}	1.03 ± 0.00^{abc}
	60	15.63 ± 2.89^{bcd}	0.99 ± 0.02^{abc}
	90	16.15 ± 2.16^{bcd}	0.99 ± 0.04^{abc}
Unica	0	16.31 ± 1.54^{bcd}	1.05 ± 0.00^{ab}
	30	16.05 ± 0.32^{bcd}	1.05 ± 0.01^{ab}
	60	19.33 ± 3.76^{ab}	1.09 ± 0.02^{a}
	90	14.95 ± 1.51^{bcd}	0.96 ± 0.00^{abc}
Wanjiku	0	13.32 ± 0.41^{cd}	1.04 ± 0.00^{abc}
	30	12.91 ± 0.84^{cd}	1.06 ± 0.00^{ab}
	60	22.07 ± 2.88^{a}	1.12 ± 0.02^{a}
	90	14.13 ± 0.77^{cd}	0.57 ± 0.21^{d}
P Value		0.0073	<.0001
Mean		15.61	0.99
CV (%)		21.79	12.43

Means within a column with the same letters are not significantly different at ($P<0.001$), CV= Coefficient of variation

4.3.3 Specific gravity of potato tubers

The interaction effect of study sites and phosphorus rates on specific gravity of potato tubers was significant ($P<0.05$). The application of highest fertilizer rate of 90 kg P ha^{-1} led to reduced specific gravity of potato tubers at KALRO, Molo (Table 14). Other treatments and control had no significant influence on the specific gravity of potato tubers at both study sites.

The interaction effect of study sites and varieties on specific gravity of potato tubers was significant ($P<0.05$) (Table 15). Wanjiku at KARLO Molo had significant lower values. There was no significant difference in specific gravity of tubers in other treatments.

The interaction effect of varieties and phosphorus on specific gravity of potato tubers was highly significant ($P<0.001$) (Table 16).
Shangi with 0 and 60 kg P ha^{-1}, Dutch Robyjn and Unica with 0, 30, 60 and 90 kg P ha^{-1} and Wanjiku with 0, 30, 60 kg P ha^{-1} recorded significantly higher specific gravity of tubers (Table 16). However increasing the amount of phosphorus to 90 kg P ha^{-1} reduced the specific gravity of potato tubers for Wanjiku variety.

4.4 Correlation analysis

A correlation analysis was performed to determine the simple correlation coefficient between growth, yield and quality of potato as affected by variety and P application (Table 17). The results of the study show that plant height was positively correlated with number of stems per plant (r = 0.711***). Plant biomass was significantly and positively correlated with number of stems per plant (r = 0.21*), plant height (r = 0.39***), number of tubers (r = 0.49***), tuber weight (r = 0.59***), tuber size (r = 0.42***), and marketable tuber yield (r = 0.35**). The result indicated that growth parameters contributed to increase in yield because the number of tubers per hill was significantly and positively correlated with number of stems (r = 0.67***), plant height (r = 0.51***), tuber weight (r = 0.79***), tuber size (r =0.68***), and marketable tuber yield (r = 0.67***). The finding also showed that tuber weight was positively correlated with plant height (r = 0.60***), number of stems (r = 0.58***), large sized tubers (r = 0.70***), medium sized tubers (r = 0.69***) and marketable tuber yield (r = 0.60***). The marketable tuber yield is positively correlated with large sized tubers (r = 0.94***) and medium sized tubers (r = 0.68***).

The dry matter content was significantly and positively correlated with starch content of the tubers (r = 0.80***). Specific gravity of tubers was significantly correlated with dry matter content (r = 0.28*) and starch content (r = 0.29*)

Table 17. Correlation analysis of growth and yield parameters of potato varieties propagated from rooted apical cuttings

PAR	NS	PLH	BW	NT	TW	LST	MST	MKTY
NS	1							
PLH	0.711***	1						
BW	0.21*	0.39***	1					
NT	0.67***	0.51***	0.49***	1				
TW	0.58***	0.60***	0.59***	0.79***	1			
LST	0.51***	0.41***	0.42***	0.68***	0.70***	1		
MST	0.59***	0.47***	0.48***	0.76***	0.69***	0.66***	1	
MKTY	0.52***	0.36**	0.35**	0.67***	0.60***	0.94***	0.68***	1

NS = number of stems per plant, PLH = plant height, BW = biomass weight, NT = number of tubers per plant, TW = tuber weight, LST = large sized tubers, MST = medium sized tubers and MKTY = marketable tuber yield. ** significant (P<0.05), ***significant (P<0.001)

4.5 Phosphorus uptake

Study sites and variety interacted to significantly (P<0.01) influence phosphorus uptake prior to flowering stage (leaves sampled at 42 DAP). Dutch Robyjn variety at Egerton study site and Unica variety at KALRO, Molo showed greatest P uptake. Shangi and Wanjiku varieties showed lower P uptake at both study sites (Table 18).

Table 18. Interaction effect of study sites and varieties on phosphorus uptake

Study sites	Variety	P uptake (%)
Egerton	Shangi	0.22 ± 0.02^{b}
	Dutch Robyjn	0.32 ± 0.01^{a}
	Unica	0.23 ± 0.03^{b}
	Wanjiku	0.24 ± 0.02^{b}
KALRO Molo	Shangi	0.21 ± 0.02^{b}
	Dutch Robyjn	0.27 ± 0.01^{ab}
	Unica	0.32 ± 0.04^{a}
	Wanjiku	0.21 ± 0.02^{b}
P Value		0.0018
Mean		0.25
CV (%)		10.12

Means within a column followed by the same letters are not significantly different at ($P<0.01$), CV= Coefficient of variation

Phosphorus uptake before flowering stage (42 DAP) differed depending on the variety and rate of phosphorus applied ($P<0.01$). Unica variety and P rate of 30 kg P ha^{-1} recorded the highest P uptake (0.36%) followed by Dutch Robyjn variety at all P treatments that were not significantly different. Wanjiku and Shangi variety recorded the least P uptake across all treatments.

The main effect of study sites on P uptake prior to maturity of the potato (leaves sampled at 84 DAP) was significant ($P<0.001$). Egerton study site recorded higher P uptake of 0.42% as compared to KALRO Molo at 0.37%. The main effect of variety on P uptake prior to maturity (84 DAP) was significant ($P<0.001$). Unica variety recorded the highest P uptake of 0.47% followed by Dutch Robyjn variety with 0.39% then Wanjiku variety at 0.38% and Shangi variety at 0.37%. The P application rates on P uptake prior to potato maturity (84 DAP) was significant ($P<0.01$). Potato planted with 30 kg P ha^{-1} and 90 kg P ha^{-1} recorded higher P uptake of 0.43% and 0.41% respectively. The crops grown without applied P fertilizer recorded better P uptake than those grown with 60 kg P ha^{-1}.

Study sites effect on P uptake by the potato tubers was significant ($P<0.05$). The potato tubers at Egerton recorded higher P uptake of 0.18% as compared to KALRO Molo at 0.11%.

4.6 Phosphorus use efficiency

The main effect of phosphorus application rate on PUE was significant ($P< 0.001$). P rate of 30 kg P ha^{-1} recorded the greatest PUE of 239.79 followed by 60 kg P ha^{-1} (126.40). The least PUE was obtained by application of 90 kg P ha^{-1} (73.45). Study sites and varieties independently did not significantly (0.05) increase PUE.

Study sites and varieties interaction effect on PUE was significant ($P< 0.01$). Unica variety at Egerton study site recorded the greatest PUE. Wanjiku variety at KALRO, Molo recorded the greatest PUE (Table 19). Shangi and Dutch Robyjn varieties recorded lower phosphorus use efficiency at both study sites. However, all varieties while at Egerton study site showed greater phosphorus use efficiency as compared to KALRO Molo.

Table 19. Interaction effect of study sites and varieties on phosphorus use efficiency

Study sites	Variety	PUE
Egerton	Shangi	149.23 ± 46.97^{bc}
	Dutch Robyjn	137.15 ± 30.45^{bc}
	Unica	284.88 ± 61.33^{a}
	Wanjiku	108.83 ± 45.31^{bc}
KALRO Molo	Shangi	97.53 ± 34.84^{c}
	Dutch Robyjn	77.80 ± 41.33^{c}
	Unica	98.27 ± 23.57^{c}
	Wanjiku	218.69 ± 38.43^{ab}
P value		0.001
Mean		146.54
CV (%)		72.08

Means within a column with the same letters are not significantly different at ($P<0.01$), CV= Coefficient of variation

CHAPTER FIVE

DISCUSSION

5.1 Effect of P rates on growth of seed potato varieties propagated from rooted apical cuttings

The rooted apical cuttings are an alternative to conventional potato seed tubers. They are produced from tissue culture plantlets that are grown in coco plugs media to enable shooting and rooting process. In Kenya Stokman Rozen Company located in Naivasha produces them. They were acclimatized to the external environmental conditions through hardening off process in the screen houses before transplanting to the open fields. The ability of the plants to withstand the new environmental conditions increases their ability to survive until maturity. Tsoka *et al.* (2012) reported that plants derived from apical stem cuttings survive better than tissue culture plantlets. The growth of the plants depends on the photosynthesis ability, which is influenced by the leaf area of the plants, canopy development and efficiency of the leaves to absorb light energy (Hughes, 1974). The factors that influence photosynthesis are; light intensity, day length, temperature, water and mineral nutrition available in the soil (Hughes, 1974).

