INTEGRATION OF BIOCHAR AND INORGANIC FERTILISER ON SOIL BIOCHEMICAL PROPERTIES, NUTRIENT USE EFFICIENCY AND YIELD OF POTATO (*Solanum tuberosum* L.) IN NJORO SUB COUNTY, NAKURU COUNTY, KENYA

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EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

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

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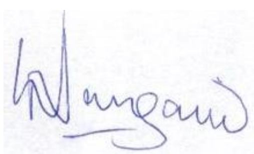
Recommendation

This thesis has been submitted for examination with our approval as the University Supervisors.

Signature:  Date: 28th July 2023

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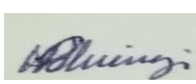
Signature:  Date: 16th July 2023

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DEDICATION

I dedicate this work to my dearest husband Zebosi Brian and my lovely son Zebosi Ethan Jonathan.

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ABSTRACT

Declining soil fertility is a major hindrance to potato farming in Kenya. The objective of the study was to determine the effects of biochar and Diammonium Phosphate (DAP) on growth, yield, nutrient use efficiency and selected soil properties in potato farming. A 2-season study was conducted at Egerton University agricultural field and in a farmer's field in Mau Narok using a split plot design in a randomized complete block (RCBD) arrangement. Biochar and DAP were applied at three levels (0, 5 and 10 t ha^{-1}) and (0, 250, 500 kg ha^{-1}), respectively resulting in 9 treatment combinations. Two potato varieties (*Shangi* and *Destiny*) were used in the study. The high number of potato stems was observed in plots that received B0D500, B5D500 and B10D500 at ($P \leq 0.001$). These results were consistent for both varieties in the two sites and seasons. Application of B5D500 resulted in the tallest plants that were not significantly different from plants in plots fertilised with B0D500 and B10D500 at ($P \leq 0.001$). Plots that received only biochar produced the shortest potatoes plants, that were not significantly different from the control. The highest number of tubers per plant, total tuber yield and marketable yield was obtained from plots treated with B0D500, B5D500 and B10D500 with B5D500 producing the highest marketable tuber yield of 39.9 t ha^{-1} and the lowest was from control and plots that received sole biochar application at ($P \leq 0.001$). The highest pH of 7.54 and 7.39 were obtained after applying B5D0 and B5D500 respectively. Sole application of DAP acidified the soils while soil pH became alkaline with biochar application at ($P \leq 0.001$). The highest soil phosphorus of 136 mg kg^{-1} was observed in B5D250 plots at ($P \leq 0.001$). Soils amended with B5D250, B10D250, B5D500 and B5D0 gave the highest soil nitrate and ammonium at ($P \leq 0.001$). Soils amended with B5D500, B10D500 and B10D250 gave the highest ($P \leq 0.001$) alkaline phosphomonoesterases while the highest acid phosphomonoesterases were observed under B0D500. Plots amended with B5D500, B10D500, B5D0, B10D0 gave the highest potato dry matter ($P \leq 0.001$). Highest N uptake was from plots with B0D500, B5D500, B10D500 and B5D250. The greatest P uptake was from plots treated with B0D500, B10D500 and sole use of biochar ($P \leq 0.001$). Treatment B5D0 gave the highest nitrogen use efficiency of 560.38 kg ha^{-1}. Biochar application of B5D0 significantly affected ($P \leq 0.001$) gave the highest phosphorus use efficiency of 2451.67 kgP ha^{-1}. These results confirm that use of biochar especially its integration with inorganic fertiliser is a sustainable strategy that increases potato growth, yield and nutrient use efficiency and improves soil properties.

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LIST OF ABBREVIATIONS AND ACRONYMS

ADC	Agricultural Development Corporation
AE	Agronomic Efficiency
ANOVA	Analysis of Variance
CAN	Calcium Ammonium Nitrate
CEC	Cation Exchange Capacity
C: N	Carbon: Nitrogen ratio
DAP	Di ammonium Phosphate
dap	Days after planting
GDP	Gross Domestic Product
INM	Integrated Nutrient Management
KES	Kenyan Shillings
LSD	Least Significant Difference
MSE	Mean Square Errors
NUE	Nutrient Use Efficiency for Nitrogen
PUE	Phosphorus Use Efficiency for Phosphorus
RCBD	Randomized Complete Block Design
SIN	Soil Inorganic Nitrogen
TSP	Triple Super Phosphate
$t\ ha^{-1}$	Tonnes per hectare
AE_N	Nitrogen Agronomic Efficiency
AE_P	Phosphorus Agronomic Efficiency
ANR_N	Nitrogen Use Efficiency
ANR_P	Phosphorus Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Potato (*Solanum tuberosum* L.) is a major food crop that is grown by most farmers in developing countries (Muthoni *et al*., 2013). In Kenya, it is considered as the second major and staple crop after maize that contributes significantly to food security and the country's economy (Waaswa, 2021). Despite its importance, tuber yields are still low (7-10 t ha^{-1}) against the attainable yield of 40 t ha^{-1}. The potato crop continues to perform below its yield potentials besides the efforts by the farmers to increase the cultivation area (Hoolst *et al.*, 2016). This is attributed to declining soil fertility, climate change, pests and diseases and use of low quality seed (Gicheru, 2012).

Declining and low soil fertility due to several causes such as erosion, depletion and imbalance of organic matter, poor responsive soils i.e., soils that are slow to respond to fertiliser application poses a major threat to potato productivity and economic returns of resource-poor potato farmers. To address this issue of low soil fertility, farmers have continuously replenished the depleted nutrients through use of chemical fertilisers. However due to the high cost of the fertilisers, farmers use lower rates that cannot sufficiently support high crop yield. Potato farmers in Kenya use on average less than half of the 90 kg N ha^{-1} and 230 kg P_2O_5 ha^{-1} recommended Diammonium Phosphate (DAP) fertiliser (Muthoni, 2016). Most farmers in Nakuru grow different potato varieties which include *Destiny* and *Shangi* that were used in this study. These varieties are preferred due to their high yielding capacity, short growing period and moderate resistance to most diseases (NPCK, 2019).

Nitrogen (N) and phosphorus (P) are the main limiting essential nutrients needed for potato reproduction and growth. Owing to its short growth cycle and high yielding capacity, the potato crop greatly responds to both N and P nutrients supplied to it (Hailu *et al*., 2017). The potato crop needs on average 90 to 190 kg N ha^{-1} for its entire growth cycle. Nitrogen plays an important role in growth of the crop by determining the physiology and morphology of the crop. Specifically, it promotes vegetative growth including leaf canopy development, which is essential for light interception for photosynthesis. Nitrogen is also vital for tuber initiation and growth as well as tuber quality through influencing tuber protein content, size and dry matter content of the tubers

(Hailu *et al*., 2017). However, the nutrient is not readily available in the soils in the right proportions, since its easily lost from the soil through erosion, volatisation, crop removal, immobilisation and leaching (Musyoka *et al.*, 2017).

Phosphorus (P) is an essential nutrient for potato mainly at early growth stages and tuber development. Phosphorus facilitates proper root growth, enhances vegetative cover, dictates the nutrient content in potatoes and promotes disease resistance (Rosen *et al*., 2014). In the early stages of potato growth, P is important for cell division and plant metabolism. Due to these numerous roles in the plant, it is required in high quantities during potato growth cycle (Mokrani *et al.*, 2018).Phosphorus availability in the soil is influenced by acidity levels in the soil where P is fixed at pH less than 5.5, soil microbial populations in which soil bacteria solubilise precipitated forms of calcium phosphate and incorporation of organic and inorganic fertilisers which are sources of P (Kwabiah *et al*., 2003). Amendment of soil with biochar has been shown to increase P availability up to 45% in the soil by reducing the effect of factors that limit P availability (Zhang *et al*., 2020).

Biochar is a carbon (C)-rich organic material made by pyrolysis method which is the thermal degradation of biological matter under anaerobic conditions (Zhang *et al*., 2020). It contains numerous nutrients such as organic carbon, phosphorus, nitrogen and secondary elements (calcium and magnesium) (Solaiman *et al*., 2019). In Kenya, charcoal for fuel is traditionally made in earth mounds or earth covered pit kilns. Besides, the produced charcoal, charcoal dust that serves as biochar is produced in this process. This biochar is a good soil amendment that improves soil conditions (Cornelissen *et al*., 2016).

Nutrient use efficiency (NUE) is a measure of the degree to which plants use the available mineral elements (Agüero & Kirschbaum, 2013). Nutrient use efficiency minimises nutrient losses through erosion, runoff, leaching and other loss pathways (Hailu *et al*., 2017). The use of inorganic fertilisers increases crop yields. However, they have low nutrient use efficiencies which can be boosted by integration with organic fertilisers (Selladurai & Purakayastha, 2016).

Phosphomonoesterase enzymes play a crucial role in P mineralisation (Margalef *et al*., 2017). This is achieved by the enzymes catalysing the hydrolysis of ester–phosphate bonds thus releasing phosphates which are utilised by plants and microbes. Phosphomonoesterases are made up of two enzymes: acid and alkaline phosphomonoesterases These enzymes are produced from both soil microorganisms such as fungi, bacteria and also by plant cells (Rejsek *et al*., 2012).

Soil pH is one of the vital soil properties that affects crop performance. Soil pH influences the availability of nutrients to crops mostly nitrogen and phosphorus (Kizito *et al.,* 2019). If the soils are very acidic there is a tendency of some nutrients being fixed leading to their imbalances in the soil (Muthoni & Nyamongo, 2009).

Biochar increases arbuscular mycorrhiza population in the soil and strengthens its association with the plant roots for P absorption. It also favors fungi hyphae to absorb P from the soil and make it available for plant uptake (Solaiman *et al*., 2019). This has made biochar one of the better soil amendments that has gained attention in recent years (Calys-Tagoe *et al*., 2019). Research conducted by Kizito *et al*. (2019) showed that the use of biochar as soil amendment significantly increased pH, soil carbon content and the total amount of magnesium and calcium in the soil.

Biochar incorporation into soil increases soil aggregate stability by increasing exchangeable cations of the soil such as calcium (Fungo *et al.,* 2017). Under acidic, highly weathered soils of the humid tropics regions, the hydroxyl and carboxylic groups present on the oxidised biochar surface are adsorbed by clay particles for macro-aggregate formation (Fungo *et al*., 2017). This improvement in soil properties enhances crop productivity and sustains soil quality. For example, maize planted on biochar amended soil increased its grain yield to about 25% compared to none biochar amended soil (Kizito *et al*., 2019). Nitrogen application on the biochar amended soil also increased sweet potato tuber yield by 100% and aboveground biomass by about 75% (Walter & Rao, 2015).

Previous studies conducted in Kenya indicate that biochar increases crop productivity and improves soil properties such as porosity, water holding capacity and nutrient content (Kätterer *et al.,* 2019). Most households depend on wood for fuel in rural areas of Kenya enabling biochar availability and at a cheaper or no cost. However, the wood used in traditional cook stoves is not enough to meet the fuel needs but this wood can effectively be used by the improved pyrolytic stoves (Torres-Rojas *et al*., 2011). Also the vast amount of various biomass (wood, rice (*Oryza sativa*) husks, maize (*Zea mays* L.) stalks, sugarcane (*Saccharum officinarium*) residues available in Kenya can be used to produce the biochar (Torres-Rojas *et al*., 2011). Pyrolytic stoves that produce biochar are effective at using less biomass, controlling air pollution compared to the traditional cook stoves and promotes carbon sequestration leading to improved soil fertility (Whitman *et al*., 2011).

Additionally, Kenyans have adopted the use of pyrolytic stoves due to its numerous benefits like use of less wood, reduced time of cooking and the biochar produced improves soil properties (Cornelissen *et al*., 2016). On average,13.2% of Kenyans both in rural and urban households are currently using the pyrolytic stoves (Ministry of Energy, 2019). A pyrolytic stove can on average produce 0.46 t ha^{-1} of biochar per year while lowering wood use by 27% (Torres-Rojas *et al*., 2011). Biomass is readily available since Kenya is an agricultural country with more than 69% biomass available for fuel use (Waaswa *et al.,* 2022). In Kenya, 0.52 tonnes of biochar produced by each household can equate to 18 tonnes of carbon after application in the soil (Torres-Rojas *et al*., 2011).

Biochar is an organic soil amendment that improves fertiliser use efficiency of chemical fertilisers (Clare *et al*., 2014; El-Sobky & Abdo, 2021). This is attributed to its physical and chemical characteristics which enables it to adsorb nutrients, increase the soil's water holding capacity, reduce nutrient leaching, act a soil conditioner improving soil aeration and porosity (Obia *et al*., 2018; Qian *et al*., 2014; Sika & Hardie, 2014). Despite the potential of biochar to increase crop yield by enhancing fertiliser use efficiency with reduced costs of production, the knowledge of its effects on potato production is still limited. Integration of biochar and chemical fertiliser is a fundamental sustainable solution to improve crop productivity (Saah *et al.,* 2022). In Kenya, research has focused on the fertiliser recommendation for increased potato yield and little attention has been paid to the effect of alternative amendments such as biochar on nutrient use efficiency and potato tuber yield. Therefore, there is a gap that needs to be bridged in order to increase potato yields through optimising fertiliser use efficiency by using biochar in Nakuru County, Kenya. Nakuru is one of the major potato growing areas in Kenya with approximately 20,000 potato farmers who grow different potato varieties on about 38,000 acres (Waaswa *et al.,* 2021a).

1.2 Statement of the problem

Potato (*Solanum tuberosum* L.) is the second most important staple crop which contributes to food security and household incomes for farmers in Kenya. Despite its importance, tuber yields are still very low (7-10 t ha^{-1}) against the attainable yield of 40 t ha^{-1} due to several constraints such as low soil fertility, limited use of fertiliser and poor agronomic management practices. Potato farmers have attempted improving soil fertility by applying synthetic fertilisers mainly Diammonium Phosphate (DAP). Despite the efforts by farmers to apply DAP, recurrent losses are registered. This is because they apply sub-optimal rates i.e. less than half of the recommended 500 kg ha^{-1} occasioned by low incomes of the smallholder farmers. On the other hand, biochar is locally available as household charcoal residue and contains organic carbon, phosphorus, nitrogen, magnesium, and calcium. Therefore, biochar presents a cheap and sustainable available additional resource for enhancing fertiliser use efficiency. Nitrogen and phosphorus are the most limiting nutrients for potato growth and are low in most soils due to dynamics like P fixation and N losses from the soil. However, biochar has proven to increase nitrogen and phosphorus uptake by plants. Biochar has the potential to increase nutrient use efficiency if integrated with other fertilisers. Nevertheless, little is known about the right combination of biochar and other fertilisers and its effect on growth and yield, soil properties, and nutrient use efficiency under potato production. This study intends to bridge this knowledge gap.

1.3 Objectives

1.3.1 General objective

To contribute to improved food security by increasing potato yields through optimising fertiliser use efficiency using biochar in Nakuru County, Kenya.

1.3.2 Specific objectives

i. To determine the effect of different rates of biochar and inorganic fertiliser on potato growth and yield.

ii. To determine the effect of different rates of biochar and inorganic fertiliser on nitrogen and phosphorus use efficiencies in potato production.

iii. To determine the effect of different rates of biochar and inorganic fertiliser on soil phosphomonoesterases, inorganic nitrogen, extractable phosphorus and soil pH

1.4.1 Hypotheses

i. Biochar and inorganic fertiliser levels have no significant effect on potato growth and yield.

ii. Biochar and inorganic fertiliser levels have no significant effect on nitrogen and phosphorus use efficiencies in potato production.

iii. Biochar and inorganic fertiliser levels have no significant effect on soil phosphomonoesterases, inorganic nitrogen, extractable phosphorus and soil pH.

1.5 Study justification

Potato farming in Kenya faces a major problem of low and declining soil fertility. This has greatly lowered the yield of the crop which is the second major food crop that serves as food security crop to the country. The potato crop needs sufficient amounts of nutrients with phosphorus and nitrogen as the most limiting nutrients. Farmers have tried to solve this issue by use of synthetic fertilisers. However, this has not been greatly successful since inappropriate rates are applied due to the low economic status of the farmers and/or illiteracy levels. This therefore calls for sustainable measures to enhance fertiliser use efficiency. Integration of biochar with chemical fertilisers increases crop yields through enabling nutrient uptake (Saah *et al.,* 2022). Globally, farmers are using biochar as a soil amendment to increase crop production and promote carbon sequestration (Liu *et al.,* 2017).

However, the practice has not been adopted in Kenya possibly due to limited knowledge about use of biochar. Hence this calls for research on effects of biochar on nitrogen and phosphorus use efficiencies and tuber yield in potato production. This study aimed at contributing to knowledge that may be utilised in potato production through improved nutrient management.

CHAPTER TWO

LITERATURE REVIEW

2.1 Economic importance of potato production

Potato is one of the major food crops that ranks third globally after rice and wheat (Hudu *et al*., 2018). It is a food security crop worldwide that plays a major role in fighting hunger and also an economic crop that contributes to poverty reduction (Waaswa *et al.*, 2021b). It is a source of employment to thousands of people that are employed directly as farmers and or indirectly as middlemen, potato traders, drivers among others (Wijesinha-Bettoni & Mouillé, 2019). Potato farmers in Kenya are about 800,000 who produce almost 1 to 1.4 million tonnes of potato per year earning approximately KES 30 to 40 billion annually. In Kenya, 98% of potato farmers are small scale farmers who account for 83% of the country's potato production (Janssens *et al*., 2013). Additionally, potato is a vital source of energy to both humans and animals and supplements the major cereals (Wijesinha-Bettoni & Mouillé, 2019). It is also rich in a variety of nutrients including vitamins, carbohydrates and minerals which are essential for human growth (Zaheer & Akhtar, 2016). The potato's short growth cycle renders it a reliable solution to food shortages. Most potato varieties have a short life cycle, attaining maturity within three to four months, hence the crop can be grown throughout the year (Hudu *et al*., 2018). In Kenya, potato is the second most grown crop after maize and is grown on approximately 161,000 hectares every season producing around 1.5 million tonnes per season per year (Muthoni *et al*., 2017). The major potato growing areas in Kenya are Mau region consisting of Bomet, Kericho, Narok and parts of Nakuru county, Nyandarua county in the central province, Meru county in the eastern province, Uasin Gishu and counties in the rift valley province, Mt Elgon areas and slopes of Mt Kenya, and rift valley edges (Muthoni *et al*., 2017).

2.2 Ecological conditions for potato production

For the potato crop to grow well, it needs between 500 to 700 mm of water throughout its life cycle (Gitari *et al*., 2018a). This leads to poor performance if grown in areas that persistently experience dry spells. Most potato growing areas in Kenya receive bimodal rainfall that favors potato growth and good performance (Muthoni *et al*., 2017). Potato growth is favored by temperatures of between 8^oC to 23^oC (Jaetzold *et al.*, 2012). Potato crop performs best in well drained loamy fertile soils;

the presence of such conditions leads to high potato productivity and these are common in the highland areas of Kenya (Girma *et al.*, 2017).

2.3 Soil fertility status in potato growing areas in Kenya

Declining soil fertility, mainly linked to high soil erosion rates (Nyawade *et al.*, 2019) is a major contributor to low tuber yields in potato. The decreasing soil fertility is also due to repeated cultivation with limited fertilisation making the soils depleted in nutrients that are needed for crop growth especially phosphorus and nitrogen (Muthoni & Nyamongo, 2009). In response to low fertility, farmers apply inorganic fertilisers especially Diammonium Phosphate (18% N and 46% P_2O_5) Triple Super Phosphate (TSP), or Nitrogen, Phosphorus and Potassium (NPK). These are usually applied during planting and followed with Calcium Ammonium Nitrate (CAN) or Urea as top dressing fertilisers after crop emergence (Muthoni, 2016). In addition, farmers apply organic soil amendments commonly, cattle manure, compost and farmyard manure (Musyoka *et al*., 2017)

2.3.1 Nitrogen in potato production

Nitrogen is the most limiting essential nutrient needed by crops for proper growth. It plays numerous roles in the growth of potatoes; N forms the biggest part of chlorophyll molecule that is needed by the potato to trap sunlight for use in photosynthesis. Nitrogen is present in forms of ammonium or nitrate and is used in formation of amino acids and proteins. It is involved in starch metabolism. Nitrogen forms part of the potato's dry weight about 1 to 4%. However, N nutrition remains a great hindrance to most farms since its lost from the soil through many pathways such as erosion, volatilisation, crop removal, immobilisation and leaching (Musyoka *et al*., 2017). This therefore calls for measures to control N losses and one sustainable way is encouraging N use efficiency. Therefore, for a farmer to obtain high crop yield, N should be readily supplied and be in available forms in the soil for crop uptake (Musyoka *et al*., 2017).

