EFFECT OF SOIL AMENDMENT WITH BIOCHAR, LIME AND COMPOST ON SOIL ACIDITY AND ROOT ROT IN COMMON BEAN (*Phasoelus vulgaris* L.) IN WESTERN KENYA

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DECLARATION

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

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DEDICATION

This thesis is dedicated to my loving parents, Mr. Jeremiah Wachira Kariuki and Mrs. Teresiah Nyokabi Wachira and brother Mr. Alex Kariuki Wachira.

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ABBREVIATIONS AND ACRONYMS

AG	Anastomosis group
ANOVA	Analysis of Variance
FRR	Fusarium root rot
C	Carbon
cfu	Colony Forming Units
CV	Coefficient of Variation
DAP	Diammonium Phosphate
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FRR	Fusarium root rot
GLP2	Grain Legume Program Two
Ha	Hectare
K	Potassium
KALRO	Kenya Agricultural and Livestock Research Organization
Kg	Kilogram
ml	Milliliters
mm	Millimeters
MT	Metric tonnes
N	Nitrogen
NARL	National Agricultural Research Laboratories
P	Phosphorus
pH	Potential of hydrogen
ppm	Parts per million

ABSTRACT

Root rot complex is a major biotic constraint to bean productivity in Western Kenya caused by synergistic associations of different soil borne fungal pathogens. It is aggravated by infestations of bean stem maggot and is severe in acidic soils whose fertility is low. The disease causes poor seedling emergence, low plant establishment and yield losses of up to 70%. Management of root rot by seed dressing with fungicides has a short-lived effect of two to three weeks after sowing while disease tolerant varieties are few. Thus, the study evaluated the effect of biochar, lime, compost and DAP as soil amendments on soil acidity and bean root rot.

Field experiments were conducted in farms whose soil pH was less than 5.5 at Nandi South within Kapkerer, Kiptaruswo and Koibem characterized as low, medium and high soil fertility sites respectively. The treatments used were biochar, lime, compost, diammonium phosphate and their combinations and were laid out in a Randomized Complete Block Design. The field experiment was carried out during the short rains of 2018 with a repeat in the long rains of 2019. Biochar was produced from sun-dried sugarcane bagasse and pyrolyzed in a handmade pyrolysis stove for 2 to 3 hours. Compost was prepared under a shaded area in a 5 m by 2.5 m plot in which layers of sticks and twigs, dry banana leaves, water, bio stimulant, fresh leaves of *Tithonia diversifolia*, cow manure and soil were repeatedly staked to a height of 2 meters. Biochar, compost, lime and diammonium phosphate were applied at rates of 1t/ha, 2t/ha, 2t/ha and 67kg/ha respectively. Soil samples were analyzed for pH, nutrient content and quantification of root rot pathogens. Root rot pathogens were isolated from amended soils through serial dilution and plated into molten potato dextrose agar media. Their colonies were counted and number of colony forming units determined. Root rot and stem maggot incidences were determined by counting above ground symptomatic plants. Bean root rot, stem maggot incidences and plant mortality were assessed at two, four and six weeks after emergence and expressed into percentages while yield and yield components were assessed at physiological maturity.

Combined application of biochar, lime, compost and DAP had significantly higher effects than their sole application on soil acidity and bean root rot. Sole application of lime, two-way combination of biochar with lime and three-way combination of biochar with lime and compost, significantly ($P \leq 0.05$) soil pH by 0.6 to 0.8 units. Prevalent root rot pathogens isolated from soil were *Rhizoctonia solani*, *Fusarium oxysporum* and *Fusarium solani*. The effect of the

amendments on population of root rot pathogens, varied per pathogen. Both an increase and a decrease in population of *Rhizoctonia solani* was noted among the treatments. All the treatments had significantly ($p \leq 0.05$) higher population of *F. oxysporum* and lower population of *F. solani* compared to non-amended soils.

In both seasons, non-amended plots had significantly higher percentage plant emergence and stand counts than amended plots. This effect was mostly noted in treatments containing DAP. The effect of the treatments on plant mortality varied in season whereby, the treatments had significantly higher plant mortality in the short rains of 2018 and significantly low plant mortality in the long rains of 2019. Application of biochar + lime, biochar + compost + DAP, biochar + lime + DAP and compost +lime +DAP significantly reduced bean mortality by 68% to 90%. In both seasons, most of the treatments had significantly reduced incidence of bean root rot by 52% to 77% compared to non-amended soils. This was noted in treatments of lime, biochar +lime, biochar +lime+ DAP and biochar + lime + compost, biochar + compost +lime + DAP, lime + DAP and biochar + DAP.

Incidences of bean stem maggot were significantly ($P \leq 0.05$) reduced in application of biochar + compost +lime + DAP, biochar + lime and biochar + compost by 52% to 77%. Application of biochar + lime+ compost resulted in a significant increase on biomass by up to 30% while application of biochar + lime+ DAP significantly increased the number of pods per plant and seeds per pod by 63 and 77% respectively. Additionally, application of biochar + lime, biochar + lime +DAP and biochar + lime +compost significantly increased grain yield by 204%, 201% and 217% respectively.