The study sites and variety had significant influence on survival of the rooted apical cuttings, plant height, number of stems and days to physiological maturity of the potato crop. This can be attributed to differences in rainfall amounts, soil types and temperature at the study sites, which promoted physiological growth of the crop. The other factors that affect potato growth are genetics of the crop, climatic conditions and management of the crop from planting until harvesting (Öztürk *et al*., 2010). This shows that some varieties are well adapted to cooler environments (Asfaw *et al*., 2015) and have varied characteristics and genetic makeup that influences vegetative growth, high yields and disease resistance (Abalo *et al*., 2003). The rate of plant growth at Mauche site was slower compared to other sites, and they eventually died. This could be attributed to failure of the rooted apical cuttings at Mauche site to acclimatize to the low temperatures and was affected by stress. The night temperatures at Mauche often go to below 4°C, (Climatic data.org, 2019), this could even reach freezing point that was so damaging to the rooted apical cuttings.

The number of stems per plant, plant height increased with plant growth. Phosphorus is a vital nutrient which enhances early crop development of shoots and roots (Belachew, 2016; Ekelof, 2007; Hopkins *et al*., 2014; Jenkins & Ali, 2000). Phosphorus increases growth rate of all plant parts, improves on canopy development and leaf size though the number of leaves may not be increased (Shunka *et al*., 2017). Appropriate amounts of phosphorus will provide energy for ion uptake and transport during the early stages of growth to facilitate proper crop growth and reproduction (Hopkins *et al.,* 2014). This is in conformity with the report of Grant *et al.* (2001), that adequate phosphorus application is important from the earliest stages of crop growth. This agrees with results of Misgina, (2016), Kumar *et al*. (2012) Rosen & Bierman (2008), and they reported that P rates increased the number of stems per plant. Alam *et al*. (2007) Hassanpanah *et al*. (2009); Nizamudin *et al*. (2003), and Zelalem *et al.* (2009); similarly found that control treatment recorded the least number of stems per plant in potatoes grown under field conditions.

The interaction effect of study sites and phosphorus rates, variety and P rates significantly increased plant height and number of stems. Phosphorous boosts the metabolic activity of the plants during the early growth stages that encourages stem elongation, number of stems, days to 50% flowering and days to 50 % physiological maturity. This result agrees with the work of Firew *et al*. (2016), Belachew (2016) and Misgina (2016), who reported that the height of potatoes (*Solanum tuberosum L.*) increased with increase in the amount of P applied (Kumar *et al*., 2012).. This result also agrees with the findings of Belachew, (2016) and Ekelof (2007), who reported that phosphorus enhances early crop development. This contradicts the findings of Misgina, (2016) and Zelalem *et al*. (2009) they reported that increased phosphorus rates delayed the days to 50 % physiological maturity of potato plants, who attributed this to sustained physiological activities of the plants, excessive accumulation of photosynthetic assimilates that lead to continued photosynthesis and growth of the plants. The differences in the days to 50% flowering and days to physiological maturity could be due to varietal differences, genetic makeup and response to the environmental conditions (Kawakami *et al.,* 2012; Kaguongo *et al.,* 2010).

5.2 Effects of phosphorus rates on yield of potato varieties propagated from rooted apical cuttings

Timely application of phosphorus (P) promotes early tuber development, increases tuber number and tuber size (Koch *et al*., 2020; Shunka *et al.,* 2017; Jenkins & Ali, 2000). The interaction effect of phosphorus and variety on plant biomass, size of tubers and number of eyes was highly significant. Phosphorus is vital for physiological processes in tuber formation and this could be attributed to increase in number of eyes produced. The varieties showed different amounts of biomass in response to the P rates due to differences in vegetative growth and use of available P. Zelalem *et al.* (2009), reported an increase in biomass weight after application of nitrogen phosphorus and potassium fertilizer. This is in conformity with results of Gitari *et al.*(2018), who reported that increase in P led to increase in formation of medium size tubers. In this study, Dutch Robyjn recorded high number of small size tubers which is sign of low yields. This study agrees with findings of Lung'aho *et al.* (2006), who reported reasons as to why farmers rejected potato varieties. They reported that Dutch Robyjn variety was rejected due to low yields. Phosphorus plays several plant functions including photosynthesis and transformation of sugars and starches. It also increases accumulation of assimilates that are converted into carbohydrates in tubers which increases tuber size (Chala *et al.*, 2017). These results are in agreement with the study of Belachew, (2016) who reported that increase in the phosphorus applied led to increase in number of large sized tubers obtained.

The interaction of study sites and variety on plant biomass, number of tubers, tuber weight, tuber size and number of eyes was highly significant. Adequate application of P influences total leaf area that increases light interception by the crops and this contributes directly to biomass accumulation (Alvarez-Sanchez *et al*., 1999; Jenkins & Ali, 2000; Zelalem *et al*., 2009). According to Zewide *et al*. (2012), adequate application of P_2O_5 significantly increased the above ground shoot biomass by 8.78% and underground biomass by 61.4%. The increase in biomass could be attributed to the prevailing climatic conditions and genetic makeup of the variety that supports biomass accumulation (Shunka *et al.,* 2017). The accumulation of biomass also varies amongst the varieties that are grown for example Jalene variety that was grown in this experiment showed the highest accumulation of biomass with application of nitrogen and phosphorus (Misgina, 2016; Zelalem *et al*., 2009). This could be attributed to the high number of tubers. The vegetative growth of the variety contributes to the high number of stems which correlates with the number of tubers formed (Belachew, 2016) ; CIP, 2017; Chala *et al*., 2017).

The factors that affect tuber weight are variety, location, organic matter content and total nitrogen (Zelalem *et al.,* 2009). This agrees with the current study because the soils had moderate amount of organic matter content and adequate total nitrogen and the varieties recorded different tuber weight. Jenkins and Mahmood (2003) reported that the average tuber weight of tubers is obtained when all the macro nutrients of NPK are adequately supplied.

The application of phosphorus increases number of tubers, tuber weight and marketable tuber yield of potatoes. Phosphorus is important for plant growth. This together with the fact that the rooted apical cuttings were of good quality contributed to the high yields obtained. In this study increasing the amount of P to 90 kg P ha^{-1} led to marketable tuber yield increase of 14,236 tonnes per hectare. This agrees with findings of (Belachew, 2016; Rosen and Bierman, 2008) who reported that increase in P applied led to increase in marketable tuber yield. The results are in conformity with the findings of Chala *et al.* (2017) and Zelalem *et al*. (2009).

The initial soil analysis showed that the study sites, had moderate levels of total nitrogen and total organic carbon which are essential for crop growth. These in addition with applied phosphorus could have promoted the growth and photosynthesis rate of the potato plants and promoted tuber formation. Mona *et al.* (2012) who used NPK fertilizer reported that increase in the amount of NPK applied in the soil increased the number of tubers per hill, tuber size and tuber weight.

The rainfall received in the study areas was adequate to support potato growth and the rooted apical cuttings were of good quality this could be attributed to the increased yields obtained. This is in conformity with the findings of (Rosen *et al*., 2014) who reported that the quality of seeds planted and rainfall amounts also contribute to the size and weight of the tubers that are harvested. These favourable conditions lead to increased accumulation of carbohydrates, proteins by the plant which are translocated from source to the sink hence increase in tuber weight (Chala *et al*., 2017; Gaur *et al.,* 2017). Increase in tuber weight is also associated with greater partitioning of the metabolites and adequate translocation of the photosynthates to the reproductive plant structures (Gaur *et al*., 2017).

The varieties utilized available P differently and this could be the reason for the difference in marketable tuber yield. These result agrees with the findings of Tein *et al.* (2014) who reported that varieties have different P requirements and P uptake which influences P utilization by the plants. This could be attributed to favourable conditions of optimum rainfall and warm temperatures at KALRO Molo that influenced higher marketable tuber yield. This is in accordance with the findings of Chala *et al*. (2017), they reported that growth factors like soil moisture, light and nutrients favoured photosynthesis and accumulation carbohydrates to the tubers.

The interaction effect of study sites and phosphorus on large size tubers was significant. Egerton study site received high amount of rainfall coupled with warm temperatures. This could be the reason for the high number of large size tubers obtained at Egerton study site as compared to KALRO Molo study site. According to the study by Otroshy (2006), the changes in day and night temperatures were reported to reduce the number of mini tubers formed per cutting. There was positive correlation between size of tubers and tuber weight with R values of $r^2 = 0.99$ and $r^2 = 0.94$ respectively; the bigger the tubers the higher the tuber weight. This agrees with findings of Merga, (2018) who reported that ideal tubers should be medium sized. This differences in size of tubers could be attributed to varietal differences, soil fertility levels and environmental factors like soil moisture and rainfall. The eyes in potato tubers are important because new plants grow and sprout establishment is effective. The size and shape of tubers affected the formation of eyes in tubers. The higher the number of eyes in tuber the higher the quality of the seed. Lung'aho *et al.* (2006), reported that farmers selected seed potato basing on the quality of eyes as it's related to number of stems produced which correlates to yield.

Phosphorus uptake and phosphorus use efficiency (PUE)

The main effect of phosphorus and variety on P uptake by the leaves prior to flowering and prior to maturity was significant but P uptake by the tubers was not significant. This could be attributed to age of the plants which leads to reduced concentration of P in the potato tubers. The soil pH at the study sites was at a range of 5.0 to 6.21 which might have favoured availability of phosphorus to the potato crops. This availability made the acquisition of phosphorus by the plants easy and led to increased P uptake. This result is in conformity with findings of Hopkins *et al*. (2014); Thornton *et al.* (2014); Rosen *et al*. (2014), who reported that soil pH affects the availability of phosphorus in the soil.