2.3.2 Phosphorus in potato production

Phosphorus and nitrogen are the major nutrients that farmers constantly apply to sustain crop growth and yield (Hailu *et al*., 2017). Besides nitrogen requirements, potatoes also need phosphorus nutrient in larger quantities for proper plant growth (Gaur *et al*., 2017). Phosphorus is required for the proper growth of potato and promotion of tuber and root development, building resistance to diseases, for the nutritive content as well as canopy establishment (Rosen *et al*., 2014). With adequate phosphorus supply, potato productivity is enhanced by the higher leaf area, lateral stem growth and dry matter content. In potatoes, the plants with more number of leaves during the growth cycle produces higher yields (Martins *et al*., 2018). Therefore, inadequate supply of the nutrient to potatoes inhibits potato stem and root system, low leaf growth which results into reduced tuber yields and tuber size. Phosphorus in potatoes also contributes to the nutritive content of the plant through influencing the uptake of other nutrients such as nitrogen, magnesium which are important in the crop's growth (Soratto & Fernandes, 2016). Availability of P in the soil increases the nutrient content of potatoes by promoting a high starch and protein content, increased dry matter content and decreased sugar content (Leonel *et al*., 2017). During the young phase of the crop growth, it is advisable to supply the crop with sufficient phosphorus for formation of cell components such as nucleic acids, fatty acids which aids in production of carbohydrates thus high potato tubers yield (Rosen *et al*., 2014).

Notwithstanding its benefits to the potato, phosphorus is not readily available in the soil; it is fixed in acidic soils therefore calling for its periodic addition through organic and inorganic fertilisation (Simoneti *et al*., 2016). Phosphorus availability to plants relies on the chemical composition of the soil, the applied fertiliser; P is fixed in acidic soils and the different fertilisers have different P levels. Addition of fertilisers rich in phosphorus such as organic and synthetic phosphate fertilisers in soils increases soil phosphorus levels (Girma *et al*., 2017). Applied organic manures raise soil pH thus lowering fixation of P (Hazarika *et al*., 2021). Phosphorus in the soil takes up two forms which are organic and inorganic phosphorus (Khosravi *et al.,* 2017). These P forms greatly influence the availability and movement of P in the soils. Inorganic P is readily available and mobile in the soil and increases under optimum conditions of soil moisture, temperature, well aeration i.e., sufficient oxygen and tillage that enhance soil organic matter decomposition. On the other hand, organic P is immobile and is not readily available to the plant roots (Ahmad *et al*., 2017).

2.4 Nutrient use efficiency in potato

Nutrient use efficiency (NUE) is a measure of the degree to which plants use the available mineral elements (Agüero & Kirschbaum, 2013). There is a close relationship between nutrient use efficiency and amount of nutrient applied. Low fertiliser inputs results into a higher nutrient use efficiency and vice versa. In addition, the highest nutrient use efficiency is obtained under low yields. An increase in fertiliser application leads to an increase in yield up to a certain level maximum at which it decides to decline as nutrient use efficiency also declines (Hu *et al.,* 2016).

Nutrient use efficiency minimises nutrient losses through erosion, runoff, leaching and other loss pathways (Hailu *et al*., 2017). The use of inorganic fertilizers increases crop yields. However, they have low nutrient use efficiencies which can be boosted by integration with organic fertilizers (Selladurai & Purakayastha, 2016). To achieve higher nutrient use efficiency, the inorganic fertilisers should be applied at the correct rate, using the right application method, and applied at the correct time of plant growth. This in return lowers environmental pollution (Rietra *et al*., 2017). Furthermore, to achieve optimal nutrient use efficiency of chemical fertilisers, fertilisers should be manufactured in such a way that reduces negative nutrient interactions whilst raising positive nutrient interactions (Rietra *et al*., 2017).

Improvement in the crop rhizosphere i.e. the area closest to the plant system in which plant roots release exudates (Nihorimbere *et al*., 2011) improves nutrient use efficiency thus contributing to high yields while maintaining soil and environmental quality (Zhang *et al*., 2010). The rhizosphere is significantly characterised by soil microbial colonisation that is pivotal in plant nutrition than the bulk soil. These soil microbes promote potato growth by aiding in nutrient solubilisation of phosphates, nitrogen fixation and plant growth promoting rhizobacteria, suppression of pathogens that cause bacterial wilt disease in potatoes (Chamedjeu *et al.,* 2019; Kesaulya *et al.,* 2015; Pfeiffer *et al.,* 2017; Yasmin *et al*., 2009).The rhizosphere can be improved by addition of biochar that promotes soil microbial populations and activities and harmonises crop nutrient needs with nutrients supplied by the rhizosphere (Zhang *et al*., 2010).

Farmers usually add N and P to their farms by use of synthetic fertilisers rich in these nutrients. Phosphorus undergoes many dynamics in the soil from fixation in acidic soils by iron and aluminum oxides. On the other hand, N is easily lost from the soil through many pathways such as erosion, volatisation, crop removal, immobilisation, and leaching (Gitari *et al*., 2018b). This requires need for adoption of strategies that increase P and N use efficiencies since chemical fertilisers have low NUE. In crops, Nitrogen use efficiency and Phosphorous use efficiencies are rarely beyond 58% and 31% respectively (Selladurai & Purakayastha, 2016). Nutrient use efficiency in potatoes greatly determines the tuber yield, this is as a result of reduced nutrient losses (Alva *et al*., 2011). To achieve higher nutrient use efficiency in potatoes, fertilisers should be supplied to the soil in right quantities, right plant stage and strategically placed to easily be absorbed by the shallow rooted tuber crop (Jate, 2010; Roberts, 2007; White *et al*., 2018)

2.4.1 Nitrogen use efficiency

Nitrogen use efficiency is the ratio of yield obtained to amount of N fertiliser applied (Baligar *et al.*, 2001). Nitrogen use efficiency largely depends on N amounts supplied by the soil N, applied fertiliser, N taken up by the plant, N lost from the soil and N taken up by the plants (Agegnehu *et al*., 2016). Below are formulae for calculating nitrogen use efficiency (Baligar *et al*., 2001).

Equation 1: N uptake calculation formula

$$\text{N uptake (Kg N ha}^{-1}) = \frac{[\text{N (\%)} \times \text{dry matter (kg ha}^{-1})]}{100}$$

Equation 2: N Agronomic efficiency formula

$$\text{AE}_\text{N}\ \text{(Kg Kg N}^{-1}) = \frac{[\text{Yield}_\text{F}\ (\text{Kg ha}^{-1}) - \text{Yield}_\text{C}\ (\text{Kg ha}^{-1})]}{\text{Quantity of N applied (Kg N ha}^{-1})}$$

Equation 3: N Use efficiency formula

$$\text{ANR}_\text{N}\ (\%) = \frac{[\text{N uptake}_\text{F}\ (\text{Kg N ha}^{-1}) - \text{N uptake}_\text{C}\ (\text{Kg N ha}^{-1})]}{\text{Quantity of N applied (Kg N ha}^{-1})} \times 100$$

Where F means fertilised, and C means control where no fertiliser was applied.

The amount of nitrogen a certain crop demands for growth greatly dictates Nitrogen Use Efficiency (Agegnehu *et al*., 2016). This is attributed to the genetics of the crop i.e. how the crop responds to the nitrogen content in the soil (Ben Zekri *et al*., 2019). Therefore, nitrogen use efficiency relies greatly on N uptake, N assimilation, N translocation, N recycling and remobilisation within the plant (Musyoka *et al*., 2017; Perchlik & Tegeder, 2017). Nitrogen fertiliser use efficiency is a serious issue that should be properly addressed due to high costs associated with purchasing the fertilisers and the high risk of nitrate fertiliser pollution (Anas *et al*., 2020; Kanter *et al*., 2016). Not only does N productivity associated with integration of organic and inorganic N fertilisers improve soil health and quality, it promotes N use efficiency.

The combination of synthetic N fertiliser and organic manure consistently increased N uptake efficiency in potato by 20% and 14 to 33% compared with the control that is not amended in both the field and pot experiments respectively (Hailu *et al*., 2017). Application of 130 kg N/ha using urea fertiliser gave the highest NUE of 236.44 kg/kg of N in potato in mollic Andosols (Satognon *et al*., 2021). Co-application of 179 kg N ha^{-1} fertiliser and manure resulted into a higher tuber yield and nitrogen uptake efficiency by 20% than using of only chemical fertiliser at 224 kg N ha^{-1}. A similar increment was registered in the container experiments were tuber yield and nitrogen uptake efficiency increased by 14 to 33% when chemical fertiliser was combined with manure than when chemical fertiliser was applied alone (Nyiraneza & Snapp, 2007).

In addition, in potatoes, N use efficiency varies within potato cultivars and this has been proven by many studies (Awgchew *et al*., 2016; Maltas *et al*., 2018). Nitrogen use efficiency is higher in cultivars that are late maturing than cultivars that mature early (Hailu *et al*., 2017; Nieto, 2016). Organic matter, proper water management and nitrogen use efficiency can increase crop productivity which can be achieved through biochar application.

2.4.2 Phosphorous use efficiency

Phosphorus use efficiency is defined as amount of total biomass, or yield obtained per unit of phosphorus taken up (Veneklaas *et al*., 2012).

Below are indices of phosphorus use efficiency (Baligar *et al.*, 2001).

Equation 4: P uptake calculation formula

$$\text{P uptake}\ (\text{Kg P ha}^{-1}) = \frac{[\text{P}\ (\%)\ \times \text{dry matter}\ (\text{kg ha}^{-1})]}{100}$$

Equation 5: P Agronomic efficiency formula

$$\text{AE}_\text{P}\ (\text{Kg Kg P}^{-1}) = \frac{[\text{Yield}_\text{F}\ (\text{Kg ha}^{-1}) - \text{Yield}_\text{C}\ (\text{Kg ha}^{-1})]}{\text{Quantity of P applied (Kg P ha}^{-1})}$$

Equation 6 : P Use efficiency formula

$$\text{ANR}_\text{P}\ (\%) = \frac{[\text{P uptake}_\text{F}\ (\text{Kg P ha}^{-1}) - \text{P uptake}_\text{C}\ (\text{Kg P ha}^{-1})]}{\text{Quantity of P applied (Kg N ha}^{-1})} \times 100$$

Where F means fertilised, and C means control where no fertiliser was applied

Increase in cost of synthetic fertilisers, need for environmental protection from phosphorus losses and exhaustion of phosphorus mineral resources has resulted into the need to improve phosphorus use efficiency (PUE) (Thornton *et al*., 2014). Potato has a higher sensitivity in soils low of P, thus low phosphorus uptake efficiency.

The limited availability of phosphorus in soils low of P results into its increased demand by the potato for its growth and this calls for soil management practices that promote phosphorus use efficiency (White *et al*., 2018). The low root to shoot ratio of the potato accompanied with few root hairs that aid in P absorption also contributes to potatoes' low P use efficiency that need to be improved through integrated nutrient management (INM) (Thornton *et al*., 2014). Integrated Nutrient Management where organic fertilisers are used in combination with inorganic fertilisers is an effective way to increase phosphorus use efficiency in potato production (Girma *et al*., 2017). Phosphorus use efficiency in potato production can be increased through developing cultivars that have a wider root system with numerous root hairs that is effective at P uptake (Johnston *et al.*, 2000), use of potato varieties that are resistant to root diseases, healthy roots are efficient at P absorption (Ekelöf *et al.*, 2012) and improving the rhizosphere (Hopkins *et al*., 2014; Thornton *et al*., 2014). Phosphorous Use Efficiency can also be increased by use of agronomic practices that facilitate P uptake such as liming, cover cropping, band placement of fertilisers, conservation tillage, use of beneficial soil microbes, composting, using of soil amendments that raise microbial populations that aid in P transformations (Kunwar *et al*., 2018). An example of these is application of biochar which increases arbuscular mycorrhiza colonisation in roots and activity that is essential in P uptake and increases nutrient use efficiency (Thornton *et al*., 2014).

Phosphorous Use Efficiency in potato production can be enhanced through liming of acidic soils where P is fixed and rendered unavailable to the potato plant. The inorganic P fertilisers undergo chemical reactions in acidic soils forming interactions with mineral oxides especially iron and aluminum oxides lowering fertiliser use efficiency. However, addition of biochar improves P use efficiency in the acidic soils by decreasing P adsorptions while increasing desorption. The arbuscular mycorrhiza absorbs the P making it available for the plant thereby inhibiting P chemisorption in acidic soils (Zwetsloot *et al*., 2016).

Phosphorus use efficiency increased by 15% more than Triple Super Phosphate (TSP) when biochar fertilisers from sugarcane residues where applied in clayey soils (Borges *et al*., 2020) . In a field experiment of maize by Arif *et al*. (2017), the highest PUE was observed in plots that received both 50% farm yard manure and poultry manure with biochar. And for wheat in the same experiment, PUE was highest in plots that were fertilised with both 100% farmyard manure and poultry manure with biochar. Xin *et al*. (2017) found out that P content and uptake was significantly increased by addition of compost. Addition of NPK at full rate, half rate of compost and NPK, full rate of compost gave phosphorus use efficiencies of 53.7, 59.9 and 61.7% respectively.

2.5 Biochar as a soil amendment

Biochar is a carbon rich product produced by pyrolysis method where there is incomplete combustion of biomass in the absence of oxygen or presence of limited oxygen (Liu *et al*., 2017). Over the past years, biochar has gained global attention as a soil amendment that has demonstrated ability to improve soil quality through enhancing soil physical and chemical properties and mitigate climate change (Li *et al*., 2018). Biochar has numerous associated economic and environmental benefits; lowering global warming through reducing emission of greenhouse gases, increasing crop performance, providing a bio-resource that can be used in energy, agriculture and industries. Use of biochar as an organic soil amendment also controls environmental pollution whereby crop residues and other organic wastes are converted into an energy source (Waaswa & Satognon, 2020).

Production and use of biochar is source of income to most farmers (Oni *et al*., 2019). This study used wood as the biochar feedstock because can be locally made by the farmers and its ready availability. Charcoal offers a main source of feedstock for biochar production in most of the humid areas (Coomes & Miltner, 2017). In Kenya, most small-scale charcoal producers make charcoal by pyrolysing wood in an earth mound, or they use drum kilns made of steel. The large-scale charcoal producers on the other hand pyrolyse the wood in brick kilns. Pyrolysis method is used to control complete combustion of the wood where the wood is burnt in limited oxygen to form charcoal (Shikorire *et al*., 2019). The pyrolysis process usually lasts for hours to weeks. Charcoal production process leaves behind a byproduct or residue of black carbon ash called biochar. Residues of the formed charcoal (biochar) are effective at improving the physical, chemical, and biological properties of soil which is witnessed by the high fertility of the soils at the kiln sites where the charcoal ash has dropped. These kiln soils are usually darker in color indicating high organic matter levels (Coomes & Miltner, 2017). These charcoal residues are rich in soil organic carbon and other nutrients like nitrogen and phosphorus (Heitkötter & Marschner, 2015). Natural vegetation is used by most families in Sub Saharan Africa as firewood or for charcoal, these vegetation products or charcoal are source of feedstock (Gwenzi *et al.*, 2015). An estimation of 75% of Kenyan households rely on wood and charcoal for fuel. Rural households account for 93.2% charcoal and wood use (Ministry of Energy, 2019). In addition, 66% of rural households derive their livelihood from charcoal business (World Agroforestry Centre (ICRAF) *et al*., 2020). Most farmers depend on charcoal production for fuel, economic benefits and for biochar production for use in the gardens to increase on crop productivity. It is approximated that one kilogram of wood feedstock on average produces 118g of saleable charcoal and 20g of biochar (Coomes & Miltner, 2017).

Effects of biochar incorporation into the soil can be observed through changes in the soil physical and chemical properties, non-toxic plant tissues, quality of water bodies and unpolluted environment. By improving soil fertility, biochar helps in bringing degraded soils into use thus increasing agriculture land (Wr,àö,â•bel-Tobiszewska, 2014). Furthermore, biochar offers an affordable sustainable solution to soil nutrient replenishment to most low resource farmers by cutting down the cost associated with the use of inorganic fertilisers (Mensah & Frimpong, 2018). Biochar combination with chemical fertilisers gives higher crop yields, lowers nutrient losses and promotes nutrient use efficiency when compared with other organic manures such as farmyard manure and vermicompost. This makes biochar one of the best organic soil amendments. Therefore, this calls for advocacy and promotion of biochar through creating awareness (Yadav *et al*., 2019).

Biochar is enriched with numerous functional groups and exchangeable sites that enable it to reduce on nutrient leaching. It also provides conducive micro habitat for soil microbes involved in nutrient cycling (Xia *et al*., 2022). Wood biochar induces availability of P through influencing soil microbial activities such as activities of the phosphomonoesterase enzymes that play a vital role in mineralisation and solubility of P (Vithanage *et al*., 2018).

Research done by different scientists shows biochar integration with mineral fertilisers promotes plant growth (Helliwell, 2015; Kizito *et al*., 2019; Schulz & Glaser, 2012). Combination of biochar with synthetic fertilisers greatly improves crop uptake of nutrients of N, P, K, Ca, Mg leading to higher nutrient use efficiencies (Oladele *et al*., 2019; Omara *et al*., 2020). This is attributed to biochar's ability to boost nutrient and water use efficiencies, enhance soil properties which do promote high crop performance (Agegnehu *et al.*, 2021). Biochar influences N availability that is due to its properties that heightens N use efficiency, high organic matter levels and improved absorption of N (Farooque *et al.*, 2020; Zahid *et al.*, 2018). Nitrogen use efficiency is also improved by biochar reducing leaching due to its greater surface area, charge density and negative surface charge (Dong *et al*., 2015). Ability of biochar to enhance N availability is attributed to improved mineralisation of the soil organic N to inorganic N (Shan & Coleman, 2020).

Furthermore, biochar addition leads to an enhancement in soils' water holding capacity thus reduced loss of N from leaching and runoff (Walter & Rao, 2015). The interface between biochar and soil brings about N transformation through increased mineralisation of organic N to inorganic N that is utilised by the crop plant (Ding *et al*., 2016). Biochar promotes N mineralisation by providing energy in form of carbon and substrates to the N mineralising microorganisms (Clough *et al*., 2013). Moreover, the microbes also act on the organic matter in biochar thus releasing N by co-metabolism and mineralization of soil organic matter (Nguyen *et al*., 2017). Furthermore, biochar boosts soil moisture (Karim *et al.*, 2020) and pH by lowering toxic elements and metal toxicity providing favorable conditions in the rhizosphere for mineralisation (Shetty & Prakash, 2020). However, this mineralisation is lowered by adsorption of organic matter on the biochar surfaces thus not readily available for action by microorganisms (Hagemann *et al*., 2017; Kizito *et al*., 2019). Mineralisation is higher in wood material with C: N ratio lower than 20. If the C: N ratio is higher than 20 it will result into immobilisation. Woody biochar does not significantly reduce soil inorganic nitrogen compared to other plant produced biochar (Nguyen et al., 2017).

Biochar surfaces are filled with functional groups that enable chemisorption of soil inorganic nitrogen. These functional groups comprise of hydroxyl, lactol, carboxylic groups. These are negatively charged thus NH4+ -N adsorption through electrostatic forces. However, this adsorption is not strong enough basing on the fact that biochar is mainly negatively charged. Biochar has the ability to retain nitrification inhibitors therefore enhancing nitrification by stimulating nitrifiers such as ammonia oxidizing bacteria thus higher N use efficiency (Nguyen *et al*., 2017).