The interaction of study sites and varieties on phosphorus use efficiency was significant. Potato varieties with high PUE recorded the highest marketable tuber yield. This could be attributed to the ability of the varieties to acquire P from the soil and utilize it for biomass accumulation and yield. Wanjiku and Unica variety had high P acquisition and utilization ability which led to increase in yield as in conformity with the findings of Nyiraneza *et al.* (2017). This results also agrees with the following findings (Bayuelo & Ochoa, 2014; Fernandes *et al*., 2014; Wishart *et al*., 2013), that reported that differences in phosphorus utilization efficiency is influenced by cultivar characteristics such as root weight, root length and diameter.

Phosphorus availability in the soil is affected by the soil pH and is more available at slightly acidic soils (Hopkins *et al*., 2014). The soil pH at the study sites was at a range of 5.0 to 6.21 which might have favoured availability of phosphorus to the potato crops. This availability made the acquisition of phosphorus by the plants easy and led to increased phosphorus use efficiency and increased yield. This result is in conformity with findings of Hopkins *et al*. (2014), Rosen *et al*., (2014) and Thornton *et al.* (2014), who reported that soil pH affects the availability of phosphorus in the soil.

5.3 Effects of phosphorus rates on quality of potato varieties propagated from rooted apical cuttings

The study sites and phosphorus rates had significant influence on dry matter content, starch content and specific gravity of tubers. Zelalem *et al.* (2009); reported that increase in P and N led to decreased dry matter content of tubers. This agrees with results of this study because dry matter did not differ among P treatments. Dry matter contents help to determine the quality of potatoes both for cooking and for processing (Khan *et al*., 2020).

This agrees with Zelalem *et al*. (2009), that high P rates had no significant effect on specific gravity of tubers. This study also agrees with the work of Irfan *et al*. (2015) who reported that potato varieties with very high specific gravity are not suitable for making of chips, French fries, crisps because they are brittle and hard. There are many factors that affect specific gravity of tubers that is variety, location and fertilizer treatments applied (Khan *et al*., 2020). There was positive correlation between dry matter content, starch content and specific gravity of tubers with R values of 0.56, 0.63 and 0.67 respectively. This is consistent with the findings of Chala *et al*. (2017), they found that there was positive correlation between specific gravity and dry matter content, which is an indicator, that specific gravity influences the dry matter content of potato tubers.

The interaction effect of study sites and varieties influenced dry matter content, starch content and specific gravity of tubers. The factors that affect internal tuber trait qualities are soil type, soil moisture, rainfall amounts and variety. Egerton study site and KALRO Molo have sand clay soils characterized by good drainage, high water holding capacity and the rainfall amounts received were optimum thus this could promote high dry matter content of the tubers. This study agrees with the findings of Abong *et al*., (2015) and Kooman & Haverkort (1995), they reported other factors like temperature, solar radiation and day length influence to be affecting dry matter content. This could be attributed to the less rainfall amount that was received at KALRO Molo towards physiological maturity period of the potato. Other researchers reported significant differences in tuber internal traits due to varieties (Abebe *et al*., 2013; Hassanpanah *et al*., 2011). Fresh harvested potatoes contain about 80% water and 20% dry matter (Belachew, 2016). These qualities are key for processing of potato tubers because the high amount of dry matter content influences the color of French fries, chips and crisps. This agrees with findings of Khan *et al.* (2020), they reported that tubers with high dry matter content and specific gravity are preferred for processing.

The interaction effect of varieties and phosphorus on starch content, specific gravity of tubers was significant. Phosphorus contains nucleic acids, nucleotides, coenzymes and phospholipids that are responsible for biochemical and physiological reactions using ATP (Taiz & Zeiger, 2006) that involve photosynthesis and conversion of sugar into starch in plants (Kumar *et al*., 2017; Taheri *et al*., 2012). The high amounts of rainfall that were received during tuber initiation stages could be the reasons as to why there was reduced starch content due to excessive water taken up by the tubers.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Potato is one of the major food crops grown in Kenya highlands. Farmers produce potato for subsistence and for sale under small scale depending mainly on rain fed agriculture and some small scale irrigation. However, the yield of potato is far below the national average yield due to factors like low soil fertility, pests and diseases and low quality seed. The majority of the farmers use conventional tubers saved from the previous season harvest and some from seed suppliers that are not certified. Soil fertility and good quality seed are the major contributors to potato productivity. Thus this study was conducted to determine the effect of phosphorus rates on growth, yield and quality of potato varieties propagated from rooted apical cuttings. The following conclusions are drawn from the study:

i) Growth and development of the rooted apical cuttings was enhanced by application of phosphorus fertilizer. P rate of 30 kg P ha^{-1} gave Wanjiku and Shangi varieties the optimum growth and yield at both study sites.

ii) The different rates of phosphorus had significant influence on the dry matter content, starch content and specific gravity of tubers propagated from rooted apical cuttings.

6.2 Recommendations

Basing on the results of the study, the following recommendations can be made:

i) Rooted apical cuttings can be used for propagation of potato (*Solanum tuberosum* L.) to reduce problem of low quality seed in Njoro and Molo sub counties of Nakuru county in Kenya.

ii) The application rate of 30 kg P ha^{-1} with Wanjiku and Shangi varieties can be grown in the study sites and other areas with same agro ecological zones.

iii) Further studies on effect of phosphorus on the growth of rooted apical cuttings in comparison with the conventional tubers

REFERENCES

Abalo, G., Hakiza, J. J., El-Bedewy, R., & Adipala, E. (2003). Genotype x environment interaction studies on yields of selected potato genotypes in Uganda. *African Crop Science Journal*, *11*(1), 9-15.

Abebe, T., Wongchaochant, S., & Taychasinpitak, T. (2013). Evaluation of Specific Gravity of Potato Varieties in Ethiopia as a Criterion for Determining Processing Quality. *Agriculture and Natural Resources*, *47*(1), 30-41.

Abong, G. O., Okoth, M. W., Kabira, J. N., Ogolla, J., Ouma, J. & Ngunju, C. W. (2015). Physico-chemical Changes in Popular Kenyan Processing Potato Varieties as Influenced by Storage Condition. *Current Research in Nutrition and Food Science Journal,* 3(2), 112-120.

Alam, M. N., Jahan, M. S., Ali, M. K., Ashraf, M. A., & Islam, M. K. (2007). Effect of vermicompost and chemical fertilizers on growth, yield and yield components of potato in barind soils of Bangladesh. *Journal of Applied Sciences Research*, *3*(12), 1879-1888.

Alvarez-Sánchez, E., Etchevers, J. D., Ortiz, J., Núñez, R., Volke, V., Tijerina, L., & Martinez, A. (1999). Biomass production and phosphorus accumulation of potato as affected by phosphorus nutrition. *Journal of plant nutrition*, *22*(1), 205-217.

Anderson, S. H., Gantzer, C. J., Boone, J. M., & Tully, R. J. (1988). Rapid non -destructive bulk density and soil-water content determination by computed tomography. *Soil Science Society of America Journal*, *52*(1), 35-40.

Anderson, J. M., & Ingram, J. S. I. (1993). Tropical soil biological and fertility: a handbook of methods. *Wallingford: CAB International, 2ed. 221p*.

Anjum, M. A., & Ali, H. (2004). Effect of culture medium on shoot initiation from calluses of different origin in Potato (*Solanum tuberosum* L). *Biotechnology*, *3*(2), 194-199.

Asfaw, A., Bonierbale, M., & Khan, M. A. (2015). Integrative breeding strategy for making climate-smart potato varieties for sub-Saharan Africa. *Potato and sweet potato in Africa: transforming the value chains for food and nutrition security 2015*, 134-42.

Atkinson, D., Geary, B., Stark, J., Love, S. & Windes, J. (2003). Potato varietal responses to nitrogen rate and timing in Idaho *Potato Conference on January* (Vol. 22, p. 59).

Badr, M. A., El-Tohamy, W. A. & Zaghloul, A. M. (2012). Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. *Agricultural Water Management*, *110*, 9-15.

Badoni, A. & Chauhan, J. S. (2010). In vitro sterilization protocol for micropropagation of Solanum tuberosum cv 'Kufri Himalini'. *Academia Arena*, *2*(4), 24-27.

Balemi, T. (2009). Effect of phosphorus nutrition on growth of potato genotypes with contrasting phosphorus efficiency. *African crop science journal*, *17*(4).

Belachew, B. (2016). Effect of Nitrogen and Phosphorus rates on growth, yield, yield components and quality of Potato (*Solanum tuberosum* L.) At Dedo, South West Ethiopia. *Abstract. An M.Sc Thesis presented to School of Graduate Study of Jimma University, Ethiopia.*

Bewell, E. R. (1937). The determination of the cooking quality of potatoes. *American Potato Journal*, *14*(8), 235-242.

Burlingame, B., Mouillé, B., & Charrondiere, R. (2009). Nutrients, bioactive non-nutrients and anti-nutrients in potatoes. *Journal of food composition and analysis*, *22*(6), 494-502.

Chala, G., Chindi, A. & Obsa, Z. (2017). Response of Applied Phosphorus Fertilizer Rate and Plant Spacing for Potato. *Greener Journal of Agricultural Sciences* 7, 255-262.

Champoiseau, P. G., Jones, J. B., Momol, T. M., Pingsheng, J., Allen, C., Norman, D. J. & Caldwell, K. (2010). Ralstonia solanacearum Race 3 biovar 2 causing brown rot of potato, bacterial wilt of tomato and southern wilt of geranium. Madison: *American Phytopathological Society*.
DisponibleEnHttp://Plantpath.Ifas.Ufl.Edu/Rsol/NRI_Project/Projectsummary.

Chawla, H.S. (2003), *Plant Biotechology,* Laboratory manual for Plant biotechnology, Oxford and IBH publishing Co. Pvt. Ltd. New Delhi.

Chindi, A., Woldegiorgis, G., Solomon, A., Tesema, L., Negash, K., Lemaga, B., & Schulz, S. (2013). Enhancing potato seed production using rapid multiplication techniques.

Climatic data.org. (2019). Climate Nakuru. Available online at https://weather-and-climate.com/average-monthly-min-max-Temperature,Nakuru,Kenya Accessed on 11[Th] July 2020

Ekelöf, J. (2007). Potato yield and tuber set as affected by phosphorus fertilization.

Ekin, Z. (2011). Some analytical quality characteristics for evaluating the utilization and consumption of potato (*Solanum tuberosum* L.) tubers. *African Journal of Biotechnology*, *10*(32), 6001-6010.

Ewell, P. T. (2002). Sweet potato production in Sub-Saharan Africa: Patterns and key issues. *Nairobi, Kenya: CIP*.

FAO. (2017). Data. Available at http://www.fao.org/faostat/en/#search/potatoes Accessed on 12th July, 2019.

FAO. 2018. Available at Source: http://www.fao.org/faostat/en/#data/QC

Fernandes, A. M., Soratto, R. P. & Gonsales, J. R. (2014). Root morphology and phosphorus uptake by potato cultivars grown under deficient and sufficient phosphorus supply. *Scientia Horticulturae,* 180, 190-198.

Firew, G., Nigussie, D., & Wassu, M. (2016). Response of potato (*Solanum tuberosum* L.) to the application of mineral nitrogen and phosphorus fertilizers under irrigation in Dire Dawa, Eastern Ethiopia. *Journal of Natural Sciences Research*, *6*, 19-37.

Fixen, P. E. & Bruulsema, T. W. (2014). Potato management challenges created by phosphorus chemistry and plant roots. *American journal of potato research*, *91*(2), 121-131.

Gaur, D., Singh, S. P., Sharma, K., Sharma, S. K., Dhakad, H., Dangi, R. S., ... & Rai, A. K. (2017). Effect of different phosphorus levels on growth attributes physiological parameter and grading of tuber in potato crop (*Solanum tuberosum* L.). *Int J Chem Stud*, *5*(6), 215-219.

Gebru, H., Mohammed, A., Dechassa, N., & Belew, D. (2017). Assessment of production practices of smallholder potato (*Solanum tuberosum* L.) farmers in Wolaita zone, southern Ethiopia. *Agriculture & Food Security*, *6*(1), 31.

George, E.F., Hall, M.A., & DeKlerk, G.J. (2008). Plant propagation by tissue culture 3rd Edition. The Netherland, The Back Ground Springer

Gitari, H. I., Karanja, N. N., Gachene, C. K. K. & Kamau, S. (2018). Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems. *Field Crops Research,* 222, 78–84.

Gomez, K. A., Gomez, A. A. & Gomez, A. A. (1984). Second Edition / I (Vol. 6).Statistical procedures for agricultural research. John Wiley and sons.

Grant, C.A., Flaten, D.N., Tomaisiewicz, D.J., & Sheppard, S.C. (2001). The importance of early season phosphorus nutrition. *Canadian journal of plant science*, *81*(2) 211-224.

Hassanpanah, D. (2011). Analysis of G× E interaction using the additive main effects and multiplicative interaction (AMMI) in potato cultivars. *African Journal of Biotechnology*, *10*(2), 154-158.

Hassanpanah, D., Hosienzadeh, A. A., Dahdar, B., Allahyari, N., Imanparast, L., Geren, H., & Guillen, N. (2009). 1945941. Effects of different rates of nitrogen and phosphorus fertilizers on yield and yield components of Savalan potato cultivar mini-tubers. *Journal of food, agriculture & environment*, *7*(2), 415-418.

Hassanpanah, D., Hassanabadi, H., & Chakherchaman, S. A. (2011). Evaluation of cooking quality characteristics of advanced clones and potato cultivars. *American Journal of Food Technology*, *6*(1), 72-79.

Hopkins, B., Hopkins, B. G., Horneck, D. A. & Macguidwin, A. E. (2014). Improving Phosphorus Use Efficiency through Potato Rhizosphere Modification and Extension. *American Journal of Potato Research*, *91*(2), 161–174.

Hoque, M. E. (2010). In vitro regeneration potentiality of potato under different hormonal combination. *World Journal of Agricultural Sciences*, 6, 660-663.

Horton, D. (1988). Underground Crops. Morrilton, AR 72110 USA: Longman Group,UK.

Hossain, M. J. & Nahar, M. S. (2012). Establishment and Growth of Potato Micro-Cuttings in Sand Trays. *American Journal of Plant Sciences* 3, 1219.

Hughes, J. C. (1974). Factors influencing the quality of ware potatoes. 2. Environmental factors. *Potato Research*, *17*(4), 512-547.

International Potato Center (CIP). (2017). Apical rooted cuttings to enhance seed potato production. Retrieved from npck.org/Books/Rootedcuttingsbrochuretechnologybrieflow.pdf

Irfan, M., Singh, B. N., & Singh, G. R. Effect of customized fertilizers on the performance of Potato (*Solanum tuberosum* L.). *EEC*, *2015*, 200.

Islam, M. R. & Nahar, B. S. (2012). Effect of organic farming on nutrient uptake and quality of potato. *Journal of Environmental Science and Natural Resources*, *5*, 219-224.

Jaetzold, R., Hornetz, B., Shisanya, C.A. & Schmidt, H. (2012). Farm management handbook of Kenya Vol I-IV (Western, Central, Eastern, Nyanza, Southern Rift Valley, Northern Rift Valley and Coast). Nairobi: Government Printers. Available from https://www.unitrier.de/index.php?id=58581

Janssens, S.R.M, Wiersema S.G. & Goos.H, W. (2013). The value chain for seed and ware potatoes in Kenya Opportunities for development (No. 13-080) Wageningen UR.

Jenkins, P. D., & Ali, H. (2000). Phosphate supply and progeny tuber numbers in potato crops. *Annals of Applied Biology*, *136*(1), 41-46.

Jenkins, P. D., & Mahmood, S. (2003). Dry matter production and partitioning in potato plants subjected to combined deficiencies of nitrogen, phosphorus and potassium. *Annals of applied biology*, *143*(2), 215-229.

Jiang, W., Liu, X., Wang, X., Yang, L., & Yin, Y. (2019). Improving Phosphorus Use Efficiency and Optimizing Phosphorus Application Rates for Maize in the Northeast Plain of China for Sustainable Agriculture. *Sustainability*, *11*(17), 4799.

Johansen, T. J., Lund, L.,& Nilsen, J. (2002). Influence of day length and temperature during formation of seed potatoes on subsequent growth and yields under long day conditions. *Potato research*, *45*(2-4), 139-143.

Johnston, A. E., & Syers, J. K. (2009). A new approach to assessing phosphorus use efficiency in agriculture. *Better Crops*, *93*(3), 14-16.

Kaguongo, W. (2017). National potato variety catalogue, CIP International Potato Centre. Nairobi.

Kaguongo, W., Gildemacher, P., Demo, P., Wagoire, W., Kinyae, P., Andrade, J. & Thiele, G. (2008). Farmer practices and adoption of improved potato varieties in Kenya and Uganda (No. Social Sciences working paper 2008-5). *Commercial Grafica Sucre*.

Kaguongo, W. P., Ng'ang'a, N. M., Muthoka, N., Muthami, F. & Maingi, G. (2010). Seed potato subsector master plan for Kenya (2009-2014). Seed potato study sponsored by GTZ-PSDA, USAID, CIP and Government of Kenya. Ministry of Agriculture, Kenya.

Kawakami, J., & Iwama, K. (2012). Effect of potato microtuber size on the growth and yield performance of field grown plants. *Plant Production Science*, *15*(2), 144-148.

Khan, M. Z., Akhtar, M. E., Safdar, M. N., Mahmood, M. M., Ahmad, S., & Ahmed, N. (2010). Effect of source and level of potash on yield and quality of potato tubers. *Pak. J. Bot*, *42*(5), 3137-3145.

Kingori, G. G., Nyamori, A. J. & Khasungu, I. D. (2015). Optimization of Seed Potato Specific Density, Starch and Dry Matter Contents and Tuberization Capacity of Resultant Plants through Integrated Irrigation, Nitrogen and Phosphorus Management. *Journal of Plant Sciences*, *3*, 225.

Komen, S. K., Ochuodho, J. O. & Auma, E. O. (2018). Effect of Site and Variety on Yield of Seed Potato in the North Rift Region of Kenya. *Open Agriculture, 3*(1), 296-300.

Koch, M., Naumann, M., Pawelzik, E., Gransee, A., & Thiel, H. (2020). The importance of nutrient management for potato production Part I: Plant nutrition and yield. *Potato Research*, *63*(1), 97-119.

Kochian, L. V. (2012). Rooting for more phosphorus. *Nature*, *488*(7412), 466-467.

Kooman, P. L., & Haverkort, A. J. (1995). Modelling development and growth of the potato crop influenced by temperature and day length: LINTUL-POTATO. In *Potato ecology and modelling of crops under conditions limiting growth* (pp. 41-59). Springer, Dordrecht.

Kumar, M., Baishaya, L. K., Ghosh, D. C., Gupta, V. K., Dubey, S. K., Das, A., & Patel, D. P. (2012). Productivity and soil health of potato (Solanum tuberosum L.) field as influenced by organic manures, inorganic fertilizers and biofertilizers under high altitudes of eastern Himalayas. *Journal of Agricultural Science*, *4*(5), 223.