Biochar is rich in numerous nutrients needed for crop growth. Use of biochar increases the amount of nutrients in the soil since biochar itself contains nutrients such as nitrogen, phosphorus, potassium, and carbon plus other secondary nutrients such as calcium and magnesium. On average, wood biochar contain 0.36 to 0.43g kg^{-1} of nitrogen and 1.96 to 0.02g kg^{-1} of phosphorus (Agegnehu *et al*., 2015). Biochar made from maize cobs was applied to a soil at rates of 0, 3, 6, and 10 t ha^{-1}, for one season (January to April) and later analysis of the soil chemical properties showed that biochar had increased the soil cation exchange capacity, nutrients N, P, K which subsequently led to increased maize yields. The CEC in this study increased from 5.36 to 7.47 Cmol kg^{-1}, N increased from 0.14% to 0.27%, P increased from 4.45 to 10.91 mg kg^{-1}, potassium increased from 0.44 to 1.56 mg kg^{-1} after biochar addition (Faloye *et al*., 2017)

An experiment conducted by Wang *et al*. (2019) found out that soil pH decreased significantly by 7% than the control when 5% of moso bamboo biochar was incorporated into the soils. However, addition of corn stover biochar at rates of 52, 104, and 156 t ha^{-1} to soils increased soil pH by 0.73, 0.99, and 1.36 units respectively (Chintala *et al*., 2014). Soils amended with 18 t ha^{-1} of *Lantana* biochar had the highest available phosphorus of 16.37 ± 0.52 ppm and the control soils had the lowest available phosphorus of 10.8 ± 0.21 ppm (Berihun *et al*., 2017). Combination of biochar and N fertiliser at rates of 50 and 100 kg N ha^{-1} increased grain yield by 17 and 13% respectively when compared to the control (Omara *et al*., 2020). Biochar integrated with nitrogen fertiliser increased crop yield by 30% unlike when nitrogen fertiliser was used alone (Faloye *et al*., 2017). This therefore shows biochar offers a sustainable solution for increasing fertiliser use efficiency.

Single application of biochar and urea fertiliser significantly increased activity of the urease enzyme about 33% in relation to the control. Furthermore, when the two soil amendments were combined together higher urease activity of 41% was registered compared to the enzyme's activity in soils that were solely amended with biochar or urea alone (Hangs *et al*., 2016). Combination of 30 t ha^{-1} of biochar, urea and manure increased vegetable yield by 32%, 48% when compared to application of urea fertiliser, urea and manure combined (Jia *et al*., 2012). Mesquite biochar when added to soils produced the highest onion leaf length of 32.38 cm followed by 31.33 cm from farmyard manure and 30.11 cm of NPK fertilisers. Similar trend of results was obtained in onion yield were the biochar amendment gave the highest total yield of 268.55 kg ha^{-1} followed by 211.46 kg ha^{-1} from farmyard manure application and 192.54 kg ha^{-1} from NPK fertiliser (Khan *et al*., 2019). Agronomic efficiency and nitrogen recovery increased by 140% and 191%

respectively when biochar was combined with N fertiliser in comparison with the highest rate of 90 N kg ha^{-1} of N fertiliser and the control in the 2 years of experiment (Oladele *et al*., 2019). Biochar increased P use efficiency by approximately 10% when compared to Triple Superphosphate (TSP) chemical fertiliser (Borges *et al*., 2020).

2.6 Types of biochar

Biochar has different biological, physical and chemical properties (Wr,àö,â•bel-Tobiszewska, 2014) depending on the type of biomass i.e. feedstock used for their production and the production temperatures at which the pyrolysis was carried out (Qurat-ul-Ain *et al*., 2021; Tomczyk *et al*., 2020). The physical characteristics of biochar are greatly associated with the biomass used while the chemical and biological features of biochar are as result of both the biomass used and production temperatures used (Wr,àö,â•bel-Tobiszewska, 2014). Different temperatures are used in the production of biochar usually ranging from 300^{o}C to 800^{o}C and this has a significant effect on the quality of the biochar with higher production temperatures producing biochar with less nutrients available in the amendment (Peng *et al*., 2011). Biochar produced at low temperatures (slow pyrolysis) i.e. below 500^{o}C is richer in cation exchange capacity, nitrogen, phosphorus, magnesium than the biochar produced under fast pyrolysis i.e. above 500^{o}C (Naeem *et al*., 2014). At higher production temperatures, some mineral elements undergo volatilisation, organic matter composition is broken down thereby reducing the quality of the biochar formed. However, biochar produced at higher temperatures has a higher carbon content than one formed under low temperatures (Wr,àö,â•bel-Tobiszewska, 2014).

Different biomass used in biochar pyrolysis have different sizes of pores, varying ash levels and varying chemical characteristics (Solaiman *et al*., 2019). Biochar feedstock can either be of plant or animal origin (Onwuka & Nwangwu, 2016). Plant biomass commonly used as feedstock includes wood that produces charcoal (Ndor *et al*., 2015), rice straws (Peng *et al*., 2011), acacia stems and branches (Agegnehu *et al*., 2016), corncob and orchard pruning (Mensah & Frimpong, 2018). The most commonly used animal origin feedstock is poultry litter and cow manure (Solaiman *et al*., 2019). In Kenya, the most commonly used feedstock for biochar production are banana pseudo stems, maize residues of cobs and stovers, collard green stalks and woody herbaceous trees farmers use for firewood and charcoal (Torres-Rojas *et al*., 2011). Plant based biochar has higher nutrient content than the animal-based biochar. However, animal based biochar has some higher nutrients such as total nitrogen in poultry litter (Feola-Conz *et al*., 2017). For biomass to produce high quality biochar it should meet the following parameters: black carbon content should be more than 15%, hydrogen: carbon ratio less than 0.6; and oxygen: carbon ratio less than 0.4 with a surface area greater than 100 m^2 g^{-1} (Schimmelpfennig & Glaser, 2012).

2.7 Effect of biochar on soil chemical properties

2.7.1 Effect of biochar on soil nitrogen

Addition of biochar to soils increases the nitrogen content in the soil whereby nitrogen is released from the soil stores where biochar influences nitrogen transformations leading to the release of the nutrient to the soil (Liu *et al*., 2018). Addition of biochar to the soil brings about variation in the soil's nitrogen through affecting soil inorganic nitrogen such as nitrate and ammonium. Plant roots absorb soil inorganic nitrogen for crop nutrition. Application of biochar either leads to an increment, reduction or no effect on soil inorganic nitrogen (Bai *et al*., 2015; Xu *et al*., 2015). This is attributed to many factors such as biochar duration in the soil, biochar type, its application rate and soil properties (Alghamdi, 2018; Al-Wabel *et al*., 2018). In some instances, nitrogen becomes readily available after some long period of biochar application in which the nutrient gets desorbed into the soil solution. This is because mineralisation rate is proportional to time. Biochar of plant origin usually lowers nitrogen mineralisation due to the low C: N ratio. Nitrogen mineralisation occurs when C: N ratio is below 20 and a C: N ratio beyond 20 results into N immobilisation (Manirakiza *et al.,* 2019). Biochar lowers soil acidity thereby encouraging microbial activities and population of nitrifiers which is usually lowered at soil pH below 5. Optimum soil aeration encourages mineralisation by inhibiting denitrification and promoting nitrogen microbial respiration (Nguyen *et al*., 2017). For a farmer to obtain high crop yield, N should be readily supplied and be in available forms in the soil for crops to readily take up the nutrient (Musyoka *et al*., 2017).

2.7.2 Effect of biochar on soil phosphorus

Biochar readily supplies phosphorus to the soil through different mechanisms. Phosphorus is not readily available in acidic soils as it is fixed and adsorbed onto the iron and aluminum oxides. However, biochar decreases soil acidity by making P readily available. Available P increased from 570 mg kg^{-1} in unamended soil to 722.1 mg kg^{-1} when biochar was added to the soil. The experiment took forty days (Mensah & Frimpong, 2018). Increase of available phosphorus and nitrogen in biochar amended soils is also as a result of the increased cation exchange capacity or increased exchangeable bases (Mensah & Frimpong, 2018). Integration of biochar with synthetic fertilisers reduces P sorption on soil particles leading to an increase in P use efficiency. Furthermore, biochar provides conducive environment for the microbes such as phosphate solubilising microorganisms responsible for phosphorus mineralisation. Findings by Arif *et al*. (2017) showed biochar use increased PUE whereby biochar controlled P fixation on iron and aluminum oxides, biochar increased PUE by increased mycorrhizal-fungal associations. In addition, biochar addition raises the soil pH that makes soil P available by reducing its sorption. In association, the charged surface sites of P which are positively charged facilitate the availability of soil P and this improves crop nutrition since the nutrient will be readily available to the crop roots (Mensah & Frimpong, 2018).

2.7.3 Effect of biochar on other soil chemical properties

Biochar when incorporated in soils increases soil cation exchange capacity. The soil amendment is able to retain nutrients which is also supplemented by its sorption capacity (Mensah & Frimpong, 2018). Owing to its high surface charge density, biochar is able to improve the cation exchange capacity through holding cations. This high surface charge density raises the amendment's surface sorption capability and its base saturation. The high charge density of biochar leads to an increase in the soil CEC which is coupled by formation of carboxylic groups when the aromatic carbon on the surface of the biochar is oxidised, this leads to increase in CEC (Peng *et al*., 2011). The biochar has got numerous exchange sites for cations (Méndez *et al*., 2017). In addition, it increases cation exchange capacity and nutrient use efficiency by improving water holding capacity due to its spongy nature and increased organic matter content (Solaiman *et al*., 2019).

Incorporation of biochar in soils influences soil pH where it decreases acidity by acting as a liming agent. Biochar is known to increase soil pH (Martinsen *et al.,* 2015). This favors growth of crops that do not thrive well in acidic soils (Faloye *et al*., 2017). Biochar gains its ability to change pH from its pH itself, most biochar is alkaline thus end up increasing on the pH of acidic soils. Biochar also has an ash content that enables to increase soil pH, this ash is enriched with carbonates and other metal ions such as calcium and magnesium which gives it that liming effect (Mensah & Frimpong, 2018).

The study by Nzediegwu *et al.* (2019) found out that use of biochar in a potato garden leads to reduced amount of heavy metals found in both the potato flesh and peel. Biochar retains the heavy metals by lowering their mobility and bioavailability in the soil thereby minimising the hazardous effects to human health (Nzediegwu *et al*., 2019). In addition, biochar is also known for adsorbing environmental resistant pollutants, dyes, pharmaceuticals onto its surfaces lowering their release into the soil and environment thus it has received recognition in conservation (Pan *et al*., 2021)

2.8 Effects of biochar on soil physical properties

Incorporation of biochar into the soil elevates crop growth and yield through lowering bulk density and increasing specific surface area which are necessary for proper crop growth (Lusiba *et al*., 2017). Low bulk density enables proper root proliferation and high specific surface area enables high nutrient absorption (Méndez *et al.,* 2017). Biochar has an impact on soil bulk density which it reduces by about 3 to 31%, the more biochar applied, the further decline in bulk density (Blanco-Canqui, 2017). This reduction in bulk density is attributed to two main mechanisms; the low bulk density of biochar about less than 0.6 g cm^{-3} which leads to the reduction of the soil's bulk density which is around 1.25g cm^{-3}. Therefore, thorough mixing of the two, soil bulk density is reduced through the dilution effect which is achieved through mixing of soil and biochar of two different densities. However, this mechanism works best when the difference between the densities of soil and biochar is high (Blanco-Canqui, 2017).

The other mechanism in which biochar reduces bulk density is when biochar mixes with soil, there is a further development of porosity and aggregation improvement. Biochar boosts soil porosity by about 14 to 64% (Omondi *et al*., 2016). All these two mechanisms are determined by the soil type and biochar rate applied. Furthermore, the mixing of soil with biochar increases the soil porosity, which is a result of the porous spongy nature of biochar. The improvement in soil porosity facilitates nutrient and water movement in the soil (Esmaeelnejad *et al.,* 2017).

Biochar has an effect on soil structure that influences penetration resistance (Joseph *et al*., 2020; Šimanský *et al*., 2016). Biochar undergoes interaction with the soil's inorganic particles and in this way lowers soil compaction enabling crop roots to penetrate to the deeper layers with ease in order to acquire nutrients and water (Wang *et al*., 2017). Conversely this is usually not achieved in short growing periods but rather after lengthy application of biochar such as biochar application for more than two years and in higher quantities (Blanco-Canqui, 2017). The water holding capacity of the soil is enhanced by biochar additions. This enhancement can go up to 90% and is due to the operative absorption power of the biochar units (Blanco-Canqui, 2017; Novak *et al*., 2012).

2.9 Effect of biochar on soil biological properties

2.9.1 Effect of biochar on general microbial population and activities

Biochar also enhances soil microbial population and activity by providing the microbes shelter due to its porous nature and nutrition (Mackie *et al.,* 2015; Zhang *et al*., 2014). Soil microbial populations and activities normally increase after application of biochar which is attributed to substrate availability and habitat (Dai *et al*., 2021). Soil microbes play a major role of nutrient cycling (Garcia & Kao-Kniffin, 2018). The biochar is source of substrates in form of nutrients from the organic matter to the soil microbes. In addition, the biochar provides shelter to the microorganisms from some soil predators such as mites, protozoans, and nematodes due to the small pore size of the biochar that is usually less than 5 mm in diameter. An increase in soil microorganisms by biochar is evidenced by an increase in carbondioxide levels which is an indicator of organic matter decomposition that is catalysed by soil microbes (Hardy *et al.,* 2019). Biochar incorporation is one of the factors which influences the population of different soil organisms alongside other factors such as soil temperature, moisture, root exudates (Alkorta *et al*., 2017; Azeem *et al*., 2020). This is because different types of the organisms have different ecological conditions such as pH, water stress and their nutritional needs under which they thrive. For example, bacteria require neutral to alkaline conditions, which are provided by biochar so that in such a condition bacteria population is higher than the fungi population (Rousk *et al*., 2009). In another study, Jiao *et al*. (2018) showed that addition of biochar led to absorption of antibiotics that are poisonous to potato roots, and increased potato starch, fat, protein, and vitamins content leading to high potato tuber quality.

2.9.2 Effect of biochar on phosphomonoesterase enzymes

The phosphomonoesterase enzymes availability are pH dependent; the acid phosphomonsterases are found in acidic conditions of pH range of 4 to 6 while alkaline phosphomonsterases are found in alkaline soils of pH 9 to 11 (Adetunji *et al*., 2017). These two enzymes are responsible for hydrolysis of monoester bonds of mononucleotides and sugar phosphates and phosphoprotein phosphatases (Nannipieri *et al*., 2011).

The amount of phosphomonoesterase enzymes depends on soil microbial populations, organic and inorganic fertilisers used and the agronomic practices applied (Adetunji *et al*., 2017; Cui & Holden, 2015). These enzymes transform organic phosphates stored in organic matter into inorganic forms thus the release of these enzymes relies on phosphorus contained in organic compounds, plant and microbial phosphorus needs and soil's phosphorus deficiency levels (Margalef *et al*., 2017). When soils are deficient in phosphorus, the plants and soil microorganisms respond by producing phosphomonoesterases to counteract the deficiency by solubilising and remobilising phosphates. This makes enzyme activity a measure of availability of inorganic phosphorus for plant and microbial use (Adetunji *et al*., 2017). Phosphomonoesterases enzyme activities are more in the rhizosphere than in the bulk soil medium due to modification in the rhizosphere that produces root exudates that stimulate enzyme activity. Phosphomonoesterases enzyme activities are high in soils with high organic matter. The organic matter provides substrate to the microorganisms that produce the phosphomonoesterases enzymes (Nannipieri *et al*., 2011). This explains why microbial activities are higher in soils amended with organic manures than in soils with chemical fertilisers. The enzymes' activities decrease with increase in soil depth due to limited oxygen and substrate. This explains why most microorganisms are concentrated at a soil depth of 0 -10 cm. The activities of phosphomonoesterases are a measure of soil health and quality as the enzymes are very sensitive to environmental variations and management practices (Margalef *et al*., 2017). The amount of inorganic P greatly influences the activities of the phosphomonoesterases. Inorganic P concentration is determined by various factors such as plant cover, soil microbial activities, presence of nutrient activators and inhibitors, and soil properties. All these factors are influenced by the incorporation of biochar in the soil. Therefore, biochar directly influences availability of inorganic P the P fraction which is responsible for soil phosphomonoesterases activities (Zhai *et al*., 2015). Biochar influences the soil's pH, biochar is known to increase soil pH (Martinsen *et al.*, 2015). This greatly affects phosphomonoesterases presence and activities. This is because alkaline phosphomonoesterases are predominant in alkaline soils and acid phosphomonoesterases exist mainly in acidic soils.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental sites description

A field-based experiment was carried out in two sites both located in Njoro, Nakuru county. The first site was situated in field seventeen at Egerton University and the second site was situated in Mau Narok. The site at Egerton university is located in agro-ecological zone III in Lower Highland II (0° 23′ S;35° 35′ E). The area is at an altitude of 2238m above sea level. The site receives bi-modal rainfall of approximately 1000mm annually with average temperatures of 18^{o}C to 21^{o}C (Jaetzold *et al*., 2012). The major soil type in this experimental area is mollic Andosols which is characterised by good drainage, friable and smeary feel, dark reddish-brown color, moderate fertility and sufficient depth (deep to very deep). The site characteristics provide suitable conditions for potato growth (Jaetzold *et al*., 2012).

The second site was in Mau Narok in a farmer's field in Agro-ecological zone II in Upper Highland I (0^{o} 39′ S;35 57′ E) that is found in the southwestern part of Nakuru county at a latitude of 2,900 m above sea level. The area receives bimodal rainfall ranging from 1,200 to 1,400 mm with minimum temperatures of 6 to 14^{o}C and maximum temperatures of 22 to 26^{o}C (Jaetzold *et al*., 2012). The common soil types are mollic Andosols characterised by crumby structure, good drainage, friable consistence, dark brown loams with clay loam texture and medium organic matter. Major crops grown in Nakuru are potato, maize beans and wheat (Jaetzold *et al*., 2012).

The experiment was conducted across two seasons, during the short rains of September to December 2020 in which planting was done in October 2020 and the second season: the long rains of March to June 2021 with planting done in April 2021.

3.2 Varieties

Potato seeds were purchased from Agricultural Development Corporation (ADC), Molo. Two potato varieties were planted i.e., *Shangi* and *Destiny*. *Shangi* is used for chips and *Destiny* is used for crisps. The two varieties are preferred by most farmers in Nakuru due to their short life cycles i.e. 3 to 4 months and their moderate resistance to most diseases especially late blight (*Phytophthora infestans*), potato virus X (*potato virus X*), potato leaf roll virus (*potato leaf roll virus*) and they give high yields (Hellmuth, 2019; Mumia *et al*., 2018; NPCK, 2019).

3.3 Biochar characterization

Biochar inform of charcoal dust was collected from charcoal producers in Nakuru county. This was blended thoroughly to obtain a composite biochar material. This biochar was then crushed and sieved through a 3-mm mesh (Major, 2009). This was followed by laboratory analysis of pH, total N and P, calcium and magnesium (Major, 2009). A sub-sample was tested for pH using the electrometric method, total carbon was determined by the Walkley-Black method using sulphuric acid and aqueous potassium dichromate. Total N and P were determined in a digest where the biochar was treated with hydrogen peroxide, sulphuric acid, selenium and salicylic acid (Okalebo *et al*., 2002). Calcium and magnesium were determined by atomic absorption spectrophotometry (Okalebo *et al*., 2002).

3.4 Experimental design and treatment combination

The experiment was laid out in Split Plot design in Randomized Complete Block Design (RCBD) arrangement. The varieties were the main plot with amendments as sub-plot replicated three times. Each experimental unit/plot measured 1.5m ×3m with four rows spaced at 75cm each with five plants spaced at 30cm. Two factors, that is, soil amendment (biochar and DAP) and potato genotype were assessed. Biochar and Diammonium Phosphate (DAP) were applied at three levels (0, 5, and 10 t ha^{-1}) and (0, 250, 500 kg ha^{-1}), respectively. The two amendments each at three levels gave 9 treatments that were combined with the two potato varieties to obtain 18 treatment combinations. These were then replicated 3 times to give 54 experimental units. The treatment combinations are as shown in table (1).