Kumar, V., Sharma, A., Soni, J. K., & Pawar, N. (2017). Physiological response of C3, C4 and CAM plants in changeable climate. *The Pharma Innovation*, *6*(9, Part B), 70.

Kleinkopf, G. E., Westermann, D. T., Wille, M. J., & Kleinschmidt, G. D. (1987). Specific gravity of Russet Burbank potatoes. *American potato journal*, *64*(11), 579-587.

Laboski, C. A. & Kelling, K. A. (2007). Influence of fertilizer management and soil fertility on tuber specific gravity: a review. *American Journal of Potato Research, 84*(4), 283-290.

Landon, J. R. (1991). Booker tropical soil manual Longman Scientific and Technical. *Essex, England*.

Leonel, M., Do Carmo, E. L., Fernandes, A. M., Soratto, R. P., Ebúrneo, J. A. M., Garcia, É. L., & Dos Santos, T. P. R. (2017). Chemical composition of potato tubers: the effect of cultivars and growth conditions. *Journal of food science and technology*, *54*(8), 2372-2378.

Lulai, E. C., & Orr, P. H. (1979). Influence of potato specific gravity on yield and oil content of chips. *American Potato Journal*, *56*(8), 379-390.

Lutaladio, N. & Castaldi, L. (2009). Potato: The hidden treasure. *Journal of Food Composition and Analysis*, *22*(6), 491-493.

Lung'aho, C., Nderitu, S. K. N., Kabira, J. N., El-Bedewy, R., Olanya, O. M. & Walingo, A. (2006). Yield performance and release of four late blight tolerant potato varieties in Kenya. *Journal of Agronomy*, 5, 57-61.

Margenot, A. J., Singh, B. R., Rao, I. M., & Sommer, R. (2017). Phosphorus fertilization and management in soils of Sub-Saharan Africa. *Rattan Lal, BA Stewart*, 151-208.

Margenot, A. J., Sommer, R., & Parikh, S. J. (2018). Soil Phosphatase Activities across a Liming Gradient under Long-Term Managements in Kenya. *Soil Science Society of America Journal*, *82*(4), 850-861.

McGrance, S. J., Cornell, H. J., & Rix, C. J. (1998). A simple and rapid colorimetric method for the determination of amylose in starch products. *Starch-Stärke*, *50*(4), 158-163.

Mehlich, A., Pinkerton, A., Robertson, W., & Kempton, R. (1962). Mass analysis methods for soil fertility evaluation. *Internal Publication, Ministry of Agriculture, Nairobi*.

Merga, G. (2018). Effects of nitrogen, phosphorus and cattle manure on yield and yield related traits of Potato (*Solanum tuberosum* L.) in Haramaya District, Eastern Ethiopia Haramaya University. Haramaya University.

Mikkelsen, R. L., Binder, C. R., Frossard, E., Brand, F. S., Scholz, R. W., & Vilsmaier, U. (2014). Use: What is needed to support sustainability? In *Sustainable Phosphorus Management* (pp. 207-246). Springer, Dordrecht.

Mikkelsen, R. (2015). Phosphorus management for potatoes. *Better Crops Plant Food*, *99*(4), 10-11.

Misgina, N. A. (2016). Effect of phosphorus and potassium fertilizer rates on yield and yield component of potato (S*olanum tuberosum* L.) at K/Awlaelo, Tigray, Ethiopia. *Food Science and Quality Management*, *48*, 60-69.

Mohapatra, P. P. & Batra, V. K. (2017). Tissue Culture of Potato (*Solanum tuberosum* L.): A Review. *International Journal of Current Microbiology and Applied Sciences*, *6*(4) 489–495.

Mohammed, W. (2016). Specific gravity, dry matter content, and starch content of potato (*Solanum tuberosum* L.) varieties cultivated in Eastern Ethiopia. *East African Journal of Sciences*, *10*(2), 87-102.

Mona, E. E., Ibrahim, S. A., & Manal, F. M. (2012). Combined effect of NPK levels and foliar nutritional compounds on growth and yield parameters of potato plants (*Solanum tuberosum* L.). *African Journal of Microbiology Research*, *6*(24), 5100-5109.

Monneveux, P., Ramírez, D. A., & Pino, M. T. (2013). Drought tolerance in potato (*S. tuberosum* L.): Can we learn from drought tolerance research in cereals? *Plant Science*, *205*, 76-86.

Motsara, M. R. & Roy, R. N. (2008). *Guide to laboratory establishment for plant nutrient analysis* (Vol. 19). Rome: Food and Agriculture Organization of the United Nations.

Moorby, J. (1978). The physiology of growth and tuber yield. In *The potato crop* (pp. 153-194). Springer, Boston, MA.

Moorthy, S. N., Andersson, L., Eliasson, A. C., Santacruz, S. & Ruales, J. (2006). Determination of amylose content in different starches using modulated differential scanning calorimetry. *Starch-Stärke*, *58*(5), 209-214.

Muthoni, J. & Nyamongo, D. O. (2009). A review of constraints to ware Irish potatoes production in Kenya. Journal of Horticulture and Forestry, *1*(7), 098-102.

Muthoni, J., Shimelis, H. & Melis, R. (2013). Potato Production in Kenya : Farming Systems and Production Constraints. *Journal of Agricultural Science*, *5*(5), 182–197.

Nand, K. F., Baligar, V. C., & Jones, C. A. (2011). Growth and mineral nutrition of field crops.

National potato council of Kenya. (2019) Potato variety catalogue Available at: https://npck.org/Catalogues/NPCKOnlineDocument.pdf

Naumann, M., Koch, M., Thiel, H., Gransee, A., & Pawelzik, E. (2020). The importance of nutrient management for potato production part II: Plant nutrition and tuber quality. *Potato Research*, *63*(1), 121-137.

Navarre, R., & Pavek, M. J. (Eds.). (2014). *The potato botany, production and uses*. CABI.

Nizamuddin, M., Mahmood, M., Farooq, K., & Riaz, S. (2003). Response of potato crop to various levels of NPK. *Asian J. Plant Sci*, *2*(2), 149-151.

Nyiraneza, J., Bizimungu, B., Messiga, A. J., Fuller, K. D. & Jiang, Y. (2017). Potato yield and phosphorus use efficiency of two new potato cultivars in New Brunswick, Canada. *NRC Research Press*, *97*(5), 784–795.

Nolte, P., Miller, J., Duellman, K. M., Gevens, A. J., & Banks. E (2020). Disease management. In *Potato Production Systems*, pp. 203-257. Springer, Cham.

Otroshy, M. (2006). Utilization of tissue culture techniques in a seed potato tuber production scheme.

Öztürk, E., Kavurmacı, Z., Kara, K. & Polat, T. (2010). The effects of different nitrogen and phosphorus rates on some quality traits of potato. *Potato research*, *53*(4), 309-312.

Page, A. L., Miller, R. H., Keeney, D. R., Baker, D. E., Ellis, R., & Rhoades, J. D. (1982). *Methods of soil analysis. eds* (No. 631.41 MET 9-2 1982. CIMMYT).

Pandey, K. B., & Rizvi, S. I. (2009). Plant polyphenols as dietary antioxidants in human health and disease. *Oxidative medicine and cellular longevity*, *2*(5), 270-278.

Powon, M. P., Aguyoh, J. N., & Mwaj, A. V. (2006). Growth and tuber yield of potato (Solanum tuberosum L.) under different levels of phosphorus and farm yard manure. *Agricultura Tropica ET Subtropica*, *39*(3),1-6

Riungu, C. (2011). No easy walk for potatoes. *Horticultural News. The East African Fresh Produce Journal*, *19*, 16-17.

Rosen, C. J., & Bierman, P. M. (2008). Potato yield and tuber set as affected by phosphorus fertilization. *American Journal of Potato Research*, *85*(2), 110-120.

Rosen, C. J., Kelling, K. A., Stark, J. C. & Porter, G. A. (2014). Optimizing phosphorus fertilizer management in potato production. *American Journal of Potato Research, 91*(2), 145-160.

Singh, S. K. & Lallawmkima, I. (2018). Multisource Nutrient Application in Potato for High Grade Tuber Production. *Acta Scientific Agriculture*, 2, 54–58.

Shunka, E., Chindi, A., Gebremedhin, W. G., Seid, E. & Tessema, L. (2017). Determination of optimum nitrogen and potassium levels for potato production in central high lands of Ethiopia. *Open Agriculture*, *2*(1), 189-194.

Soratto, R. P., Pilon, C., Fernandes, A. M., & Moreno, L. A. (2015). Phosphorus uptake, use efficiency, and response of potato cultivars to phosphorus levels. *Potato Research*, *58*(2), 121-134.

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Prasad, P. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, *71*(2), 632-641.

Suman, S. (2017). Plant Tissue Culture : A promising tool of quality material production with special reference to micro-propagation of Banana

Syers, K., Johnston, A. E., & Curtin, D. (2008). FAO fertilizer and plant nutrition bulletin 18. *Food and Agriculture Organization of the United Nations, Rome, Italy*.

Taheri, N., Sharif-Abad, H. H., Yousefi, K., & Roholla-Mousavi, S. (2012). Effect of compost and animal manure with phosphorus and zinc fertilizer on yield of seed potatoes. *Journal of soil science and plant nutrition*, *12*(4), 705-714.

Taiz, L., & Zeiger, E. (2006). Plant Physiology., 4th edn.(Sinauer Associates: Sunderland, MA.).

Tein, B., Kauer, K., Eremeev, V., Luik, A., Selge, A., & Loit, E. (2014). Farming systems affect potato (*Solanum tuberosum* L.) tuber and soil quality. *Field Crops Research*, *156*, 1-11.