Table 1 :Treatment combinations

Trt no.	Variety	Biochar levels (t ha^{-1})	DAP levels (Kg ha^{-1})	soil Amendment combination
1	*Shangi*	0	0	B0D0
2	*Shangi*	5	0	B5D0
3	*Shangi*	10	0	B10D0
4	*Shangi*	0	250	B0D250
5	*Shangi*	0	500	B0D500
6	*Shangi*	5	250	B5D250
7	*Shangi*	10	250	B10D250
8	*Shangi*	5	500	B5D500
9	*Shangi*	10	500	B10D500
10	*Destiny*	0	0	B0D0
11	*Destiny*	5	0	B5D0
12	*Destiny*	10	0	B10D0
13	*Destiny*	0	250	B0D250
14	*Destiny*	0	500	B0D500
15	*Destiny*	5	250	B5D250
16	*Destiny*	10	250	B10D250
17	*Destiny*	5	500	B5D500
18	*Destiny*	10	500	B10D500

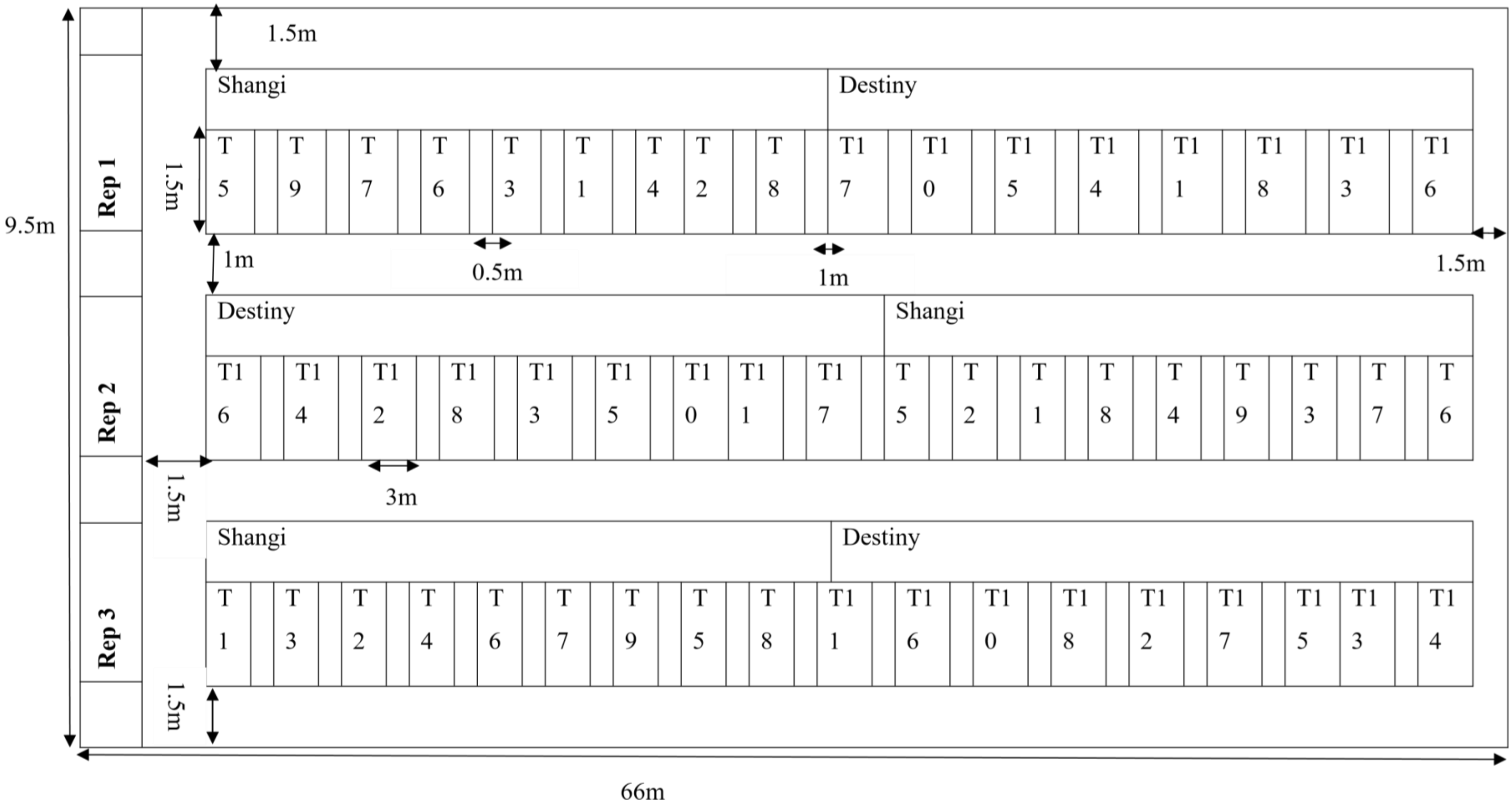

Figure 1 : Experimental Field-layout

3.5 Land preparation, planting, and management

The land was ploughed followed by harrowing to obtain a moderate tilth suitable for planting potato. Biochar and DAP were applied at planting according to the treatments. The soil amendments were applied every season. The potato seeds were planted at the recommended inter-row spacing of 75cm and intra-row spacing of 30cm (Musyoka *et al*., 2017). Uniform seeds of same size of 35 to 55 mm were used for planting.

Hand weeding was done twice. The first weeding at 2 weeks from emergence and the second weeding plus earthing was done prior to flowering. The second weeding plus earthing-up was done to ease tuberisation, moisture conservation and to control the invading weeds. Late blight disease (*Phytopthora infestans*) was prevented by spraying with Ridomil gold® a fungicide of active ingredients Metalaxyl-M 40g kg^{-1} and Mancozeb 640g kg^{-1} after every 7 days in rainy season and after every 14 days in the dry season at a rate of 40g 20 L^{-1}. Aphid infestation was controlled by spraying with pesticide Thunder® containing active ingredients Imidacloprid 100 g L^{-1} and Betacyfluthrin 45g L^{-1} at a rate of 10 ml 20 L^{-1}. Potassium was added to the soil by basal application of muriate of potash to all treatments at a rate of 50 kg ha^{-1}.

3.6 Soil sampling and analyses

Soil sampling was done twice i.e., at pre planting and post harvesting. Chemical analysis of the soil samples collected from the two sites was done at NARL-KALRO in Kabete. While the physical analyses were done in the soil science laboratory at Egerton university. The soil samples were obtained using a soil auger at depths of 0 to 15cm, 15 to 30cm following the zigzag pattern. The soil samples were first air dried and then sieved. Soil texture was determined by the hydrometer (Bouyoucos) method (Okalebo *et al*., 2002).

Cation exchange capacity CEC was determined by the ammonium saturation method using 1M ammonium acetate. 50 ml of 1N ammonium acetate solution was added to 10g of sieved, air-dried soil into a bottle. The bottle content was then shaken in a mechanical shaker at 110 rpm for 30 minutes and the sample was left to stand overnight before the second mechanical shaking 30 minutes was done. The sample in the plastic bottle was filtered, leached twice using neutral 1N KCl solution. The leachate was drained completely before the aliquot was added and topped up to the 100 ml mark. At this point, the solution was now ready for determination of the individual cations. The residue on the filter paper was then used for the determination of the cation exchange capacity of the soil. The CEC was then determined by measuring the total quantity of negative charges per unit weight of the soil which are neutralised by the exchangeable cations and expressed as milliequivalents per 100g soil (Okalebo *et al*., 2002).

Soil pH was determined in the laboratory by the electrometric method of 1: 2.5 soil: water ratio; pH meter standardised with buffers of pH 7 and 4 were used to measure the pH of the soil. A soil suspension of 1:2.5 soil water ratio was used and its pH was read from the pH meter. (Okalebo *et al*., 2002). Inorganic nitrogen was measured by the colorimetric method in which 0.5 M K_2SO_4 was used to extract ammonium and nitrate ions from the soil (Okalebo *et al*., 2002). Extractable phosphorus was determined by the Mehlich 3 method, where the soil was extracted with a mixture of 0.03N ammonium fluoride (NH_4F) + 0.025N hydrochloric (HCl) acid (Okalebo *et al*., 2002).

Soil samples for phosphomonoesterases enzymes analysis were obtained at harvest. These were randomly obtained from the rhizosphere by carefully excavating the soil next to the roots using a soil auger to minimise bulk soil i.e., soil outside the rhizosphere or soil not penetrated by roots was avoided. The soil samples were transferred into a clean bucket and thoroughly mixed to get a composite sample. Of the composite sample, only 50g was placed in bag and taken to laboratory for further analysis. To ensure the soil samples were not exposed to high temperature during transit to laboratory, samples were transported in a cool box filled with ice cubes. At arrival in the laboratory, samples were stored at 4^oC in the refrigerator until analysis (Bottomley *et al*., 2020).

During analysis, 1gof fresh, moist, and sieved soil was assayed with either pH 6.5 for acid phosphomonoesterases or pH 11 for alkaline phosphomonoesterases, 1 ml of p-nitrophenyl phosphate solution made in the same buffer was added and contents incubated at 37°C for 1 hour. 1 ml of 0.5M calcium chloride and 4 ml of 0.5M sodium hydroxide were then added to the incubated contents, swirled and suspension filtered through Whatman no. 2v folded filter paper. The yellow colour intensity of p-nitrophenol was measured using a spectrophotometer at 400 nm. Controls were performed with each soil analysed to allow for colour not derived from p-nitrophenol released by phosphatase activity. Same procedure described above was followed but the additions of 1 mL of PNP solution were made after the additions of 0.5M calcium chloride and 4 ml of 0.5M sodium hydroxide immediately before filtration of the soil suspension.

Phosphomonoesterase enzymes' activity was measured as mM pNP × kg^{-1} ×h^{-1} i.e. number of moles of p-nitrophenol produced by 1 kg of a soil at 37°C per hour (Tabatabai & Bremner, 1969).

Total nitrogen was determined using the Kjeldahl method. Sieved soil samples were oven dried at 40^o C followed by digestion using concentrated sulphuric acid containing selenium, copper sulphate and potassium sulphate. Distillation followed by titration using standardised diluted sulphuric acid were used to determine total nitrogen (Okalebo *et al*., 2002).

The Mehlich Double Acid Method was used to determine potassium, sodium, calcium and magnesium. Sieved soil samples oven dried at 40^o C were extracted with a mixture of 0.1 N HCl and 0.025 N H2SO4. Potassium, sodium and calcium were determined with a flame photometer while magnesium was determined using a UV/VIS spectrophotometer (Okalebo *et al*., 2002).

3.6.1 Soil and biochar analysis results

Table 2: Initial biochar, soil chemical and physical properties

	Soil Sample				
Study site	Egerton		Mau-Narok		Biochar
Soil depth (cm)	0-15	15-30	0-15	15-30	
Total Nitrogen (gkg^{-1})	0.24	0.24	0.26	0.24	0.35
Phosphorus (mg kg^{-1})	18.50	22.00	30.70	27.60	0.08
Potassium (Cmol kg^{-1})	1.80	1.40	1.36	0.56	0.73
Calcium (Cmol kg^{-1})	9.00	10.20	4.60	3.80	1.19
Magnesium (Cmol kg^{-1})	5.02	4.85	3.36	3.26	0.22
Sodium (Cmol kg^{-1})	0.20	0.30	0.90	0.50	--
Cation exchange capacity (Cmol kg^{-1})	29.00	32.00	24.30	25.70	--
Soil pH-H2O (1:1)	6.01	6.15	5.00	5.20	10.2
Total Org. Carbon (gkg^{-1})	2.59	2.60	2.87	2.59	--
Sand %	58.00	60.00	56.00	56.00	--
Silt %	14.00	12.00	14.00	14.00	--
Clay %	28.00	28.00	30.00	30.00	--
Texture class	SCL	SCL	SCL	SCL	--

SCL –Sandy clay loam

3.7 Data collection

3.7.1 Objective 1: Effect of different rates of biochar and inorganic fertiliser on potato growth and yield

a. Growth parameters

i. Number of stems

Number of stems per plant were counted at intervals of 45, 52, 59, and 66 days after planting.

ii. Plant height

This was measured, within the same timeframe for counting number of stems, using a meter ruler starting from the main stem base to the shoot apex.

b. Yield parameters

i. Number of tubers

At harvest, the number of tubers per plant were counted.

ii. Tuber weight

The tubers were graded into categories according to their sizes i.e. large size >55mm diameter, medium size at 35-55mm diameter then small size <35mm diameter using a potato hand grading machine (Kirigo, 2019). The weight of the tubers was determined to get total weight of tubers in each treatment.

iii. Yield

Weight was used to compute yield. The marketable yield was obtained by subtraction of the non-marketable yield from the total tuber yield.

Equation 7: Total tuber yield calculation formula

$$\text{Total tuber yield } (\text{t ha}^{-1}) = \frac{\text{Weight per plant } \times \text{plant population}}{1000}$$

iv. Dry matter

Dry matter of the potatoes was determined in the laboratory where a sub-sample of potato tubers 200 grams were sliced or grated uniformly, and oven dried at a temperature of 65°C for 72 hours to constant weight.

Equation 8: Dry matter calculation formula

$$\text{Dry matter (\%)} = \frac{\text{Weight of sample after drying}}{\text{Initial weight of sample}} \times 100$$

3.7.2 Objective 2: Effect of different rates of biochar and inorganic fertiliser on nutrient use efficiency

3.7.2.1 Nutrient uptake

Tissue analysis for N and P was done on sampled potato tubers that were oven dried at 65°C for 48 hours at NARL-KARLO Kabete Nairobi. The formulae below were used to calculate N uptake and P uptake respectively (Baligar *et al.*, 2001).

Equation 9: Nitrogen uptake calculation formula

$$\text{N uptake (Kg N ha}^{-1}) = \frac{[\text{N (\%)} \times \text{dry matter (kg ha}^{-1})]}{100}$$

Equation 10: Phosphorus uptake calculation formula

$$\text{P uptake (Kg P ha}^{-1}) = \frac{[\text{P (\%)} \times \text{dry matter (kg ha}^{-1})]}{100}$$

3.7.2.2 Agronomic efficiency

Agronomic efficiency (AE) was determined at maturity stage where the potatoes were harvested and yield in both the fertilised and unfertilised plots measured. The formulae below were used to calculate agronomic efficiency resulting from N and P application respectively (Baligar *et al.*, 2001).

Equation 11: Nitrogen agronomic efficiency calculation formula

$$\mathrm{AE}_N\ (\mathrm{Kg\ Kg\ N^{-1}}) = \frac{[\mathrm{Yield}_F\ (\mathrm{Kg\ ha^{-1}}) - \mathrm{Yield}_C\ (\mathrm{Kg\ ha^{-1}})]}{\mathrm{Quantity\ of\ N\ applied\ (Kg\ \ N\ ha^{-1})}}$$

Equation 12: Phosphorus agronomic efficiency calculation formula

$$\mathrm{AE}_P\ (\mathrm{Kg\ Kg\ P^{-1}}) = \frac{[\mathrm{Yield}_F\ (\mathrm{Kg\ ha^{-1}}) - \mathrm{Yield}_C\ (\mathrm{Kg\ ha^{-1}})]}{\mathrm{Quantity\ of\ \ P\ applied\ (Kg\ \ P\ ha^{-1})}}$$

Where F means fertilised, and C means control where no fertiliser was applied.

3.7.3 Objective 3: Effect of different rates of biochar and inorganic fertiliser on selected soil properties

(see section 3.6)

3.8 Data analysis

The data was first tested for normality using *Shapiro Wilk* test. Analysis of variance was done using General Linear model procedures of SAS 9.3 version. Comparison of treatment means was determined by Tukey's honestly significant difference at 0.05 since treatment combinations are more than four.

3.8.1 Statistical model

Equation 13: Statistical model

$$\boldsymbol{Y}_{\mathrm{ijklm}} = \mu + \mathrm{S}_{\boldsymbol{i}} + \boldsymbol{E}_{\mathrm{j}} + \boldsymbol{SE}_{\mathrm{ij}} + ß_{\boldsymbol{k}(\mathrm{ij})} + \mathrm{V}_{\mathrm{l}} + \mathrm{VS}_{\mathrm{jl}} + \mathrm{VE}_{\mathrm{jl}} + \mathrm{VSE}_{\mathrm{ijl}} + \mathrm{V}ß_{\mathrm{k(ij)l}} + \mathrm{A}_{\mathrm{m}} + \mathrm{AS}_{\mathrm{im}} + \mathrm{AE}_{\mathrm{jm}} + \mathrm{ASE}_{\mathrm{ijm}} + \mathrm{AV}_{\mathrm{lm}} + \mathrm{AVS}_{\mathrm{ilm}} + \mathrm{AVE}_{\mathrm{jlm}} + \mathrm{AVSE}_{\mathrm{ijlm}} + \mathcal{E}_{\mathrm{ijklm}}$$

Where;

Y_{ijklmn} = overall yield, µ = overall mean, S_i = effect due to the ith season, E_j = effect due to the jth environment, SE_{ij} = effect of interaction of ith season and jth environment, $ß_{k(ij)}$ = effect due to the kth block, V_l = effect due to the lth variety levels, VS_{il} = effect of interaction due to the lth variety levels and ith season, VE_{jl} = effect of interaction due to the jth environment and the lth variety levels, VSE_{ijl} = effect of interaction due to the lth variety levels, ith season and jth environment, $Vß_{k(ij)l}$ = effect of interaction due to the lth variety levels and kth block, A_m =effect due to the mth soil amendment levels, AS_{im} = effect due to the m^{th} soil amendment levels and i^{th} season, AE_{jm} = effect due to the m^{th} soil amendment levels and j^{th} environment, ASE_{ijm} = effect due to m^{th} soil amendment levels, i^{th} season and and j^{th} environment, AV_{lm} = effect due to the m^{th} soil amendment levels and l^{th} variety levels, AVS_{ilm} = effect due to the m^{th} soil amendment levels, l^{th} variety levels and i^{th} season, AVE_{jlm} = effect due to the m^{th} soil amendment levels, l^{th} variety levels and j^{th} environment, $AVSE_{ijln}$ = effect due to the m^{th} soil amendment levels, l^{th} variety levels, i^{th} season and j^{th} environment, ε_{ijklmn}= random error term

CHAPTER FOUR

RESULTS

4.2 Effect of different rates of biochar and inorganic fertiliser on potato growth

4.2.1 Number of stems

The different applied fertilisers significantly increased number of stems at ($P<0.001$). Treatments 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest number of stems (Table 3). The lowest number of stems was registered in control and plots that were amended with sole biochar at 5 or 10 t ha^{-1} (B5D0 and B10D0). At Egerton in the short rains season, there were no significant differences across treatments for number of stems for *Destiny*. In contrast, *Shangi* planted in the same season and site; there were significant differences on the number of stems. But for both varieties,500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced the highest number of stems. In the same site during the long rains, the number of stems differed significantly for *Destiny* across the applied fertilisers with the highest number of stems still being recorded for plots amended with 500 kg ha^{-1} DAP and 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP. The controls and plots singly amended with 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar produced potatoes with the lowest number of stems (Table 3). This was also observed during the long rains at Egerton where B0D500 gave the highest number of stems while 10 t ha^{-1} Biochar gave the lowest stems for both varieties. Similar trend was observed in Mau Narok, during the short rains where 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced the highest number of stems for *Destiny* with the least from control, 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar. The same trend was observed in *Shangi*. Still in the long rains, for *Destiny*, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest number of stems while for *Shangi* the highest was obtained from plots treated with 500 kg ha^{-1} DAP while the control and 10 t ha^{-1} Biochar gave the lowest number of stems for all varieties. In the two study sites there was consistence of trend where 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP treatments produced the highest number of stems for both varieties in the two seasons and lowest number of stems from the control and plots with sole application of biochar.

Table 3: Effect of biochar and DAP on the number of stems at 52 dap at Egerton and Mau Narok, Kenya.

	Egerton				Mau Narok			
	Short rain season		Long rain season		Short rain season		Long rain season	
Treatment	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*
B0D0	2.58^{a}	2.25^{cd}	3.72^{c}	2.97^{c}	2.25^{c}	2.25^{b}	4.85^{ab}	3.50^{ab}
B0D250	2.92^{a}	2.70^{bcd}	4.27^{abc}	3.53^{abc}	3.08^{abc}	2.75^{ab}	5.25^{ab}	4.50^{a}
B0D500	3.33^{a}	3.33^{ab}	5.25^{a}	4.32^{a}	3.42^{ab}	2.85^{ab}	5.47^{ab}	4.75^{a}
B5D0	2.58^{a}	1.95^{d}	3.75^{bc}	2.78^{c}	2.50^{bc}	2.42^{ab}	4.92^{ab}	3.62^{ab}
B5D250	3.00^{a}	3.00^{abc}	4.63^{abc}	3.25^{bc}	3.17^{abc}	2.88^{ab}	5.58^{ab}	4.33^{a}
B5D500	3.43^{a}	3.66^{a}	5.08^{ab}	4.02^{ab}	3.75^{a}	3.33^{a}	6.00^{a}	4.55^{a}
B10D0	2.25^{a}	2.25^{cd}	3.42^{c}	2.73^{c}	2.77^{abc}	2.33^{ab}	4.75^{b}	2.92^{b}
B10D250	2.82^{a}	2.83^{abcd}	4.17^{abc}	3.33^{bc}	3.17^{abc}	2.53^{ab}	5.67^{ab}	4.75^{a}
B10D500	2.87^{a}	3.50^{ab}	4.50^{abc}	3.53^{abc}	3.25^{abc}	2.75^{ab}	5.28^{ab}	3.98^{ab}
MSD	*NS*	*0.91*	*1.36*	*0.91*	*1.11*	*1.07*	*1.24*	*1.25*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP, dap: days after planting.

4.2.2 Plant height

The different types and levels of soil amendments applied resulted into significant differences in potato plant heights ($p \leq 0.001$). Soil amendments 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest plant height (Table 4), (Table 5). Plots that received only biochar produced the shortest potato plants that were not significantly different from the control. An increment in biochar application from 5 t ha^{-1} to 10 t ha^{-1} decreased potato plant height. Generally, for both sites, plots treated with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced the tallest potato plant heights in both seasons and varieties (Table 4), (Table 5).

Table 4 : Effect of biochar and DAP on the plant height at Egerton, Kenya.

	Egerton											
	Short rain season (October - December 2020)						Long rain season (April - July 2021)					
	Destiny			*Shangi*			*Destiny*			*Shangi*		
Treatment	45dap	52dap	66dap	45dap	52dap	66dap	45dap	52dap	66dap	45dap	52dap	66dap
B0D0	20.33[a]	29.07[b]	54.25[a]	41.75[a]	59.96[b]	84.17[c]	16.42[a]	29.08[b]	46.67[b]	43.00[a]	57.00[b]	77.17[a]
B0D250	22.88[a]	37.50[ab]	57.92[a]	45.58[a]	68.50[ab]	89.25[bc]	18.33[a]	30.33[b]	49.67[b]	43.75[a]	62.42[ab]	81.58[a]
B0D500	24.13[a]	41.83[ab]	60.08[a]	46.75[a]	72.00[ab]	96.25[ab]	19.17[a]	36.17[ab]	55.33[ab]	46.67[a]	69.00[a]	87.83[a]
B5D0	19.92[a]	30.00[ab]	52.42[a]	39.43[a]	60.42[b]	88.83[bc]	17.92[a]	29.92[b]	44.75[b]	44.33[a]	58.33[b]	79.00[a]
B5D250	23.75[a]	37.33[ab]	56.67[a]	45.58[a]	72.00[ab]	95.33[ab]	20.33[a]	32.33[ab]	52.17[ab]	46.08[a]	58.17[b]	82.67[a]
B5D500	24.57[a]	42.75[a]	61.58[a]	47.71[a]	76.00[a]	102.17[a]	22.50[a]	38.50[a]	61.17[a]	40.17[a]	67.42[ab]	88.67[a]
B10D0	18.00[a]	32.58[ab]	52.67[a]	41.27[a]	60.33[b]	87.17[bc]	17.17[a]	29.17[b]	49.58[b]	46.25[a]	59.42[ab]	79.33[a]
B10D250	21.18[a]	36.38[ab]	56.75[a]	45.25[a]	67.75[ab]	95.75[ab]	18.67[a]	30.33[b]	50.75[ab]	48.42[a]	63.42[ab]	80.17[a]
B10D500	22.83[a]	38.38[ab]	55.00a	48.83[a]	70.25[ab]	94.00[abc]	17.92[a]	32.92[ab]	53.42[ab]	46.25[a]	62.50[ab]	84.83[a]
MSD	*NS*	*13.25*	*NS*	*NS*	*12.69*	*10.67*	*NS*	*7.49*	*10.72*	*NS*	*10.64*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP, dap: days after planting.

Table 5: Effect of biochar and DAP on the plant height at Mau Narok, Kenya.

	Mau Narok											
	Short rain season (October - December 2020)						Long rain season (April - July 2021)					
	Destiny			*Shangi*			*Destiny*			*Shangi*		
Treatment	45dap	52dap	66dap	45dap	52dap	66dap	45dap	52dap	66dap	45dap	52dap	66dap
B0D0	7.67^{b}	15.50^{bc}	41.00^{bc}	19.75^{b}	32.83^{fg}	62.67^{c}	20.25^{c}	32.25^{b}	49.25^{b}	34.33^{a}	49.67^{d}	76.92^{c}
B0D250	12.67^{ab}	21.58^{abc}	45.07^{abc}	25.83^{ab}	40.33^{def}	70.83^{abc}	24.67^{abc}	36.67^{ab}	55.25^{ab}	39.17^{a}	57.17^{abcd}	85.42^{abc}
B0D500	15.17^{ab}	28.50^{a}	50.33^{ab}	29.33^{a}	50.00^{ab}	75.75^{ab}	24.42^{abc}	38.75^{ab}	59.17^{a}	43.33^{a}	61.67^{bc}	91.00^{a}
B5D0	8.17^{b}	15.00^{c}	39.42^{c}	19.83^{b}	32.25^{g}	65.17^{bc}	20.00^{c}	31.50^{b}	49.50^{b}	35.75^{a}	50.42^{cd}	81.00^{abc}
B5D250	13.83^{ab}	24.33^{abc}	48.33^{abc}	26.92^{a}	43.17^{bcd}	69.83^{abc}	25.75^{ab}	38.08^{ab}	56.50^{ab}	39.42^{a}	58.75^{abcd}	88.58^{ab}
B5D500	18.50^{a}	29.00^{a}	54.33^{a}	25.25^{ab}	51.83^{a}	78.92^{a}	28.67^{a}	43.33^{a}	62.33^{a}	41.75^{a}	63.08^{a}	90.75^{a}
B10D0	10.33^{ab}	20.00^{abc}	40.75^{bc}	19.58^{b}	34.50^{efg}	66.08^{abc}	21.67^{bc}	33.00^{b}	50.17^{b}	34.58^{a}	51.75^{bcd}	79.58^{bc}
B10D250	12.75^{ab}	23.50^{abc}	42.17^{bc}	24.67^{ab}	41.42^{cde}	70.67^{abc}	24.67^{abc}	37.42^{ab}	54.00^{ab}	38.08^{a}	56.42^{abcd}	85.50^{abc}
B10D500	14.67^{ab}	25.250^{ab}	45.08^{abc}	27.75^{a}	48.92^{abc}	73.67^{abc}	26.08^{ab}	41.33^{a}	57.92^{ab}	40.92^{a}	59.92^{abc}	89.00^{ab}
MSD	*8.54*	*9.78*	*10.01*	*7.05*	*8*	*12.97*	*5.48*	*8.17*	*8.99*	*NS*	*10.09*	*10.13*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP, dap: days after planting.

4.3 Effect of different rates of biochar and inorganic fertiliser on potato yield

4.3.1 Total tuber yield

The different treatments significantly increased total tuber yield ($P \leq 0.001$). Incorporation of 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP recorded the highest total tuber yield and lowest yield was from control and plots that received biochar application only (Table 6), (Table 7).

At Egerton in the short rain season, plots amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced the highest yields and controls produced the lowest yield for both varieties. Still in the long rain season, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP had the highest total yields for destiny soils however for *Shangi*, the highest yields were from plots fertilised with 500 kg ha^{-1} DAP (Table 6). Similarly, in Mau Narok for all varieties and seasons, still 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest potato tuber yields (Table 7).

4.3.2 Marketable tuber yield

The applied fertiliser treatments significantly ($P<0.001$) affected the marketable tuber yields. Soils amended with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest marketable tuber yield with the least recorded from the control and sole biochar plots (Table 6), (Table 7). In Egerton during the short rain season, soil amendments of 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 250 kg ha^{-1} DAP gave the highest marketable tuber yield for *Destiny*. However, for *Shangi*, the highest marketable tuber yield was from plots amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP. However, for the long rain season, treatments 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest marketable tuber yields for both varieties (Table 6). A similar trend was obtained in Mau Narok with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP giving the highest marketable tuber yields (Table 7). Throughout the seasons, sites and varieties the controls, 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar had the lowest marketable tuber yield (Table 6), (Table 7).

Table 6: Effect of biochar and DAP on potato total yield ($t\ ha^{-1}$) and marketable yield ($t\ ha^{-1}$) at Egerton, Kenya.

Egerton								
	Short rain season				Long rain season			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
Treatment	Yield	Mkt yield	Yield	Mkt yield	Yield	Mkt yield	Yield	Mkt yield
B0D0	12.02^{c}	9.47^{b}	9.16^{g}	6.64^{e}	25.02^{e}	14.00^{f}	23.48^{d}	15.73^{d}
B0D250	18.03^{b}	12.44^{b}	14.68^{fg}	10.52^{de}	27.89^{de}	23.84^{de}	31.59^{bcd}	23.11^{abcd}
B0D500	22.79^{a}	11.02^{b}	25.47^{bc}	16.47^{c}	37.45^{abc}	27.84^{bcd}	44.55^{a}	31.44^{a}
B5D0	12.36c	7.22^{b}	15.95^{ef}	9.27^{de}	34.82^{bcd}	25.51^{cde}	26.14^{cd}	21.80^{bcd}
B5D250	16.42^{bc}	14.58^{ab}	22.05^{cd}	18.40^{bc}	36.49^{abcd}	33.16^{abc}	32.35^{bcd}	24.98^{abcd}
B5D500	26.41^{a}	21.84^{a}	32.39^{a}	25.96^{a}	44.45^{a}	37.02^{a}	30.53^{bcd}	27.98^{ab}
B10D0	13.78^{bc}	8.22^{b}	16.60^{def}	9.79^{de}	24.91^{e}	17.16^{ef}	23.62^{d}	18.18^{cd}
B10D250	12.69^{c}	10.38^{b}	21.15^{cde}	13.45^{cd}	31.94^{cde}	23.16^{de}	39.53^{ab}	30.78^{ab}
B10D500	24.14^{a}	14.46^{ab}	30.82^{ab}	22.52^{ab}	42.85^{ab}	36.22^{ab}	34.86^{bc}	26.47^{abc}
MSD	*4.64*	*7.54*	*6.10*	*4.98*	*8.77*	*9.13*	*9.46*	*9.48*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Mkt: Marketable, MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Table 7: Effect of biochar and DAP on potato total yield (t ha^{-1}) and marketable yield (t ha^{-1}) at Mau Narok, Kenya.

Mau Narok

	Short rain season				Long rain season			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
Treatment	Yield	Mkt yield	Yield	Mkt yield	Yield	Mkt yield	Yield	Mkt yield
B0D0	12.71^{d}	6.44^{d}	26.37^{d}	13.26^{c}	17.44^{bc}	14.40^{bc}	20.41^{c}	19.29^{b}
B0D250	18.39^{cd}	8.85^{cd}	29.19^{bcd}	15.49^{c}	22.31^{ab}	19.04^{abc}	28.05^{ab}	25.27^{ab}
B0D500	26.55^{ab}	15.47^{bc}	33.44^{ab}	23.33^{ab}	25.35^{a}	24.18^{ab}	28.16^{ab}	27.85^{ab}
B5D0	14.25^{cd}	10.47^{cd}	26.70^{d}	17.34^{bc}	13.25^{c}	12.51^{c}	20.78^{c}	19.33^{b}
B5D250	20.06^{bc}	15.02^{bc}	29.66^{bcd}	22.67^{ab}	23.79^{ab}	20.85^{abc}	26.32^{abc}	25.02^{ab}
B5D500	29.39^{a}	24.90^{a}	36.54^{a}	28.76^{a}	27.51^{a}	25.14^{a}	31.68^{a}	30.76^{a}
B10D0	15.06^{cd}	11.07^{cd}	27.11^{cd}	15.13^{c}	18.28^{bc}	16.31^{abc}	22.13^{bc}	20.75^{ab}
B10D250	19.07^{cd}	14.49^{bc}	29.75^{bcd}	25.62^{a}	24.86^{ab}	24.30^{a}	26.85^{abc}	26.00^{ab}
B10D500	28.06^{a}	20.42^{ab}	35.21^{ab}	28.67^{a}	26.88^{a}	22.89^{ab}	29.12^{a}	25.19^{ab}
MSD	*7.33*	*6.63*	*6.54*	*6.24*	*6.87*	*9.97*	*6.96*	*10.36*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Mkt: Marketable, MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.3.3 Number of potato tubers as affected by application of biochar and fertiliser

Number of tubers per plant significantly varied across the treatments ($p \leq 0.001$). Soils with fertiliser treatments 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} on average produced the highest number of tubers per plant. The lowest number of tubers per plant were registered under control and in soils amended with only biochar (Table 8), (Table 9). In Egerton during the short rain season the highest number of tubers was from plots that received 500 kg ha^{-1} DAP which was not significantly different from plots amended with 250 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} for *Destiny*. The same treatments gave higher yields for *Shangi* grown in the same site and season. For the long rain season in Egerton, the highest number of tubers per plant 15.50, 14.83 and 14.67 were registered in plots that received 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 250 kg ha^{-1} respectively for *Destiny*. For *Shangi* the highest number of tubers was in plots fertilised with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} (Table 8). Still in Mau Narok, during the short rain season the soil amendments of 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} gave the highest number of tubers per plant for *Destiny.* However, there were no significant differences of treatments on number of tubers per plant with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} still registering the highest for *Shangi.* In the long rains number of tubers differed significantly across the treatments with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} producing the highest for both varieties (Table 9).

4.3.4 Assessment of tuber dry matter across treatments

The soil amendments significantly influenced dry matter of the potatoes ($P<0.001$). Plots amended with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, 10 t ha^{-1} Biochar with 500 kg ha^{-1}, 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar gave the highest potato dry matter (Table 8), (Table 9). At Egerton in the short rain season, applied soil amendments of 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar with 500 kg ha^{-1} gave the highest dry matter. However, in the long rain season, more dry matter was found in plants that were grown on soils that received 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP (Table 8).

In Mau Narok during the short rain season, higher potato dry matter was found in potatoes grown on soils amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, 10 t ha^{-1} Biochar and 10 t ha^{-1} Biochar with 250 kg ha^{-1} DAP. In the long rain season more potato dry matter was achieved in soils treated with 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar (Table 9). At Egerton during short rain season, there was no significant effect of the fertilisers on dry matter for *Destiny*. Nevertheless, soils in which 5 t ha^{-1} Biochar was added gave the highest dry matter for *Destiny* while soils which were applied with 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced highest dry matter for *Shangi*. However, in the long rain season at the same location, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP soil amendment produced the highest dry matter for *Shangi*. It should be noted that for *Destiny* the applied soil amendments did not significantly affect the dry matter (Table 8). At Mau Narok in the short rain season, the greatest dry matter was from plots fertilised with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar. During the long rain season in Mau Narok, the fertilisers did not significantly affect dry matter of the two varieties (Table 9).

Table 8: Effect of biochar and DAP on number of tubers per plant and dry matter (%) at Egerton, Kenya.

Egerton								
	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	tubers/plant	DM (%)	tubers/plant	DM (%)	tubers/plant	DM (%)	tubers/plant	DM (%)
B0D0	6.17[cd]	38.00[a]	7.23[c]	36.67[ab]	10.67[c]	25.78[a]	10.92[de]	24.19[b]
B0D250	8.90[abc]	40.17[a]	8.77[abc]	37.67[ab]	12.42[abc]	24.06[a]	12.83[bcde]	25.76[ab]
B0D500	10.90[a]	37.17[a]	10.33[abc]	39.00[ab]	15.50[a]	28.19[a]	16.17[ab]	24.14[b]
B5D0	6.00[cd]	42.00[a]	7.60[c]	33.33[b]	10.75[c]	25.46[a]	11.92[cde]	27.98[ab]
B5D250	7.77[abcd]	37.50[a]	11.07[abc]	36.00[ab]	12.33[abc]	25.02[a]	14.52[abcd]	25.29[ab]
B5D500	10.74[ab]	35.83[a]	12.00[ab]	38.50[ab]	14.67[abc]	26.09[a]	15.75[abc]	30.48[a]
B10D0	5.27[d]	40.33[a]	7.90[bc]	37.17[ab]	10.83[bc]	25.16[a]	9.83[e]	24.09[b]
B10D250	7.60[bcd]	41.83[a]	9.80[abc]	34.67[b]	14.83[ab]	26.54[a]	13.75[abcde]	25.86[ab]
B10D500	8.53[abc]	36.67[a]	12.27[a]	42.00[a]	14.08[abc]	26.59[a]	17.42[a]	25.79[ab]
MSD	*3.19*	*NS*	*4.23*	*6.69*	*4.01*	*NS*	*4.08*	*6.12*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), DM: Dry Matter, MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Table 9: Effect of biochar and DAP on number of tubers per plant and dry matter (%) at Mau Narok, Kenya.

Mau Narok

	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	tubers/plant	DM (%)	tubers/plant	DM (%)	tubers/plant	DM (%)	tubers/plant	DM (%)
B0D0	6.31^{abc}	36.17^{b}	9.37^{a}	36.50^{ab}	6.25^{abc}	25.74^{a}	7.25^{bc}	24.08^{a}
B0D250	8.07^{abc}	39.00^{b}	10.70^{a}	31.83^{b}	8.25^{abc}	28.63^{a}	9.50^{abc}	25.22^{a}
B0D500	8.80^{ab}	36.33^{b}	12.57^{a}	39.50^{ab}	9.58^{a}	26.77^{a}	11.33^{a}	27.06^{a}
B5D0	5.43^{c}	36.17^{b}	9.10^{a}	41.83^{a}	5.08^{c}	26.18^{a}	6.58^{c}	27.39^{a}
B5D250	8.20^{abc}	35.67^{b}	11.33^{a}	39.17^{ab}	7.25^{abc}	26.18^{a}	9.08^{abc}	25.02^{a}
B5D500	9.20^{a}	48.00^{a}	12.93^{a}	42.00^{a}	9.08^{ab}	26.33^{a}	11.25^{a}	25.06^{a}
B10D0	6.10^{bc}	35.50^{b}	9.80^{a}	42.00^{a}	5.50^{bc}	29.07^{a}	6.42^{c}	23.63^{a}
B10D250	7.20^{abc}	37.00^{b}	10.70^{a}	42.33^{a}	8.47^{abc}	26.28^{a}	9.58^{abc}	25.16^{a}
B10D500	8.57^{ab}	37.50^{b}	12.53^{a}	37.00^{ab}	9.50^{a}	26.34^{a}	10.25^{ab}	24.97^{a}
MSD	*3.05*	*7.47*	*NS*	*8.38*	*3.61*	*NS*	*3.36*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), DM: Dry Matter, MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.4 Effect of different rates of biochar and inorganic fertiliser on selected soil properties

4.4.1 Soil pH

Soil pH was significantly affected by soil amendment applied ($P \leq 0.001$). Application of DAP with no biochar amendment significantly acidified the soils while the biochar increased soil pH making it alkaline. Generally, the soil pH under different soil amendments across different seasons and locations varied between 4.92 and 7.54 (Table 10). At Egerton, treatment B5D500 increased soil pH from the initial 6.01 to 6.55 and 7.25 in fields planted to *destiny* and *shang*i, respectively in both seasons. This was not significantly different from other treatments that had biochar (Table 10). At Mau Narok in the short rain season, soil amendment B5D0 gave the highest soil pH of 7.54 from the initial soil pH of 5.00 which was not significantly different from B10D250 and B10D500 on soils planted with destiny. However, in the same season under soils grown with *shangi*, B5D500 had the highest soil pH of 7.39 from the initial soil pH of 5.00. Still, this was not significantly different from the soil amendments of B5D0, B5D250 B10D500. In the long rain season, B5D0 had the highest soil pH for both varieties that was not significantly different from all the other amendments that had biochar. The lowest pH of 4.90 at Egerton was found with 250 kg ha^{-1} DAP during the second season under *Destiny*. At Mau Narok study site, the lowest soil pH in this site in the short rain season averaged 5.31 and was found from the control that was not significantly different from the soil pH measured in soils amended with 250 kg ha^{-1} DAP and 500 kg ha^{-1} DAP under *Shangi* variety. In the long rain season, control and 500 kg ha^{-1} DAP still had the lowest soil pH both under *Destiny* (Table 10).