Teshome, S., Bobo, T. & Wako, B. (2019). Response of Application Time and Method of Inorganic Phosphorus Fertilizer on Irish Potato (*Solanum tuberosum* L .) Production at Bore and Anasora Area, Southern Oromia, Ethiopia. *Technology*, *2*(4), 45–54.

Thornton, M. K., Novy, R. G. & Stark, J. C. (2014). Improving phosphorus use efficiency in the future. *American journal of potato research*, *91*(2), 175-179.

Toroitich, P. K. (2017). A Model for early detection of potato late blight disease: a case Study in Nakuru County (Doctoral dissertation, Strathmore University).

Tsoka, O. Demo, P. Nyende, A.B. & Ngamau, K. (2012). Potato seed tuber production from in vitro and apical stem cutting under aeroponic system. *African Journal of Biotechnology*, *11*(12), 612–618.

Van de Wiel, C. C., van der Linden, C. G., & Scholten, O. E. (2016). Improving phosphorus use efficiency in agriculture: opportunities for breeding. *Euphytica*, *207*(1), 1-22.

VanderZaag, P., & Escobar, V. (1990). Rapid multiplication of potatoes in the warm tropics: rooting and establishment of cuttings. *Potato research*, *33*(1), 13-21

Westermann, D. T.,& Kleinkopf, G. E. (1985). Phosphorus Relationships in Potato Plants 1. *Agronomy Journal*, *77*(3), 490-494.

Westermann, D. T. (2005). Nutritional requirements of potatoes. *American Journal of Potato Research*, *82*(4), 301-307.

Wishart, J., George, T. S., Brown, L. K., Ramsay, G., Bradshaw, J. E., White, P. J. & Gregory, P. J. (2013). Measuring variation in potato roots in both field and glasshouse: the search for useful yield predictors and a simple screen for root traits. *Plant and Soil*, *368*(1-2), 231-249.

Yasmin, A., Jalbani, A. A. & Raza, S. (2011). Effect of growth regulators on meristem tip culture of local potato cvs. Desiree and Patrones. *Pakistan Journal of Agriculture, Agricultural Engineering, and Veterinary Science, 27*(2), 143-149.

Zelalem, A., Tekalign, T. & Nigussie, D. (2009). Response of potato (*Solanum tuberosum* L.) to different rates of nitrogen and phosphorus fertilization on vertisols at Debre Berhan, in the central highlands of Ethiopia. *African Journal of Plant Science*, *3*(2) 16-24.

Zewide, I., Mohammed, A. & Tulu, S. (2012). Effect of different rates of nitrogen and phosphorus on yield and yield components of potato (Solanum tuberosum L.) at Masha District, Southwestern Ethiopia. *International Journal of Soil Science*, *7*(4), 146-156.

Zewide, I., Ibrahim, A. M., & Tadesse, S. T. (2016). Potato (*Solanum tuberosum* L.) Growth and Tuber Quality, Soil Nitrogen and Phosphorus Content as Affected by Different Rates of Nitrogen and Phosphorus at Masha District in Southwestern Ethiopia. International journal of Agricultural Research, 11 (3), 95-104.

APPENDICES

Appendix A: Research permit

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Date of Issue: **19/March/2020**

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This is to Certify that Ms.. Pauline Aarakit of Egerton University, has been licensed to conduct research in Nakuru on the topic: EFFECTS OF PHOSPHOROUS APPLICATION RATES ON GROWTH, YIELD AND QUALITY OF SEED POTATO VARIETIES (Solanum tuberosum L.) PROPAGATED BY ROOTED APICAL CUTTINGS for the period ending : 19/March/2021.

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Appendix B: Abstract of the publication

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Full Length Research Paper

Effect of phosphorus application rates on the quality of potato propagated from rooted apical cuttings

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This study determined the effect of phosphorus application rates on quality of potato tubers. Field experiments were set up at Egerton University, Njoro and Kenya Agricultural Livestock and Research Organization (KARLO), Molo. A randomized complete block design with split plot arrangement and three replicates were used. Main plot factors were varieties (*Shangi, Dutch Robyjn, Unica* and *Wanjiku*). Sub plot factors were phosphorus levels (0, 30, 60, 90 kg P ha^{-1}). Data collected was subjected to analysis of variance (ANOVA) using SAS software version 9.3. Application of 0 and 60 kg P ha^{-1} at KALRO Molo resulted in significantly higher ($P<0.05$) tuber dry matter contents of 23.49 and 25.76%, respectively. Unica variety at Egerton site and Dutch Robyjn and Wanjiku at KARLO, Molo site recorded significantly higher ($P<0.001$) dry matter and starch contents of 24.70, 25.52, and 23.45%, respectively. Wanjiku variety and application of 60 kg P ha^{-1} resulted in significantly higher ($P<0.05$) tuber starch content of 22.07%. Shangi with 0 and 60 kg P ha^{-1}, Dutch Robyjn and Unica with 0, 30, 60 and 90 kg P ha^{-1} and Wanjiku with 0, 30, and 60 kg P ha^{-1} recorded significantly higher ($P<0.001$) specific gravity of tubers. Application of phosphorus is recommended for improvement in quality of potato propagated from rooted apical cuttings.

Key words: Dry matter, potato, rooted apical cuttings, specific gravity, starch content.

Appendix C: Rainfall and Temperature averages for Egerton and KALRO Molo study sites

Months	July	August	September	October	November	December	January
Egerton							
Rainfall (mm)	146	76.4	89.7	161.6	289.4	223.6	83.9
Temperature ℃	19.1	19.2	20.5	19.3	19.3	18.9	19.6
Molo							
Rainfall (mm)	109.3	79.7	79.6	178.4	237.4	198.2	76.8
Temperature ℃	17	18	18	19	19	18	19

Appendix D: Analysis of variance for plant survival at 14 and 28 DAP for all study sites

		14 DAP				28 DAP			
Source of variation	**d.f**	**SS**	**Mean Square**	**F Value**	**Pr > F**	**SS**	**Mean square**	**F Value**	**Pr > F**
Location	2	543.513	271.556	49.55	<.0001	1048.847	524.423	56.53	<.0001
Replicate	2	5.013	2.506	0.46	0.634	20.847	10.423	1.12	0.3297
Variety	3	256.250	85.416	15.57	<.0001	203.131	67.710	7.30	0.0002
Replicate*Variety	6	41.708	6.951	1.27	0.280	47.430	7.905	0.85	0.5334
Location*Variety	6	264.208	44.034	8.03	<.0001	159.263	26.543	2.86	0.0136
Phosphorus	3	50.750	16.916	3.08	0.0314	52.576	17.525	1.89	0.1373
Variety*Phosphorus	9	27.194	3.021	0.55	0.8332	81.618	9.068	0.98	0.4642
Location*Phosphorus	6	21.875	3.645	0.66	0.6782	46.486	7.747	0.84	0.5460
Location*Variety*P	18	132.847	7.380	1.35	0.1804	143.402	7.966	0.86	0.6277
Error	88	482.611111	5.484217			816.388	9.277		
Total	143								

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix E: Analysis of variance for plant survival at 42 and 56 DAP for all study sites

		42 DAP				56 DAP			
Source of variation	**d.f**	**SS**	**Mean square**	**F Value**	**Pr > F**	**SS**	**Mean square**	**F value**	**Pr > F**
Location	2	4705.847	2352.923	350.32	<.0001	215.219	107.609	359.47	< .0001
Replicate	2	28.930	14.465	2.15	0.1221	2.507	1.253	4.19	0.0183
Variety	3	148.798	49.599	7.38	0.0002	6.987	2.329	7.78	0.0001
Replicate*Variety	6	58.013	9.668	1.44	0.2087	1.961	0.326	1.09	0.3736
Location*Variety	6	137.763	22.960	3.42	0.0044	4.696	0.782	2.61	0.0222
Phosphorus	3	2.354	0.784	0.12	0.9500	1.025	0.342	1.14	0.3367
Variety*Phosphorus	9	68.506	7.611	1.13	0.3483	3.590	0.398	1.33	0.2319
Location*Phosphorus	6	52.541	8.756	1.30	0.2639	3.459	0.576	1.93	0.0853
Location*Variety*P	18	133.847	7.435	1.11	0.3593	3.458	0.192	0.64	0.8566
Error	88	591.055	6.716			26.343	0.299		
Total	143								

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix F: Analysis of variance for Number of stems per plant at 28 and 42 DAP for all study sites

		28 DAP				42 DAP			
Source of variation	**d.f**	**SS**	**Mean square**	**F value**	**Pr>F**	**SS**	**Mean square**	**F Value**	**Pr >F**
Location	2	23.323	11.661	409.14	< .0001	34.108	17.054	208.93	<.0001
Replicate	2	0.321	0.160	5.63	0.0050	0.033	0.016	0.21	0.8143
Variety	3	0.495	0.165	5.80	0.0012	0.423	0.141	1.73	0.1668
Replicate*Variety	6	0.525	0.087	3.07	0.0089	1.251	0.208	2.55	0.0251
Location*Variety	6	0.688	0.114	4.03	0.0013	1.266	0.211	2.59	0.0235
Phosphorus	3	3.852	1.284	45.05	< .0001	9.637	3.212	39.35	<.0001
Variety*Phosphorus	9	0.430	0.047	1.68	0.1063	0.680	0.075	0.93	0.5064
Location*Phosphorus	6	2.109	0.351	12.34	< .0001	0.745	0.124	1.52	0.1805
Location*Variety*P	18	0.548	0.030	1.07	0.3961	2.413	0.134	1.64	0.0665
Error	88	2.508	0.028			7.183	0.081		
Total	143								
CV (%)		10.81				11.95			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix G: Analysis of variance for Number of stems per plant at 56 DAP for all study sites