Table 10: Effect of biochar and DAP on soil pH at Egerton and Mau Narok Kenya.

	Egerton				Mau Narok			
	Short rain season		Long rain season		Short rain season		Long rain season	
Treatment	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*
B0D0	5.66^{abc}	5.99^{bc}	5.05^{c}	4.99^{c}	5.43^{d}	5.31^{d}	4.97^{c}	5.29^{bc}
B0D250	5.55^{bc}	5.75^{c}	4.90^{c}	5.07^{c}	5.46^{d}	5.55^{d}	5.24^{bc}	5.05^{c}
B0D500	5.42^{c}	6.14^{abc}	5.27^{bc}	5.19^{bc}	5.36^{d}	5.60^{cd}	5.19^{bc}	5.29^{bc}
B5D0	6.01^{abc}	6.23^{abc}	5.93^{a}	5.71^{ab}	7.54^{a}	6.68^{ab}	5.69^{abc}	6.24^{a}
B5D250	6.19^{abc}	6.77^{abc}	5.65^{ab}	5.93^{a}	6.43^{c}	6.61^{ab}	5.49^{abc}	5.72^{abc}
B5D500	6.55^{a}	7.25^{a}	5.65^{ab}	5.79^{ab}	6.58^{bc}	7.39^{a}	6.07^{ab}	6.29^{a}
B10D0	6.07^{abc}	6.86^{abc}	6.01^{a}	5.24^{bc}	6.49^{bc}	6.58^{b}	6.28^{a}	6.51^{a}
B10D250	5.92^{abc}	6.78^{abc}	5.70^{ab}	5.75^{ab}	7.26^{a}	6.33^{bc}	5.82^{abc}	5.76^{abc}
B10D500	6.38^{ab}	7.04^{ab}	5.82^{ab}	6.02^{a}	7.11^{ab}	6.85^{ab}	6.08^{ab}	6.00^{ab}
MSD	*0.95*	*1.12*	*0.57*	*0.64*	*0.69*	*0.78*	*1.03*	*0.87*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.4.2 Soil phosphomonoesterases

Both enzymes were significantly affected by soil amendment ($P \leq 0.001$). There were significant differences of both enzymes in the applied treatment factors. Sole application of biochar was not significantly different from unamended soils for the acid enzymes. Combination of biochar and DAP induced significant increases in soil alkaline enzymes, but these were not significantly different. Generally, the controls (soils with no amendment) recorded the lowest alkaline enzymes that were not significantly different from alkaline enzymes under sole application of DAP (Table 11), (Table 12). In Egerton during the short rains, soil amendment 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP under both varieties, gave the highest alkaline enzymes. However, in the long rains, soils under 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP planted with *Shangi* gave the highest alkaline enzymes while for *Destiny* the highest was under 10 t ha^{-1} Biochar with 250 kg ha^{-1} DAP but still these two were not significantly different from 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP (Table 11). In Mau Narok, 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP amended soils gave the highest alkaline enzymes for both varieties during both rains. Acid soil phosphomonoesterases, in Mau Narok, the highest acid enzymes were under the recommended rate of DAP followed by integration of biochar and DAP (Table 12).

Table 11: Effect of biochar and DAP on soil acid and alkaline phosphomonoesterases at Egerton, Kenya.

Egerton								
	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme
B0D0	165.49[cd]	61.69[d]	127.49[b]	76.67[d]	56.81[cd]	23.85[c]	90.46[a]	29.50[b]
B0D250	241.18[a]	36.29[e]	114.84[b]	87.33[d]	76.81[bc]	28.92[bc]	98.94[a]	33.68[ab]
B0D500	261.77[a]	102.09[c]	185.97[a]	109.79[c]	101.02[a]	36.44[abc]	115.48[a]	32.89[ab]
B5D0	135.25[d]	122.91[abc]	118.96[b]	119.00[bc]	53.14[d]	32.44[abc]	84.81[a]	29.33[b]
B5D250	230.41[ab]	137.48[a]	163.03[a]	150.26[a]	91.47[ab]	37.88[ab]	101.88[a]	35.98[ab]
B5D500	188.46[bc]	139.13[a]	163.91[a]	144.55[a]	95.05[ab]	37.94[ab]	112.78[a]	38.24[ab]
B10D0	155.53[cd]	106.24[bc]	104.48[b]	110.04[c]	59.22[cd]	35.93[abc]	83.39[a]	27.44[b]
B10D250	182.07[c]	124.39[abc]	161.49[a]	131.86[ab]	84.97[ab]	43.83[a]	100.49[a]	36.99[ab]
B10D500	166.80[cd]	133.87[ab]	162.68[a]	144.41[a]	90.96[ab]	43.43[a]	100.91[a]	43.45[a]
MSD	*44.76*	*27.79*	*33.81*	*21.67*	*23.19*	*13.23*	*NS*	*11.16*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), acid and alkaline enzymes (mM pNP × kg^{-1} × h^{-1}), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Table 12 : Effect of biochar and DAP on acid and alkaline phosphomonoesterases at Mau Narok, Kenya.

Mau Narok

	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme
B0D0	109.46^{cd}	23.41^{d}	87.15^{def}	25.92^{d}	92.67^{abc}	18.73^{b}	85.31^{ab}	28.07^{c}
B0D250	135.06^{bc}	88.71^{c}	136.52^{bc}	36.73^{d}	101.66^{abc}	18.42^{b}	97.30^{ab}	29.47^{c}
B0D500	174.54^{a}	94.36^{c}	179.49^{a}	106.94^{b}	108.22^{ab}	30.83^{ab}	111.19^{a}	30.39^{c}
B5D0	101.91^{de}	123.40^{ab}	76.43^{ef}	116.16^{b}	74.10^{c}	32.52^{a}	94.03^{ab}	31.37^{c}
B5D250	111.98^{cd}	140.01^{a}	107.72^{cde}	123.43^{b}	107.85^{ab}	37.94^{a}	106.30^{ab}	38.93^{abc}
B5D500	154.44^{ab}	135.40^{a}	134.12^{bc}	120.79^{b}	112.52^{a}	37.76^{a}	113.43^{a}	42.61^{abc}
B10D0	69.61^{e}	90.72^{c}	72.22^{f}	75.43^{c}	80.67^{bc}	33.51^{a}	75.81^{b}	36.38^{bc}
B10D250	154.69^{ab}	106.61^{bc}	114.45^{cd}	103.27^{b}	90.77^{abc}	40.76^{a}	86.77^{ab}	49.84^{ab}
B10D500	146.18^{ab}	143.62^{a}	156.27^{ab}	150.36^{a}	88.76^{abc}	44.13^{a}	93.20^{ab}	51.99^{a}
MSD	*33.09*	*26.29*	*34.28*	*25.96*	*27.98*	*13.55*	*30.81*	*15.53*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), acid and alkaline enzymes (mM pNP × kg-1 × h-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.4.3 Inorganic nitrogen

Soil ammonium and nitrate were both significantly influenced by incorporated soil amendments $P \leq 0.001$. The highest increases in soil nitrate and ammonium for the two sites in the two seasons were observed in plots where biochar interacted with di-ammonium phosphate (Table 13), (Table 14). Applied soil amendments of 10 t ha^{-1} Biochar with 250 kg ha^{-1} DAP, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest soil nitrate in Egerton for season one and season two respectively all planted with *Destiny*. The lowest soil nitrate concentration was observed where no soil amendments were applied (Table 13). Conversely, in Mau Narok, 5 t ha^{-1} Biochar, 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP gave the highest soil nitrate in season one and season two respectively all under *Shangi* (Table 14). Like Egerton, control gave the lowest soil nitrate (Table 13), (Table 14).

4.4.4 Extractable phosphorus

Soil phosphorus significantly varied in the applied soil amendments ($P \leq 0.001$). Significant increases in soil P were observed from application of recommended rate of DAP, combination of biochar and inorganic fertiliser of DAP. Low soil P levels were found in soils under sole biochar and unamended soils. Soil P levels were different during the growing seasons ($P \leq 0.001$) (Table 13), (Table 14). The highest soil phosphorus of 136 Mg kg^{-1} was observed under 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP grown with *Shangi* variety in the short rain season at Mau Narok. The lowest 2.0 Mg kg^{-1} was found in soils amended with 5 t ha^{-1} Biochar during the long rains planted with *Destiny* during the long rains in Mau Narok. However, the low soil phosphorus under 5 t ha^{-1} Biochar was not significantly different from soil phosphorus levels of other soil amendments (Table 14). In Egerton during the short rains the highest soil phosphorus was under soils amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP planted with *Shangi* and was not significantly different from soils under recommended rate of DAP all planted with *Destiny*. Soil amendment 10 t ha^{-1} Biochar had the least soil phosphorus, which was not significantly different from 5 t ha^{-1} Biochar, and the control all planted with *Destiny*. However, in the long rains the highest soil phosphorus was found in 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP planted with *Shangi* and did not differ significantly from the soil phosphorus in all the other soil amendments (Table 13). In Mau Narok, during the short rains, 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP soils had the most soil phosphorus and was planted with *Shangi*. Unamended soils planted with *Destiny* had the least soil phosphorus. In the long rains season, soils amended with 10 t ha^{-1} Biochar had the highest soil phosphorus but was not significantly different from all the other soils under the different soil amendments.

Table 13: Effect of biochar and DAP on soil nitrate, ammonium and phosphorus Egerton, Kenya.

Egerton												
	Short rain season						Long rain season					
Variety	*Destiny*			*Shangi*			*Destiny*			*Shangi*		
Treatment	Nitrate-N	NH4+	P	Nitrate-N	NH4+	P	Nitrate-N	NH4+	P	Nitrate-N	NH4+	P
B0D0	57.34^{d}	11.97^{e}	16.63^{e}	84.74^{d}	23.11^{c}	33.90^{ab}	35.78^{ef}	42.49^{d}	4.40^{a}	26.92^{f}	13.81^{d}	3.53^{a}
B0D250	112.79^{bc}	29.49^{cd}	28.70^{bc}	174.58^{b}	30.46^{bc}	24.37^{bc}	81.43^{d}	56.96^{c}	3.87^{a}	58.90^{de}	28.12^{bc}	6.20^{a}
B0D500	136.46^{ab}	41.75^{bc}	38.32^{ab}	187.88^{ab}	38.53^{ab}	30.17^{ab}	129.12^{c}	78.11^{b}	4.16^{a}	103.55^{bc}	38.52^{ab}	7.60^{a}
B5D0	72.15^{cd}	15.54^{e}	17.60^{de}	93.98^{d}	22.83^{c}	39.83^{a}	25.55^{f}	25.37^{ef}	4.20^{a}	20.22^{f}	20.74^{cd}	4.50^{a}
B5D250	136.17^{ab}	47.63^{ab}	26.89^{cd}	202.11^{ab}	36.46^{ab}	40.07^{a}	159.57^{b}	84.98^{ab}	4.87^{a}	120.84^{b}	38.53^{ab}	4.52^{a}
B5D500	160.39^{a}	57.19^{a}	40.20^{a}	216.14^{a}	48.11^{a}	36.60^{a}	194.67^{a}	92.14^{a}	6.78^{a}	154.57^{a}	50.18^{a}	5.30^{a}
B10D0	58.84^{d}	13.01^{e}	16.23^{e}	109.37^{d}	20.73^{c}	32.07^{ab}	18.49^{f}	18.07^{f}	3.88^{a}	36.33^{ef}	14.33^{d}	5.73^{a}
B10D250	122.10^{ab}	20.32^{de}	28.30^{bc}	142.70^{c}	24.58^{c}	24.07^{bc}	71.43^{d}	35.28^{de}	3.48^{a}	76.53^{cd}	21.49^{cd}	5.60^{a}
B10D500	117.07^{ab}	30.77^{cd}	29.90^{bc}	174.43^{b}	30.45^{bc}	18.80^{c}	55.76^{de}	57.37^{c}	4.53^{a}	86.94^{cd}	28.27^{bc}	8.12^{a}
MSD	*43.49*	*13.19*	*10.12*	*30.05*	*11.78*	*11.15*	*28.43*	*13.95*	*NS*	*30.82*	*12.05*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Nitrate-N: Nitrate Nitrogen (MgNO3/L), NH4+: Ammonium nitrogen (Mg NH4+/L), P: Phosphorus (mg kg^{-1}), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Table 14: Effect of biochar and DAP on soil nitrate, ammonium and phosphorus at Mau Narok, Kenya.

Mau Narok

	Short rain season						Long rain season					
Variety	*Destiny*			*Shangi*			*Destiny*			*Shangi*		
Treatment	Nitrate-N	$NH4^{+}$	P	Nitrate-N	$NH4^{+}$	P	Nitrate-N	$NH4^{+}$	P	Nitrate-N	$NH4^{+}$	P
B0D0	84.32^{d}	18.38^{ef}	29.73^{d}	131.76^{c}	13.19^{e}	11.02^{d}	39.63^{b}	76.64^{d}	4.92^{a}	34.76^{f}	63.67^{d}	4.23^{a}
B0D250	117.86^{cd}	36.25^{bcd}	45.47^{c}	190.89^{b}	34.58^{cd}	19.48^{d}	137.00^{a}	113.04^{c}	3.05^{a}	61.43^{ef}	146.74^{c}	4.12^{a}
B0D500	140.05^{bc}	45.27^{b}	98.17^{a}	242.36^{a}	48.76^{bc}	37.27^{c}	146.92^{a}	153.07^{b}	5.53^{a}	118.88^{cd}	191.65^{b}	3.37^{a}
B5D0	103.38^{cd}	15.03^{f}	23.70^{de}	116.45^{c}	15.67^{e}	16.10^{d}	36.24^{b}	40.73^{e}	2.00^{a}	82.41^{de}	68.09^{d}	3.30^{a}
B5D250	179.37^{ab}	43.70^{bc}	33.73^{cd}	134.12^{c}	61.33^{b}	136.00^{a}	151.63^{a}	177.18^{a}	3.62^{a}	162.61^{ab}	276.43^{a}	3.77^{a}
B5D500	206.98^{a}	74.50^{a}	15.48^{e}	185.52^{b}	88.09^{a}	87.83^{b}	165.74^{a}	185.21^{a}	2.10^{a}	173.12^{a}	265.21^{a}	3.20^{a}
B10D0	117.62^{cd}	33.40^{d}	90.37^{a}	68.17^{d}	25.33^{de}	17.10^{d}	40.67^{b}	37.28^{e}	6.23^{a}	65.84^{ef}	59.62^{d}	4.37^{a}
B10D250	178.59^{ab}	27.17^{de}	100.47^{a}	134.67^{c}	33.31^{cd}	37.47^{c}	123.59^{a}	38.00^{e}	2.80^{a}	106.69^{cd}	82.14^{d}	4.53^{a}
B10D500	173.32^{ab}	33.97^{cd}	74.47^{b}	128.85^{c}	38.01^{cd}	42.90^{c}	73.59^{b}	65.16^{d}	3.12^{a}	123.65^{bc}	88.95^{d}	5.28^{a}
MSD	*40.79*	*9.97*	*10.12*	*37.89*	*16.65*	*11.15*	*47.78*	*21.44*	*NS*	*39.42*	*33.04*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Nitrate-N: Nitrate Nitrogen (MgNO3/L), NH4+: Ammonium nitrogen (Mg NH4+/L), P: Phosphorus (mg kg-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.5 Effect of different rates of biochar and inorganic fertiliser on nutrient use efficiency

4.5.1 Agronomic efficiency

Nitrogen use efficiency (NUE)

The applied soil amendments significantly affected nitrogen use efficiency (NUE) where 5 t ha^{-1} Biochar gave the highest NUE, and the control had the lowest NUE (Table 15), (Table 16). At Egerton, fertiliser application at 5 t ha^{-1} Biochar gave the highest NUE of 306.76 kg ha^{-1} for *Shangi*. The same fertiliser gave the highest NUE at Mau Narok for *Destiny* variety. At Egerton, in the short rain season, the highest NUE of 306.76 kg ha^{-1} was from soils treated with 5 t ha^{-1} Biochar planted with *Shangi*. However, in the long rain season, NUE was not significantly different for all plots and varieties. The biggest NUE of 134.99 kg ha^{-1} was from soils treated with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and planted with *Destiny* (Table 15). At Mau Narok in the short rain season, NUE was not significantly affected by fertilisers for plots planted with *Shangi*. The highest NUE of 560.38 kg ha^{-1} was from plots amended with 5 t ha^{-1} Biochar and planted with *Destiny*. Nevertheless, in the long rain season, NUE was not significantly different across the applied fertilisers for all varieties but the highest NUE of 144.19 kg ha^{-1} was in plots fertilised with 250 kg ha^{-1} DAP planted with *Shangi* (Table 16).

Phosphorus use efficiency (PUE)

Fertiliser application significantly affected PUE ($P<0.001$) where plots fertilised with 5 t ha^{-1} Biochar, 10 t ha^{-1} Biochar gave the highest PUE with the control giving the lowest PUE. For both seasons, the highest PUE was under plots amended with 5 t ha^{-1} Biochar (Table 15), (Table 16). At Egerton, high PUE of 1779.58 kgP ha-^{1} was from *Shangi* variety grown on soils fertilised with 5 t ha^{-1} Biochar. At Mau Narok, the highest PUE was still from plots treated with 5 t ha^{-1} Biochar for both varieties. At Egerton during the short rain season, PUE for *Destiny* was not significantly different across the fertilisers but was significant for *Shangi* with the highest PUE got in soils treated with 5 t ha^{-1} Biochar. Still the same fertiliser 5 t ha^{-1} Biochar, gave the highest PUE in the long rain season in plots planted with *Destiny* (Table 15). In Mau Narok, during the short rain season, the highest PUE was from plots amended with 5 t ha^{-1} Biochar and planted with *Destiny*, however, for *Shangi*, PUE was not significantly different across the applied soil fertilisers. Conversely during the long rain season at the same site, PUE was not significantly different for the two varieties across all the applied fertilisers, however plots fertilised with 5 t ha^{-1} Biochar and grown with *Destiny* gave the highest PUE (Table 16).

Table 15: Effect of biochar and DAP on nitrogen and phosphorus use efficiencies at Egerton, Kenya.

Egerton

	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	NUE	PUE	NUE	PUE	NUE	PUE	NUE	PUE
B0D0	0.00^{c}	0.00^{a}	0.00^{e}	0.00^{c}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}
B0D250	146.73^{ab}	102.42^{a}	66.98^{d}	99.64^{c}	106.98^{a}	96.63^{a}	53.24^{a}	48.09^{a}
B0D500	101.55^{ab}	91.72^{a}	156.92^{c}	141.74^{c}	130.53^{a}	117.89^{a}	66.66^{a}	60.21^{a}
B5D0	104.28^{ab}	84.17^{a}	306.76^{a}	1779.58^{a}	88.00^{a}	385.00^{a}	19.24^{a}	84.17^{a}
B5D250	64.34^{bc}	70.11^{a}	187.48^{bc}	210.87^{bc}	104.12^{a}	117.10^{a}	46.69^{a}	52.52^{a}
B5D500	116.49^{ab}	118.54^{a}	190.70^{bc}	194.06^{bc}	134.99^{a}	137.37^{a}	82.31^{a}	83.76^{a}
B10D0	49.91^{bc}	218.33^{a}	222.00^{b}	971.25^{b}	67.05^{a}	293.33^{a}	21.24^{a}	92.92^{a}
B10D250	7.69^{c}	10.14^{a}	139.95^{c}	184.68^{bc}	72.25^{a}	95.34^{a}	38.39^{a}	50.67^{a}
B10D500	99.28^{ab}	96.66^{a}	155.91^{c}	175.36^{c}	108.77^{a}	122.34^{a}	62.69^{a}	70.51^{a}
MSD	*82.34*	*NS*	*59.19*	*791.46*	*NS*	*NS*	*NS*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), NUE=nitrogen use efficiency (kgN Ha-1), PUE=phosphorus use efficiency (kgP Ha-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Table 16: Effect of biochar and DAP on nitrogen and phosphorus use efficiencies at Mau Narok, Kenya.

Mau Narok

	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	NUE	PUE	NUE	PUE	NUE	PUE	NUE	PUE
B0D0	0.00[b]	0.00[b]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]
B0D250	54.31[b]	49.06[b]	49.28[a]	60.47[a]	104.47[a]	94.36[a]	144.19[a]	130.24[a]
B0D500	117.23[b]	105.89[b]	155.57[a]	140.52[a]	80.86[a]	73.04[a]	73.13[a]	66.06[a]
B5D0	560.38[a]	2451.67[a]	119.62[a]	1106.67[a]	65.33[a]	285.83[a]	21.53[a]	94.17[a]
B5D250	162.67[b]	182.96[b]	61.02[a]	68.62[a]	99.53[a]	111.94[a]	83.89[a]	94.35[a]
B5D500	157.25[b]	160.02[b]	20.12[a]	20.48[a]	86.95[a]	88.48[a]	91.29[a]	92.90[a]
B10D0	0.28[b]	1.25[b]	6.76[a]	29.58[a]	44.29[a]	193.75[a]	49.14[a]	215.00[a]
B10D250	78.69[b]	103.83[b]	163.78[a]	172.14[a]	83.30[a]	109.93[a]	73.15[a]	96.54[a]
B10D500	126.39[b]	142.16[b]	0.52[a]	0.58[a]	71.67[a]	80.61[a]	61.77[a]	69.47[a]
MSD	*335.09*	*1556.8*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), NUE=nitrogen use efficiency (kgN Ha-1), PUE=phosphorus use efficiency (kgP Ha-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

4.5.2 Nutrient uptake

Nitrogen uptake

Nitrogen uptake was significantly influenced by addition of soil fertilisers ($P<0.001$). DAP of 500kg ha^{-1}, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP combination of, 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP gave the highest N uptake (Table 17), (Table 18). In Egerton, soils treated with the recommended rate of DAP of 500kg ha^{-1} gave the highest N uptake for both varieties in the short rain season. The same trend was observed for *Shangi* in the long rain season, but for *Destiny*, 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP produced the highest N uptake in the long rain season (Table 17). In Mau Narok in the short rain season, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave the highest N uptake for *Destiny* and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP for *Shangi*. On the other hand, in the long rain season, 10 t ha^{-1} Biochar gave high N uptake for *Destiny* whereas soils amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP for *Shangi* (Table 18).

P uptake

P uptake was significantly affected by the applied soil amendments with highest P uptake recorded under soil amendments of 500 kg ha^{-1} DAP, 10 t ha^{-1} Biochar, 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 5 t ha^{-1} Biochar ($P<0.001$) (Table 17), (Table 18). In Egerton, during the short rain season for both varieties, the greatest P uptake was under soils treated with 500 kg ha^{-1} DAP. In the long rain season, the soil amendments did not show any significant differences in P uptake for *Destiny*. However, there were significant differences in P uptake for *Shangi* were the highest uptake was under plots amended with 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 250 kg ha^{-1} DAP (Table 17). For Mau Narok in the short rain season there was no significant difference in P uptake for both varieties. However, plots amended with 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, 5 t ha^{-1} Biochar had the highest P uptake for *Destiny* and *Shangi* respectively. A similar trend was observed in the long rain season for both varieties with soil treatments of 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP, 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP giving the highest P uptake for *Destiny* and *Shangi* respectively (Table 18).

Table 17: Effect of biochar and DAP on nitrogen and phosphorus uptake at Egerton, Kenya.

Egerton								
	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	NU	PU	NU	PU	NU	PU	NU	PU
B0D0	22.86^{bc}	7.16^{d}	36.55^{a}	10.71^{ab}	84.48^{e}	26.25^{a}	106.59^{b}	24.98^{bcd}
B0D250	31.96^{b}	15.03^{ab}	17.01^{d}	8.29^{ab}	108.43^{d}	22.03^{a}	50.70^{de}	22.73^{cd}
B0D500	55.08^{a}	16.59^{a}	37.39^{a}	10.82^{a}	175.47^{b}	24.31^{a}	127.55^{a}	22.30^{cd}
B5D0	15.18^{c}	7.91^{cd}	23.23^{cd}	6.86^{b}	57.45^{g}	22.80^{a}	77.76^{c}	29.77^{abc}
B5D250	27.28^{b}	11.67^{bcd}	21.83^{cd}	9.64^{ab}	189.25^{a}	25.62^{a}	64.02^{cd}	21.39^{d}
B5D500	28.75^{b}	8.35^{cd}	35.55^{a}	10.75^{ab}	131.94^{c}	24.07^{a}	125.66^{a}	26.12^{abcd}
B10D0	25.91^{bc}	9.93^{cd}	26.60^{bc}	9.84^{ab}	78.75^{ef}	26.32^{a}	36.54^{e}	13.58^{e}
B10D250	29.11^{b}	15.07^{ab}	22.41^{cd}	7.51^{ab}	66.69^{fg}	23.51^{a}	46.33^{e}	30.79^{ab}
B10D500	27.86^{b}	12.33^{abc}	31.69^{ab}	9.74^{ab}	109.69^{d}	21.41^{a}	101.79^{b}	33.65^{a}
MSD	*11.13*	*4.8*	*8.12*	*3.9*	*12.39*	*NS*	*15.56*	*7.65*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), NU=Nitrogen uptake (kgN Ha-1), PU = phosphorus uptake (kgP Ha-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP

Table 18: Effect of biochar and DAP on nitrogen and phosphorus uptake at Mau Narok, Kenya.

Mau Narok								
	Short rain season				Long rain season			
Variety	*Destiny*		*Shangi*		*Destiny*		*Shangi*	
Treatment	NU	PU	NU	PU	NU	PU	NU	PU
B0D0	49.33^{c}	11.76^{a}	18.99^{d}	8.31^{a}	87.04^{d}	14.96^{a}	85.70^{cd}	10.99^{a}
B0D250	61.94^{b}	13.44^{a}	27.49^{cd}	6.74^{a}	115.63^{c}	15.17^{a}	65.03^{e}	11.51^{a}
B0D500	49.12^{c}	13.99^{a}	28.21^{cd}	8.24^{a}	116.74^{c}	16.27^{a}	70.23^{de}	11.73^{a}
B5D0	73.39^{a}	14.39^{a}	49.18^{b}	9.82^{a}	126.97^{b}	18.73^{a}	125.37^{b}	14.29^{a}
B5D250	55.96^{bc}	16.36^{a}	33.20^{c}	9.38^{a}	85.14^{d}	19.22^{a}	80.89^{cde}	14.41^{a}
B5D500	78.78^{a}	17.15^{a}	47.06^{b}	8.42^{a}	86.87^{d}	17.29^{a}	158.69^{a}	14.38^{a}
B10D0	72.26^{a}	14.11^{a}	30.56^{c}	6.75^{a}	145.22^{a}	14.64^{a}	61.57^{e}	12.43^{a}
B10D250	55.95^{bc}	13.22^{a}	27.41^{cd}	7.31^{a}	88.78^{d}	15.75^{a}	90.96^{c}	13.45^{a}
B10D500	49.55^{c}	16.46^{a}	67.46^{a}	6.03^{a}	113.42^{c}	15.01^{a}	138.75^{b}	16.54^{a}
MSD	*9.97*	*NS*	*9.59*	*NS*	*9.37*	*NS*	*19.73*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), NU=Nitrogen uptake (kgN Ha-1), PU = phosphorus uptake (kgP Ha-1), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP

CHAPTER FIVE

DISCUSSION

5.1 Effect of different rates of biochar and inorganic fertiliser on potato growth

Plant growth was greatly influenced by single application of recommended rate of DAP, or its co-application with biochar at 5 or 10 t ha^{-1}. 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP influenced growth more than 500 kg ha^{-1} DAP. This is attributed to the synergistic effect of combining biochar and inorganic fertiliser. Similar findings were also reported by Walter & Rao (2015) who got positive results on sweet potato growth after combination of biochar and inorganic fertilisers and attributed these results to biochar's ability to enhance soil physical properties of porosity and reduced soil bulk density (Walter & Rao, 2015). Similar positive findings were reported by Dong *et al*. (2015) on rice when biochar was amended with urea which increased rice growth. Also, Sarfraz *et al*. (2017) observed an increase in plant height in maize when biochar was mixed with nitrogen fertilisers. A study done by Arif *et al*. (2017) found a positive increase in growth of maize when biochar was mixed with inorganic fertiliser and this was explained by the collaboration of the two where biochar improved soil properties as the inorganic fertiliser readily supplied nutrients for growth. Numerous studies show that integration of biochar and inorganic fertilisers increases crop growth, and this is because of the synergistic effect. Combination of biochar and inorganic fertiliser increase plant growth because biochar has the ability to improve soil conditions by increasing the soils' water holding capacity, reducing soil bulk density and nutrient leaching (McElligott, 2011). Biochar is also known to improve soil chemical and physical conditions such as soil nutrients, improving soil aeration, water permeability, these all favour crop growth (Huang *et al*., 2019; Pandian *et al*., 2016; Schulz *et al.*, 2013). Both 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP increased potato growth, however, 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP increased more growth than 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP B10D500 and this could be due to immobilisation of nutrients caused by increase of biochar from 5 t ha^{-1} to 10 t ha^{-1} (Bruun *et al*., 2011).

The inorganic fertiliser DAP supplied the required nutrients for potato growth as reflected in both the number of stems and plant height which made it superior to sole biochar that releases nutrients slowly. Inorganic fertilisers are rich in nutrients required by plants which are released readily. However, application of half rate 250 kg ha^{-1} DAP did not increase potato growth as 500 kg ha^{-1}

DAP due to inadequate supply of the nutrients. Sole biochar application did not significantly increase potato growth and similar results were reported by Major *et al*. (2010b) where use of biochar as a soil amendment had no positive influence on maize growth who attributed these results to low nutrient content of the biochar and nutrient immobilisation (Bruun *et al*., 2011). Low response of plant height from sole biochar application was also reported by Hamzah & Shuhaimi, (2018) as biochar rated increased. The low response of potato height to biochar application could be that biochar positive effects are usually realised in extremely nutrient poor soils which was not the case with the study sites. In moderately fertile soils, minor, negative or no effects have been reported on plant growth after biochar additions (Uzoma *et al*., 2011). An increase of sole biochar from 5 t ha^{-1} to 10 t ha^{-1} led to an increase in crop growth due to an increment of effects of biochar on growth (Walter & Rao, 2015). The differences in crop growth in seasons and locations could be due to genetic differences of the grown varieties; *Shangi* and *Destiny* have different growth patterns (NPCK, 2019), differences in rainfall patterns of the two sites and the two seasons and soil conditions of the sites, soil, and biochar interaction.

5.2 Effect of different rates of biochar and inorganic fertiliser on potato yield

Farmers in Kenya mostly use chemical fertilisers to obtain high potato yields. The commonly used fertiliser is DAP that is followed by top dressing with mostly CAN or urea. These fertilisers are rich in nutrients mainly nitrogen and phosphorus that are the most limiting for potato growth. In this study use of DAP specifically 500 kg ha^{-1} DAP the recommended rate resulted into high yields since this fertiliser readily releases nutrients for the crop growth. The application of 250 kg ha^{-1} DAP gave lower yields than 500 kg ha^{-1} DAP due to low nutrients supplied by the half rate of the fertiliser. However, amendment 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP produced more yields than sole use of 500 kg ha^{-1} DAP. To maintain soil productivity and achieve higher crop yields, new amendments such as biochar are being promoted. Combination of biochar and DAP gave higher potato yields and this result is supported by Walter & Rao (2015) who realized a positive effect of combination of biochar and NPK on sweet potato yield. Application of 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP gave more yields than 5 t ha^{-1} Biochar with 250 kg ha^{-1} DAP. This is attributed to the higher nutrient content found in the recommended rate.

Several studies have shown an increase in crop yield when biochar is combined with chemical fertiliser due to reduced leaching of the soil nutrients, additive effect of the two fertilisers (Badu *et al.,* 2019). Also Kätterer *et al*. (2019) observed an increase in maize and soya beans after biochar additions in Kenya and Adekiya *et al*. (2020) reported an increase in cocoyam yields after biochar additions. The authors attributed this increase to improved soil physical, chemical and biological conditions after biochar additions. The yields were different for the two varieties, sites, and seasons. *Shangi* yielded more than *Destiny* in all sites and in both seasons. Potato yield varied significantly through the seasons where during, the short rain season, Mau Narok yielded more than Egerton. However, in the second season, Egerton produced more yields than Mau Narok.

The potato yields for the varieties are determined by a variety's yield potential (White *et al*., 2018). Furthermore, the performance of potatoes is influenced by site due to different soil types and climatic conditions. Biochar performance is also influenced by soil type of a given site (McElligott, 2011).

Yield also varied across seasons due to residual effects of the treatments and changes in climatic conditions. Biochar effects are able to be realised in subsequent seasons which explains the increased yields in the second season (Ruža *et al*., 2013). Biochar is also able to resist decomposition which enables it to persist in the soil and be of benefit for the next cropping season (Major, 2010a). It should be noted that biochar potential reduces with time calling for its replenishment after some time like after two or three cropping seasons (Cornelissen *et al*., 2018; Huang *et al*., 2019; Steiner *et al*., 2007). This was reported by Huang *et al*. (2019) were grain yield increased for the two seasons while there was a decline in soil properties in the second season. Similar results were obtained in this study were soil nutrients declined in the second season across the two sites while potato yields increased in the second season. These results are also explained by biochar's ability to improve soil physical conditions like reducing bulk density, improving soil structure and water retention. Sole biochar application gave relatively low yields because of the low mineralisation rate to supply adequate nutrients to the potato crop. This is supported by similar results from Kizito *et al*. (2019) who also experienced low maize grains from soil biochar applications. There was a decline in yield in the second season in Mau Narok. This can be attributed to the low rainfall received and the decline in soil properties as observed in the results. This is explained by the fact that there is a possibility of either an increase, decrease or neutral effect after biochar incorporation in the soils (Sorrenti, 2015).

The yielding of potatoes is usually affected by climatic factors such as insufficient rain. This gives an explanation of the decreased yield in Mau Narok in the long rain season as a result of a dry period that occurred during the season (Ruža *et al*., 2013). Plots fertilised with DAP produced high tuber weights than the unfertilised plots due to the readily availability of nutrients needed for plant growth and development. Phosphorus is essential for physiological growth of the potato crop as it significantly contributes to tuber initiation, tuber size, canopy growth and formation of starch in potatoes, resistance to diseases. Therefore, phosphorus greatly determines potato yield (Gaur *et al*., 2017).

5.3 Effect of different rates of biochar and inorganic fertiliser on selected soil properties

5.3.1 Soil pH

The pH of the two sites was acidic typical of most potato growing areas in Kenya. One of the causes of acidity in these areas is the constant use of chemical fertilisers mostly DAP which acidifies the soils in the long run (Muthoni & Nyamongo, 2009). This calls for environmentally friendly amendments such as biochar that can aid raise the soil pH to the most favourable pH for potato growth.

In this study, there was an increase in soil pH after application of biochar amendments mainly at the end of the first season either singly or in combination with inorganic fertiliser. Increments of biochar from 5 t ha^{-1} to 10 t ha^{-1} either in sole or in combination with fertiliser resulted into either an increase or a decrease in soil pH. The increase in soil pH could be due to the pH of the applied biochar which is alkaline in nature thus, there was a liming effect of biochar on the soils. These results are in line with those of Mensah and Frimpong (2018). Many studies have found the same results of increase in pH after applying biochar to acidic soils (Nigussie *et al*., 2012; Rees *et al*., 2014; Zahid *et al*., 2018). Biochar is also known to produce carbonates that are liming in nature that aid in raising the pH by reacting with soils hydrogen ions (Madiba *et al*., 2016). However, in the second season there was a decline in soil pH after application of biochar. Some fewer studies have also observed a decline in soil pH after biochar use (Ezike, 2016; Prommer *et al.*, 2014; Sarfraz *et al*., 2017; Zhang *et al*., 2019a). They suggested that this could be due to oxidation of COO- form of acidic carboxyl groups (Cheng *et al*., 2006). This decrease in soil pH was also attributed to the buffering capacity of the soil. Soil buffering capacity is the ability of the soil to resist changes in its pH. Different soil types have different buffering capacities which determine their response to changes in their soil pH. Acidic soils with a high buffering capacity have the ability to resist an increase in soil soil pH. (Meng *et al.,* 2019; Wang *et al.,* 2015).

Also Yang *et al*. (2015) found out that biochar caused a sharp decline in soil pH which could have been due to the short period in which biochar effect could not be manifested. This calls for long term biochar studies to adequately quantify the sustainability of the amendment. On the other hand, sole application of DAP lowered soil pH due to its acidifying character. This is because this fertiliser promotes nitrification which lead to a lower soil pH (Ezike, 2016; Kaboneka *et al.,* 2019). However, integration of biochar and DAP showed an increase in soil pH. This is consistent with results from Chan *et al*. (2007) who found an increase in soil pH when biochar was combined with nitrogenous fertiliser.

5.3.2 Inorganic soil nitrogen

Soil inorganic nitrogen (SIN) is of great importance to plants since plants take up inorganic nitrogen in forms of ammonium and nitrate (Carlisle *et al.,* 2012; Nair *et al.,* 2021). Generally, sole application of DAP or its combination with biochar increased ammonium and nitrate concentration in the soil throughout the two seasons. This confirms with the several studies that have found the significance of biochar in enhancing soil inorganic nitrogen. This is as a result of biochar improving nutrient availability (Huang *et al*., 2020; Zhang *et al.,* 2021). The combination of biochar and DAP increased both ammonium and nitrate and this is because of synergistic effect of the two fertilisers. This was also reported by Kizito *et al*. (2019) who found an increase in soil inorganic nitrogen after combination of biochar and NPK fertiliser. It is suggested that biochar could have enabled this by decreasing the leaching of nitrogen ions, encouraged nitrification by promoting microbial activity of the nitrifiers and reducing the rate of volatilisation. However, the combination of biochar with DAP at 10 tonnes led to lower results than 5 tonnes and this could be due to the increased soil C/N ratio that led to immobilisation of nitrogen. This was also reported by Huang *et al*. (2019) who observed a decline in mineral nitrogen when biochar application increased from 10 to 30 t ha^{-1}. These results show that biochar has the ability to adsorb ammonium nitrogen (Adekiya *et al*., 2020). The performance of biochar in soils depends on various factors such as environmental factor, fertilisation, soil and biochar properties, biochar application rates and climatic conditions (Moreno-Riascos *et al.,* 2020; Xu *et al.,* 2017).