Source of variation	d.f	SS	Mean squares	F value	Pr > F
Location	2	668.347	334.173	194.18	< .0001
Replicate	2	2.722	1.361	0.79	0.4566
Variety	3	25.583	8.527	4.96	0.0032
Replicate*Variety	6	17.166	2.861	1.66	0.1397
Location*variety	6	52.041	8.673	5.04	0.0002
Phosphorus	3	165.472	55.157	32.05	< .0001
Variety*phosphorus	9	18.250	2.027	1.18	0.3188
Location*phosphorus	6	15.989	2.664	1.55	0.1720
Location*Variety*P	18	56.291	3.127	1.82	0.0353
Error	88	151.44	1.721		
Total	143				
CV (%)		18.2			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix H: Analysis of variance for plant height at 14 and 28 DAP for all study sites

		14 DAP				28 DAP			
Source of variation	d.f	SS	Mean square	F value	Pr >F	SS	Mean square	F value	Pr> F
Location	2	113.393	56.696	133.93	< .0001	157.261	78.630	133.86	< .0001
Replicate	2	0.133	0.066	0.16	0.8545	5.398	2.699	4.60	0.0126
Variety	3	163.032	54.344	128.37	< .0001	150.250	50.083	85.26	< .0001
Replicate*Variety	6	4.619	0.769	1.82	0.1045	14.411	2.402	4.09	0.0012
Location*variety	6	25.990	4.331	10.23	< .0001	41.142	6.857	11.67	< .0001
Phosphorus	3	1.691	0.563	1.33	0.2691	53.451	17.816	30.33	< .0001
Variety*Phosphorus	9	4.187	0.465	1.10	0.3720	12.819	1.424	2.42	0.0164
Location*phosphorus	6	3.216	0.536	1.27	0.2811	17.795	2.965	5.05	0.0001
Location*Variety*P	18	4.035	0.224	0.53	0.9366	15.202	0.844	1.44	0.1343
Error	88	37.252	0.423			51.6921667	0.5874110		
Total	143								
CV (%)		13.71				13.72			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix I: Analysis of variance for plant height at 42 and 56 DAP for all study sites

		42 DAP				**56 DAP**			
Source of variation	d.f	SS	Mean squares	F value	Pr> F	SS	Mean squares	F value	Pr > F
Location	2	63.114	31.557	153.59	< .0001	112.903	56.451	247.35	< .0001
Replicate	2	0.432	0.216	1.05	0.3532	0.467	0.233	1.02	0.3631
Variety	3	13.002	4.334	21.09	< .0001	18.539	6.179	27.08	< .0001
Replicate*Variety	6	4.426	0.737	3.59	0.0031	4.328	0.721	3.16	0.0074
Location*variety	6	5.089	0.848	4.13	0.0011	6.806	1.134	4.97	0.0002
Phosphorus	3	22.954	7.651	37.24	< .0001	26.102	8.701	38.12	< .0001
Variety*phosphorus	9	1.233	0.137	0.67	0.7365	1.142	0.126	0.56	0.8289
Location*phosphorus	6	5.141	0.856	4.17	0.0010	6.426	1.071	4.69	0.0003
Location*Variety*P	18	2.758	0.153	0.75	0.7549	2.661	0.147	0.65	0.8515
Error	88	18.0811322	0.2054674			20.083	0.228		
Total	143								
CV (%)		13.42							

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix J: Mean squares of days to 50% flowering, days to 50% physiological maturity and plant biomass

Source of variation	D.f	Days to flowering	Days to physiological maturity	Plant biomass
Replicate	2	27.40**	40.32^{ns}	0.018***
Replicate*Variety	6	7.83^{ns}	59.14*	0.0005^{ns}
Location	1	17.51*	348.84***	0.137***
Variety	3	1341.15***	3906.70***	0.273***
Location*Variety	3	69.23***	11.37^{ns}	0.026***
Phosphorus	3	12.95*	30.76^{ns}	0.005***
Phosphorus*Variety	9	4.31^{ns}	35.47^{ns}	0.002**
Location*Phosphorus*Variety	9	4.204^{ns}	10.45^{ns}	0.001^{ns}
CV		3.65	5.43	11.55
R^2		0.93	0.88	0.94

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix K: Mean squares of number of tubers, tuber weight and marketable tuber yield

Source of variation	d.f	Number of tubers	Tuber weight	Marketable tuber yield
Replicate	2	29.54**	0.10**	5.76*
Replicate*Variety	6	7.26^{ns}	0.006^{ns}	0.99^{ns}
Location	1	2741.34***	13.36***	$2.66^{ns,}$
Variety	3	327.06***	1.39***	17.86***
Location*Variety	3	16.56**	0.09**	0.30^{ns}
Phosphorus	3	79.76***	0.14**	4.25*
Phosphorus*Variety	9	6.05^{ns}	0.02^{ns}	0.70^{ns}
Location*Phosphorus*Variety	9	1.77^{ns}	0.03*	2.53^{ns}
CV		12.86	16.68	13.03
R^2		0.94	0.94	0.45

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix L: Mean squares of effects of phosphorus rates on quality of potato

Source of variation	D.f	Number of sprouts	Large size	Medium size	Small size
Replicate	2	4.15***	13.32***	4.50***	11.91***
Replicate*Variety	6	0.14^{ns}	0.02^{ns}	0.15^{ns}	0.04^{ns}
Location	1	1472.66***	1480.51***	876.04***	41.34***
Variety	3	168.73***	181.37***	153.19***	727.23***
Location*Variety	3	238.41***	114.54***	69.01***	30.15***
Phosphorus	3	99.41***	83.59***	14.02***	16.51***
Phosphorus*Variety	9	21.29***	16.31***	9.88***	29.06***
Location*Phosphorus*Variety	9	0.71**	0.19**	0.07^{ns}	0.06^{ns}
CV		5.02	2.73	3.68	3.05
R^2		0.99	0.99	0.99	0.99

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix M: Analysis of variance for effects of phosphorus rates on dry matter content

Source of variation	d.f	Type III SS	Mean square	F value	Pr>F
Replicate	2	0.3572771	0.1786385	0.02	0.9780
Replicate*Variety	6	8.6291229	1.4381872	0.18	0.9815
Location	1	11.8933760	11.8933760	1.48	0.2276
Variety	3	60.7606115	20.2535372	2.53	0.0651
Location*Variety	3	254.0650031	84.6883344	10.56	<.0001
Phosphorus	3	169.6085781	56.5361927	7.05	0.0004
Location*Phosphorus	3	67.3386865	22.4462288	2.80	0.0469
Variety*Phosphorus	9	113.6962760	12.6329196	1.58	0.1413
ERROR	65	521.107518	8.017039		
TOTAL	95	1207.456449			
CV (%)		12.70			
R^2		0.56			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix N: Analysis of variance for effects of phosphorus rates on Starch content

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Replicate	2	2.0316813	1.0158406	0.09	0.9161
Replicate*Variety	6	11.0628021	1.8438003	0.16	0.9864
Location	1	1.8564844	1.8564844	0.16	0.6901
Variety	3	55.0285448	18.3428483	1.58	0.2016
Location*Variety	3	671.5296031	223.8432010	19.34	<.0001
Phosphorus	3	214.1391615	71.3797205	6.17	0.0009
Location*Phosphorus	3	50.7889698	16.9296566	1.46	0.2330
Variety*Phosphorus	9	293.7987510	32.6443057	2.82	0.0073
Error	65	752.407943	11.575507		
Total	95	2052.643941			
CV (%)		21.79			
R^2		0.63			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix O: Analysis of variance for effect of phosphorus rates on specific gravity of potato tubers

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Replicate	2	0.00002500	0.00001250	0.00	0.9992
Replicate*Variety	6	0.00047500	0.00007917	0.01	1.0000
Location	1	0.09375000	0.09375000	6.17	0.0155
Variety	3	0.13837500	0.04612500	3.04	0.0352
Location*Variety	3	0.21080833	0.07026944	4.63	0.0054
Phosphorus	3	0.63071667	0.21023889	13.85	<.0001
Location*Phosphorus	3	0.19721667	0.06573889	4.33	0.0076
Variety*Phosphorus	9	0.74009167	0.08223241	5.42	<.0001
ERROR	65	0.98699167	0.01518449		
	95	2.99845000			
CV (%)		12.43			
R^2		0.67			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix P: Analysis of variance for P uptake by leaves prior to flowering (42 DAP)

Source of variation	d.f	Type III SS	Mean Square	F Value	Pr > F
Location	1	0.00001250	0.00001250	0.02	0.8920
Variety	3	0.03367500	0.01122500	17.53	0.0004
Location*variety	3	0.02251250	0.00750417	11.72	0.0018
Phosphorus	3	0.00422500	0.00140833	2.20	0.1577
Variety*phosphorus	9	0.03650000	0.00405556	6.33	0.0056
Location*phosphorus	3	0.00251250	0.00083750	1.31	0.3307
CV (%)		10.12			
R^2		0.94			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix Q: Analysis of variance for P uptake by leaves prior to maturity (84 DAP)

Source of variation	d.f	Type III SS	Mean Square	F Value	Pr > F
Location	1	0.01950313	0.01950313	40.56	0.0001
Variety	3	0.04765937	0.01588646	33.03	<.0001
Location*variety	3	0.00063437	0.00021146	0.44	0.7302
Phosphorus	3	0.01010938	0.00336979	7.01	0.0099
Variety*phosphorus	9	0.01270312	0.00141146	2.94	0.0622
Location*phosphorus	3	0.00158438	0.00052813	1.10	0.3990
CV (%)		5.43			
R2		0.95			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix R: Analysis of variance for P uptake by potato tubers