Addition of biochar to soils has shown a positive, negative or neutral effect on soil inorganic nitrogen (Nguyen *et al*., 2017). This is evidenced in this study in which there were positive results in the first season which declined in the second season, and this was due to the dry season that was experienced in the second season and the soil inorganic nitrogen concentration varied across the sites since the sites have different soil properties and variation in soil inorganic nitrogen was attributed to climatic conditions. However, in the second season still the use of biochar singly or in combination with DAP gave the highest results.

Single application of biochar at 5 t ha^{-1} Biochar and 10 t ha^{-1} Biochar gave low soil inorganic nitrogen results and this could be attributed to the low nitrogen content of 0.35% in the biochar used in this study (Mensah & Frimpong, 2018). Furthermore, the biochar could have retained the ammonium and nitrates reducing their concentration in the soil solution This could also be attributed to immobilisation of N (Nguyen *et al*., 2017). Addition of inorganic fertiliser gave high soil inorganic nitrogen. This is because inorganic fertilisers readily release nutrients to the soil and in addition enhance nitrification by the nitrifying bacteria through availing the substrate to the microbe (Nguyen *et al*., 2017). Additionally, there could have been minimisation of the soil inorganic nitrogen losses like immobilisation, denitrification (Ezike, 2016). This study showed varying trends across the two seasons which trends could have been tracked under long term studies to find the effectiveness of biochar as an amendment (McElligott, 2011).

5.3.3 Soil phosphorus

P availability in the soil depends on several factors such as soil pH, organic matter. P tends to be fixed in strongly acidic soils mainly below 6. This leads to nutrient deficiency in most crops (Bayu *et al*., 2017). However, potatoes have the capacity to tolerate acidic soils. Phosphorus availability for potatoes can be increased by raising pH to 6-7 (Muthoni & Nyamongo, 2009). Across the two seasons and sites, there was an increase in soil phosphorus from sole application of DAP and from combination of DAP with biochar. An explanation for this is the readily supply of phosphorus by the chemical fertiliser. The positive effect of biochar and DAP is a result of additive effect of the two. This is attributed to an increase in soil pH after biochar amendment which made phosphorus readily available (Nigussie *et al*., 2012). Additionally, the biochar promoted phosphorus mineralisation from organic P to inorganic P. These results are in line with those of (Farooque *et al*., 2020) in which biochar application significantly increased soil available phosphorus. Some studies attribute the positive effect of biochar on soil phosphorus to the phosphorus contained in the biochar itself (Bayu *et al*., 2017). However, for this study, the biochar phosphorus was very low and could not possibly lead to a greater increment in soil phosphorus. For the P differences in sites is because the performance of biochar in soils relies mainly on environmental conditions, soil properties and climatic conditions (Ibrahim *et al*., 2017). At 10 tonnes of biochar available soil phosphorus reduced and this was due to immobilisation in which the phosphates are strongly sorbed on the biochar surfaces (Bayu *et al*., 2017).

One of the main mechanisms in which biochar increases soil available P is the enhancement of arbuscular mycorrhiza which promotes p availability and uptake (Solaiman *et al*., 2019). Literature showed that the enzymatic activity of phosphatases declined during insufficient soil moisture thus a reduction in mineralisation of phosphorus resulting into low available phosphorus (Margalef *et al*., 2017). The low levels of phosphorus in the long rain season could be due to the drop in soil pH since increased acidity tends to fix soil P making it unavailable in the soil. Furthermore, positive effects of biochar are usually observed in strongly acidic and nutritionally poor soils, however the study sites were not deficient in P which could have led to the negative results after biochar incorporation. Also, the low P levels could be attributed to immobilisation and sorption of P onto the biochar surfaces.

5.3.4 Soil phosphomonoesterases

Soil P enzymes especially the soil phosphomonoesterases play a pivotal role in mineralisation of organic P to inorganic P that can be utilised by plants (Shirzadeh *et al.*, 2022). The soil phosphomonoesterases are pH dependent with acid phosphomonoesterases thriving in acidic soils ranging from 4 to 6.5 while the alkaline phosphomonoesterases are dominant in alkaline soils of pH 9 to 11 (Adetunji *et al*., 2017). The sites in this study were averagely acidic explaining the dominance of acid phosphomonoesterases to alkaline phosphomonoesterases. Biochar has the potential to refine soil microbial activity by promoting a conducive microhabitat (Solaiman *et al*., 2019). Enzyme activities in soils are influenced by several factors like soil properties, climate, fertilisation, farm practices like tillage. In addition, biochar stimulates enzymatic activities by modifying the rhizosphere (Solaiman *et al*., 2019). The enzymes could have been affected by spraying the potatoes with chemicals to control diseases. These chemicals inhibit soil enzymatic activity where the enzymes are denatured and inhibited by the chemical compound in the pesticides. Literature also shows a decrease in soil P enzymes following fumigation (Riah *et al*., 2014). Furthermore, these soil enzymes are reported to reduce as the growing season progresses (Rejsek *et al*., 2012). This explains their decline in the second season. Soils treated with DAP shown high soil enzyme levels which was also reported by Rejsek *et al*. (2012) who explained that the inorganic fertiliser was source of substrate to the enzymes. This was also observed by other studies that reported increased phosphatase activities after applying inorganic fertilisers specifically nitrogenous fertilisers where nitrogen also greatly influences the enzymes' activities (Margalef *et al*., 2017). Acid phosphomonoesterases were higher than the alkaline phosphomonoesterases after amendment with biochar. Similar results were obtained by Antonious *et al*. (2020) after amending soils with biochar where the acid phosphomonoesterases were raised by 115% whereas the alkaline phosphomonoesterases did not show significant differences. This confirms several studies that have reported that biochar can have positive, negative or neutral effect on soil enzymes depending on its characteristics (Antonious *et al*., 2020). The soil P enzymes rely mainly on soil moisture and soil nutrients. A dry season in the second season and the reduced soil nutrients could be the possible reason behind the reduced enzyme activity in that season. Previous studies show that phosphatase activity is driven by soil moisture and soil type in which the phosphatase activities decrease more during dry soil periods (Margalef *et al*., 2017). Some studies have reported low enzyme levels under biochar amended soils due to the biochar inhibiting the enzymes or substrate (Ezike, 2016). This is contradictory to this study's findings in which biochar increased soil enzyme levels.

Effect of different rates of biochar and inorganic fertiliser on nutrient use efficiency

Nutrient use efficiency is of great importance for potato production, it exhibits how the plants utilised the applied nutrients in form of both organic and inorganic fertilisers (Baligar *et al*., 2001). Nutrient use efficiency of crops relies on various factors not limited to the crop variety's yielding capacity, the soil's nutrient content, previous crop grown on the soils, rainfall received in the area (Agegnehu *et al*., 2016). The agronomic efficiency of crops is greatly determined by the site's climatic conditions mainly rainfall and drought (Ruža *et al*., 2013). The nutrient content in potatoes shows variation across potato genotype, soil fertility status and environmental conditions (Collins *et al*., 2013). This explains the variation in nutrient use efficiency across potato varieties, seasons and locations used in this study. It should be noted that nutrient content of different potato varieties differs even when grown under similar environments (Collins *et al*., 2013). At Egerton, nutrient uptake was higher in the long rain season than in the short rain season. These results are supported by those of Sistani *et al*. (2019) who obtained more N accumulation in plant tissues after application of hard wood biochar in the drier season than in the wet season. However, these were contrasting with results obtained in Mau Narok where nutrient uptake was higher in the wetter season. Results from this study showed nutrient uptake and use efficiency increased with sole application of fertiliser, biochar alone and biochar fertiliser interactions. Inorganic fertilisers readily release nutrients for crop uptake (Ju *et al.*, 2022). The applied DAP increased soil N and P levels that resulted into the nutrients' accumulation in the potato tissues (Naumann *et al*., 2019). Similar results were observed by Walter and Rao (2015) where chemical fertiliser increased N and P uptake in sweet potatoes. On the other hand, biochars or their co-application with synthetic fertilisers are known to increase crop nutrient use efficiency (Sarfraz *et al*., 2017). The interaction of biochar and fertiliser greatly increased nutrient uptake and efficiency, and this is attributed to additive effect of the two soil amendments. These results are in line with those obtained by Zhu *et al.* (2015) where co-application of biochar and chemical fertiliser increased nutrient content in maize. Same results were obtained by Lee *et al*. (2021) after incorporation of biochar and fertiliser. Numerous studies show that biochar is a sustainable soil amendment that increases yield and nutrient use efficiency of crops (Farooque *et al*., 2020). This is attributed to biochar's ability to promote nutrient mineralisation, reduce nutrient leaching, improve soil structure and reduce bulk density thereby enhancing the soil's water holding capacity which all contribute to increased nutrient uptake (Walter & Rao, 2015). Furthermore, incorporation of biochar into soils augments the growth of crop's roots thus enabling nutrient uptake and concentration in plant tissues (Liu *et al.*, 2017). Singly application of biochar also improved nutrient uptake and efficiency. These results are consistent with results where N and P use efficiency increased in fruit nutrient content after single application of biochar. However, some studies found no effect of biochar alone or combination of biochar and fertiliser on plant nutrient uptake (Hossain *et al*., 2020). Also, Nguyen *et al*. (2016) found no effect of rice husk biochar on nitrogen uptake.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Declining soil fertility lowers potato productivity in Kenya. Sustainable strategies need to be put in place to solve this problem. This study aimed at addressing this issue by determining the effect of integration of biochar and inorganic fertiliser on potato growth, yield, nutrient use efficiency and on selected soil properties.

The conclusions below were obtained from the study:

i) Application of 500 kg ha^{-1} DAP and combination of biochar and DAP at 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP and 10 t ha^{-1} Biochar with 500 kg ha^{-1} DAP, gave the highest potato growth and yield in the two sites.

ii) The different soil amendment levels significantly influenced the selected soil properties of soil phosphomonoesterases, inorganic nitrogen, extractable phosphorus, raised soil pH and potato nutrient use efficiency.

iii) The obtained results from this study show that the combination of biochar and inorganic fertiliser had a significant effect on potato growth, yield and on selected soil properties.

6.2 Recommendations

Recommendation from the study

i) Integration of biochar and chemical fertiliser can be used to improve soil fertility in Njoro and Mau Narok sub counties of Nakuru county in Kenya.

ii) The application rate of 5 t ha^{-1} Biochar with 500 kg ha^{-1} DAP with *destiny* and *shangi* varieties can be grown in the study sites and other areas with same agro ecological zones.

Recommendations for further research

i) This study was a 2- season experiment, therefore long term field-based studies should be carried out to determine the effects of residual biochar on growth, yield, nutrient use efficiency and soil properties.

ii) Future research should focus on performance of other biochar types such as crop residues and animal wastes.

iii) *Shangi* and *Destiny* performed well in Njoro and Mau Narok implying these potato varieties are suitable for the climatic conditions and soil types.

iv) Economic analysis should be conducted to establish the optimal treatment combinations for farmers.

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APPENDICES

Appendix A: Analysis of variance for growth and yield parameters.

Source of variation	DF	Stem 52DAP	Plant height 45 DAP	Plant height 52 DAP	Plant height 66 DAP	Yield	Marketable yield	Tubers per plant	Dry matter %
Season	1	109.26***	1741.15***	1300.02***	310.08**	1624.60***	288.17**	168.82***	8155.77***
Site	1	10.15***	3195.04***	5410.91***	2462.40***	278.76**	17.43	272.66***	5.64
Site*Season	1	9.66***	2757.33***	5100.18***	5318.31***	3841.38***	1391.46***	392.37***	1.69
Rep(Site*Season)	8	0.16	17.31	7.97	13.69	2.66	12.98	1.82	10.75
Variety	1	21.55***	19119.99***	33704.27***	50793.20***	822.35***	365.07**	179.05***	11.92
Season*Variety	1	10.17***	139.81*	3.05	0.07	408.10***	180.75**	30.27**	3.83
Site*Variety	1	1.26*	1746.60***	1687.12***	438.33**	512.08***	589.28***	18.95**	4.78
Site *Season*Variety	1	0.01	1.46	11.19	371.31**	5.35	4.58	4.85	66.52*
Rep*Variety (Site*Season)	8	0.22	17.52	8.05	26.97	14.39	15.36	1.24	6.84
Trt	8	5.11***	134.64***	545.02***	480.56***	401.20***	447.92***	72.48***	19.89***
Season*Trt	8	0.24	11.1	24.98*	5.03	94.56***	10.42	2.49	5.61
Site*Trt	8	0.26	15.56	13.36	7.63	53.34***	8.33	1.88	7.75
Site*Season*Trt	8	0.12	7.24	10.55	8.924	42.37***	25.11	0.48	28.17***
Variety*Trt	8	0.05	16.28	11.33	15.05	55.84***	11.51	2.4	6.99
Season*Variety*Trt	8	0.13	4.09	11.09	11.69	52.11***	19.16	1.45	17.64**
Site*Variety*Trt	8	0.15	7.73	3.35	3.04	39.91***	19.43	2.09	33.71***
Site *Season*Variety*Trt	8	0.19	8.86	5.69	9.09	67.06***	23.18	0.81	24.49***
Error b		0.16	10.99	12.37	15.08	7.45	13.54	1.62	5.64
CV %		11.07	11.54	7.92	5.76	10.88	15.41	12.81	7.39
R^2		0.91	0.95	0.97	0.97	0.93	0.81	0.89	0.92

*, **, *** significant at ($p \leq 0.05$); ($p \leq 0.01$), ($p \leq 0.001$) respectively, Yield: Total yield, Trt: Treatment, DAP*:* days after planting, CV*:* Coefficient of Variation, R^2: R-squared.

Appendix B: Analysis of variance for selected soil parameters

Source of variation	DF	pH	Acid enzyme	Alkaline enzyme	Nitrate	Ammonium	Phosphorus
Season	1	24.89***	155671.47***	277660.40***	119363.56***	112709.00***	68117.42***
Site	1	1.19*	19581.31***	2151.27***	18306.35***	97161.31***	5777.58***
Site*Season	1	0.07	36002.63***	2364.86***	529.88	64172.11***	7204.89***
Rep(Site*Season)	8	0.06	205.44	91.38	272.32	65.36	27.21
Variety	1	1.18*	4586.48***	121.04	5745.04**	1034.46***	128.78**
Season*Variety	1	0.45	20619.98***	3.14	11117.38***	275.04*	287.50***
Site*Variety	1	0.73*	1027.17*	809.95***	3265.03*	15809.98***	958.11***
Site *Season*Variety	1	2.30**	10591.98***	2700.81***	9709.24***	13534.97***	763.51***
Rep*Variety (Site*Season)	8	0.13	96.4	27.17	321.62	29.94	8.14
Trt	8	5.25***	11003.41***	9428.13***	44948.15***	22290.56***	951.04***
Season*Trt	8	0.25**	2362.57***	4718.62***	1899.06***	5897.41***	891.68***
Site*Trt	8	0.40***	500.16***	411.23***	724.34***	5653.03***	685.99***
Site*Season*Trt	8	0.38***	891.72***	419.53***	617.42***	3746.38***	684.99***
Variety*Trt	8	0.18*	547.02***	115.35*	825.82***	318.34***	1494.56***
Season*Variety*Trt	8	0.19*	458.90**	58.86	4165.80***	276.56***	1609.13***
Site*Variety*Trt	8	0.18*	862.26***	392.88***	1190.75***	1293.91***	1419.07***
Site *Season*Variety*Trt	8	0.22*	965.55***	396.36***	2545.37***	307.22***	1272.99***
Error b		0.09	140.17	49.37	170.23	38.23	10.1
CV %		4.91	9.95	9.91	11.33	10.85	14.3
R2		0.88	0.95	0.98	0.96	0.99	0.99

*, **, *** significant at ($p \leq 0.05$); ($p \leq 0.01$), ($p \leq 0.001$) respectively, Trt: Treatment, CV: Coefficient of Variation, R2: R-squared.

Appendix C: Analysis of variance for nutrient use efficiency

Source of variation	DF	N uptake	P uptake	NUE	PUE
Season	1	199846.02***	4222.34***	95404.32	1279122.92
Site	1	8950.06***	1082.73***	2640.33	2310.12
Site*Season	1	2723.56***	1481.45***	4120.47	2768.84
Rep(Site*Season)	8	39.34	87.22	9991.07	126899.71
Variety	1	14126.44***	400.82***	6821.22	5578.76
Season*Variety	1	655.08***	157.29**	11113.36	233780.16
Site*Variety	1	33.56	242.36***	44470.36	640239.44
Site *Season*Variety	1	6066.80***	0.56	135135.53	1129185.74
Rep*Variety (Site*Season)	8	13.21	9.51	32279.11	434974.68
Trt	8	3259.84***	22.24***	45434.01***	1319812.96***
Season*Trt	8	1376.29***	21.71***	30438.42***	832652.39***
Site*Trt	8	3840.41***	18.65***	9350.75	184797.26
Site*Season*Trt	8	1402.25***	13.53*	9883.39	216701.68
Variety*Trt	8	2984.89***	24.15***	9134.34	20350.3
Season*Variety*Trt	8	1565.93***	44.73***	6765.54	53193.79
Site*Variety*Trt	8	1365.95***	18.84***	18093.13***	340061.91*
Site *Season*Variety*Trt	8	944.29***	28.76***	15681.45**	378105.44**
Error b		18.58	5.17	4982.23	130507.22
CV %		6.24	14.91	79.55	197.8
R2		0.98	0.93	0.74	0.67

*, **, *** significant at ($p \leq 0.05$); ($p \leq 0.01$), ($p \leq 0.001$) respectively, Trt: Treatment, CV: Coefficient of Variation, R2: R-squared.

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Effect of Biochar and Inorganic Fertilizer on Soil Biochemical Properties in Njoro Sub-County, Nakuru County, Kenya

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Abstract

Declining soil fertility is a major constraint to potato farming, the second most important food crop in Kenya. The objective of the study was to determine the effect of different rates of biochar and inorganic fertilizer on some soil properties; soil pH, soil phosphomonoesterases, inorganic nitrogen and extractable phosphorus. The study was conducted for two seasons (short and long rains) at two locations (Egerton University agricultural field and farmer's field in Mau Narok) using a split-plot design in a randomized complete block (RCBD) arrangement with variety as the main plot and soil amendments as the subplot. Biochar and Diammonium Phosphate (DAP) at 0, 5, and 10 $t \cdot ha^{-1}$ and 0, 250, and 500 $kg \cdot ha^{-1}$ respectively, were applied, resulting in nine treatment combinations. Two potato varieties (*Shangi* and *Destiny*) were used in the study. A combination of 5 $t \cdot ha^{-1}$ biochar and 500 $kg \cdot ha^{-1}$ DAP and sole application of biochar at 5 $t \cdot ha^{-1}$ resulted in an increase of 1.25, 2.54 units in soil pH in two seasons, respectively. Similarly, a combination of 5 $t \cdot ha^{-1}$ biochar and 250 $kg \cdot ha^{-1}$ DAP increased soil available phosphorus by 105 units from 30.7 $mg \cdot kg^{-1}$ to 136 $mg \cdot kg^{-1}$. The application rate of 5 $t \cdot ha^{-1}$ biochar with 250 or 500 $kg \cdot ha^{-1}$ DAP significantly increased soil nitrate by 102.11 and 116.14 units, respectively. Soils amended with biochar at 5 $t \cdot ha^{-1}$ combined with 500 $kg \cdot ha^{-1}$ DAP, 10 $t \cdot ha^{-1}$ of biochar combined with either 250 kg or 500 kg of DAP gave the highest alkaline enzymes (mM pNP $\times kg^{-1} \times h^{-1}$). However, the highest acid soil phosphomonoesterases were obtained under the sole application of DAP at 500 ha^{-1}. Thus, using biochar with chemical fertilizer seems a plausible option to ameliorate the declining nutrient base of farmland in Kenya, which could sustainably support potato growth.

Keywords

Biochar, Inorganic Nitrogen, Phosphorus, Soil pH, Phosphomonoesterases

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