Source of variation	d.f	Type III SS	Mean Square	F Value	Pr > F
Location	1	0.03187813	0.03187813	7.25	0.0247
Variety	3	0.01833438	0.00611146	1.39	0.3078
Location*variety	3	0.02755938	0.00918646	2.09	0.1720
Phosphorus	3	0.00565938	0.00188646	0.43	0.7372
Variety*phosphorus	9	0.07235313	0.00803924	1.83	0.1911
Location*phosphorus	3	0.00643438	0.00214479	0.49	0.6993
CV (%)		45.83			
R2		0.80			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix S: Analysis of variance for phosphorus use efficiency by potato

Source of variation	d.f	Type III SS	Mean Square	F Value	Pr > F
Replicate	2	26418.4959	13209.2480	1.18	0.3143
Location	1	39675.0975	39675.0975	3.56	0.0650
Variety	3	78972.0809	26324.0270	2.36	0.0822
Phosphorus	2	346634.8335	173317.4167	15.53	<.0001
Variety*phosphorus	6	24134.1949	4022.3658	0.36	0.9005
Location*variety	3	199221.5343	66407.1781	5.95	0.0014
Location*phosphorus	2	23407.3626	11703.6813	1.05	0.3577
CV (%)		72.08			
R2		0.56			

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

Appendix T: Analysis of variance for effect of phosphorus on growth parameters at Egerton study site

Source of variation	d.f	PS14	PS28	PS42	PS56	NS28	NS42	NS56	PLH14	PLH28	PLH42	PLH56
Replicate	2	2.583^{ns}	15.145*	6.521^{ns}	13.271^{ns}	2.770**	1.521^{ns}	0.750^{ns}	0.074^{ns}	0.523^{ns}	2.388^{ns}	2.884^{ns}
Variety	3	2.909^{ns}	3.687^{ns}	15.409*	20.250**	4.750***	7.694**	8.166**	22.096***	14.709***	74.508***	393.369***
Replicate*Variety	6	3.472^{ns}	7.895^{ns}	11.826^{ns}	13.104*	1.187**	2.381^{ns}	1.750^{ns}	0.498^{ns}	0.469^{ns}	5.273^{ns}	23.997^{ns}
Phosphorus	3	5.409^{ns}	2.909^{ns}	4.021^{ns}	4.472^{ns}	8.916***	22.583***	14.833**	0.743^{ns}	3.987**	87.050***	387.663***
Variety*Phosphorus	9	3.113^{ns}	2.187^{ns}	3.668^{ns}	6.564^{ns}	0.250^{ns}	4.268**	3.444^{ns}	0.458^{ns}	0.676^{ns}	5.289^{ns}	9.184^{ns}
CV		6.15	9.80	10.86	10.39	13.18	13.15	12.90	13.73	11.81	15.77	15.38
R^2		0.62	0.50	0.57	0.66	0.90	0.81	0.73	0.84	0.85	0.86	0.86

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

KEY: PS: Plant survival, NS: Number of stems, PLH: Plant height (14, 28, 42, 56 Days after planting)

Appendix U: Analysis of variance for effect of phosphorus rates on yield parameters at Egerton study site

Source of variation	d.f	DF	DPM	Biomass	Number of tubers	Tuber weight	Number of eyes	Marketable tuber yield	Large tubers	Medium tubers	Small tubers
Replicate	2	12.89	46.89	0.004	7.02^{ns}	0.12*	2.33***	5.68**	6.81***	2.64***	5.06***
Variety	3	427.63***	1765.90***	0.223***	229.38***	1.06***	234.85***	11.11***	122.38***	71.18***	399.13***
Replicate*Variety	6	6	5.20	39.70	0.001	13.57*	0.012	0.16	1.04	0.034	0.062
Phosphorus	3	9.58	26.02	0.001	37.50**	0.091	50.57***	1.38	45.94***	7.29***	8.97***
Variety*P	9	5.95	37.42^{ns}	0.002^{ns}	2.55^{ns}	0.049^{ns}	11.29**	1.46^{ns}	8.62***	5.09***	14.62***
CV		3.81	5.27	14.19	11.34	15.36	2.31	12.46	1.85	3.06	2.90
R^2		0.92	0.92	0.94	0.88	0.84	0.99	0.66	0.99	0.98	0.99

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

KEY: DF: Days to 50% flowering, DPM: Days to 50 % physiological maturity

Appendix V: Analysis of variance for effect of phosphorus rates on growth of potato at KALRO Molo

Source of variation	d.f	PS14DAP	PS28DAP	PS42DAP	PS56	NS28	NS42	NS56	PLH14	PLH28	PLH42	PLH56
Replicate	2	8.521^{ns}	1.937^{ns}	6.271^{ns}	6.937^{ns}	0.066^{ns}	0.036^{ns}	0.043^{ns}	0.275^{ns}	6.835**	0.244^{ns}	0.203^{ns}
Variety	3	152.576***	92.833**	70.527**	65.743**	0.056^{ns}	0.282^{ns}	0.644**	30.058***	41.699***	3.389**	3.593***
Replicate*Variety	6	10.743^{ns}	16.354^{ns}	14.381^{ns}	11.743^{ns}	0.117*	0.387*	0.333**	0.173^{ns}	3.747**	1.531**	1.462*
Phosphorus	3	6.409^{ns}	11.277^{ns}	10.027^{ns}	6.409^{ns}	1.291***	1.848***	1.570***	0.044^{ns}	18.737***	6.640***	6.178***
Variety*phosphorus	9	6.206^{ns}	10.962^{ns}	10.175^{ns}	9.335^{ns}	0.096^{ns}	0.117^{ns}	0.106^{ns}	0.258^{ns}	2.078**	0.287^{ns}	0.287^{ns}
CV		11.49	18.75	18.74	18.03	11.96	13.52	11.22	11.18	11.00	14.64	13.59
R^2		0.84	0.65	0.64	0.64	0.84	0.79	0.83	0.92	0.94	0.82	0.83

*significant P<0.01, ** Significant at P<0.05, *** significant at P<0.001, ^{ns} not significant

KEY: PS: Plant survival, NS: Number of stems, PLH: Plant height (14, 28, 42, 56 Days after planting)

Appendix W: Analysis of variance for effect of phosphorus rates on yield parameters at KALRO Molo

Source of variation	d.f	DF	DPM	Plant biomass	Number of tubers	Tuber weight	Number of sprouts	Marketable tuber yield	Large	Medium	Small
Replicate		24.145*	16.1458^{ns}	0.015***	36.521***	0.027***	1.395^{ns}	1.020^{ns}	5.687***	1.270*	6.937***
Variety		982.743***	2152.166***	0.076***	114.243***	0.430***	141.743***	7.055*	167.076***	144.909***	358.243***
Rep*Variety		7.451*	32.812^{ns}	0.000018*	0.0763^{ns}	0.000005^{ns}	0.284^{ns}	0.826^{ns}	0.0763^{ns}	0.159^{ns}	0.0763^{ns}
P		4.409^{ns}	9.888^{ns}	0.006***	45.854***	0.064***	39.076***	5.166*	34.409***	5.409***	7.576***
Variety*P		2.557^{ns}	8.500^{ns}	0.00059***	5.280***	0.012***	10.835***	1.777^{ns}	8.724***	4.854***	14.502***
CV		3.05	5.51	0.99	2.38	0.65	11.82	13.61	4.39	7.23	3.60
R^2		0.97	0.92	0.99	0.99	0.99	0.98	0.58	0.99	0.99	0.99

** Significant at $P<0.05$, and *** significant at $P<0.001$, ^{ns} not significant

KEY: DF: Days to 50% flowering, DPM: Days to 50 % physiological maturity

Appendix X: Analysis of variance for effect of phosphorus on growth parameters at Mauche study site

Source of variation	d.f	PS1	PS2	PS3	PS4	NS1	NS2	PLH1	PLH2	PLH3	PLH4
Replicate	2	3.937^{ns}	2.770^{ns}	0.314^{ns}	1.722*	0.123^{ns}	0.395^{ns}	1.215*	0.211^{ns}	4.969**	11.426***
Variety	3	18.000^{ns}	24.277*	0.268^{ns}	2.613**	0.052^{ns}	0.909^{ns}	10.852***	7.388***	31.765***	41.387***
Replicate*Variety	6	15.687^{ns}	22.381*	0.190^{ns}	1.356*	0.075^{ns}	0.618^{ns}	0.955**	0.540**	2.875**	3.598**
Phosphorus	3	12.388^{ns}	18.833^{ns}	0.105^{ns}	1.323^{ns}	0.917***	10.354***	0.847*	1.023**	18.142***	11.318***
Variety*Phosphorus	9	8.462^{ns}	11.851^{ns}	0.228*	0.564^{ns}	NS1	1.631**	0.195^{ns}	0.358*	1.166^{ns}	1.360^{ns}
CV		13.61	17.52	11.71	38.30	0.123^{ns}	15.72	15.51	8.88	12.89	10.35
R^2		0.62	0.67	0.66	0.70	0.052^{ns}	0.79	0.86	0.90	0.91	0.91

* Significant at P<0.05, ** significant at P<0.01 and *** significant at P<0.001, ^{ns} not significant at P <0.05

KEY: PS: Plant survival, NS: Number of stems, PLH: Plant height (14, 28, 42, 56 Days after planting)