The study shows that the effect of biochar, lime and compost on soil acidity and bean root rot varied in combination. Application of biochar with lime and biochar with lime and compost reduced soil acidity. Combining biochar, lime or compost with an inorganic fertilizer reduces bean root rot and increases grain yield in acidic soils. Therefore, biochar, lime and compost can be used as liming amendments in acidic soils and combined with an inorganic fertilizer to improve bean productivity.

Key words: Amendments, biochar, compost, lime, root rot, soil acidity

CHAPTER ONE: INTRODUCTION

1.1 Background information

Common bean is an important grain legume that promotes food and nutritional security in rural and urban households of developing countries (Buruchara *et al*., 2011; Chekanai *et al*., 2018). It has a high protein, mineral and nutrient content and in Kenya it's consumed together with various carbohydrate sources such as rice or maize (Broughton *et al*., 2003; Keterew *et al*., 2018). The consumption of common bean products at different plant stages enhances a staggered and prolonged supply of food to small holder farmers (Buruchara *et al*., 2011). Additionally, common bean contributes to the intensification of small holder farmer systems as it matures earlier and can be used as an intercrop (Buruchara *et al*., 2011). Improvement in soil fertility by common bean due to its ability to fix nitrogen has reduced the use of synthetic fertilizers hence promoting sustainable agriculture (Buruchara *et al*., 2011; Castro-Guerrero *et al.,* 2016).

According to Karani *et al*. (2017), about 23 million Metric tonnes of common bean is produced worldwide out of which 7 million Metric tonnes is from Latin America and Africa. Although the highest per capita consumption of common bean of 50kgs to 60kgs per person per year in Africa is in Eastern Africa, an estimated annual production of 125,000 metric tonnes is too low to meet an annual demand of 500,000 metric tonnes in Kenya (Mauyo *et al*., 2010; Buruchara *et al*., 2011). Production of common bean in Western Kenya contributes to about 22% of national output of dry bean and is carried out by small scale holder farmers whose resources are limited (Katungi *et al*., 2009;Gicharu *et al*., 2013). Additionally, due to low soil fertility and biotic stresses such as root rot, common bean production in Western Kenya has been declining (Nzungize *et al*., 2012; Kawaka *et al*., 2018; Anunda *et al*., 2019).

1.2 Problem statement

Production of common bean is constrained in areas with low soil fertility, abiotic and biotic stresses. Root rot complex is a biotic stress caused by soil borne pathogens responsible for damaging and rotting of the tap root system. In Western Kenya, bean root rot has caused grain yield losses of up to 70 % (Korayem *et al.,* 2016) which are due to the pathogens' aggressive nature and high inoculum levels. All growth stages of the crop are attacked by root rot pathogens causing poor seedling emergence, low plant establishment, flowering and podding (Muthomi *et*

al., 2007; Naseri and Mousavi, 2015). Bean root rot is severe in soils with low fertility because they have low organic matter (Otsyula *et al*., 1998). Acidic soils have low fertility and due to low pH, essential macro and micronutrients required for bean growth are reduced and unavailable (Goulding, 2016). As a result, plant tolerance to root rot, which is influenced by soil nutrition is reduced due to the effect of soil nutrients on the crop rather than on the root rot pathogens (Otsyula *et al*., 1998). In addition, high concentration of aluminium ions in acidic soils interferes with root development leading to formation of stubby roots and reduces uptake of water and nutrients (Thakuria *et al*., 2016). Soil pH is noted to influence the diversity, survival and growth of soilborne pathogens thus directly influencing the prevalence, incidence and severity of soilborne diseases (Holland *et al*., 2018). Bean root rot is also associated with bean stem maggot whose wounding on the stem bases act as entry points for soil-borne-root rot pathogens (Mwang'ombe *et al*., 2007).

Management of root rot pathogens has been unsuccessful owing to the persistent nature of chlamydospores, sclerotia and oospores which serve as survival structures and are sources of primary and secondary inoculum (Paparu *et al*., 2016; Mihajlović *et al.,* 2017). Seed dressing with chemical fungicides to manage soil borne pathogens is un-sustainable for bean production by resource poor farmers in developing countries (Nzungize *et al*., 2012). This is due to its short lived protective effect of two to three weeks after sowing after which the crop remains susceptible to attack by bean stem maggot and root rot pathogens (Nzungize *et al*., 2012). The available disease-tolerant bean varieties are few and interactions with the environment break down the resistance which requires assessment of new resistant genes and developing more tolerant varieties (Singh and Shwartz, 2010; Nzungize *et al*., 2012; Muthomi *et al*., 2014).

Soil amendments promote sustainable agriculture through improving crop productivity and do not interfere with the agroecosystem (Naseri, 2019). The use of organic soil amendments is a promising management option of soil borne diseases and are reported to have a suppressive effect (Mihajlović *et al.,* 2017). Among these amendments, are biochar, compost and lime which on incorporation enhance soil suppression (Holland *et al*., 2018; Naseri, 2019). Application of either biochar or compost has been reported to reduce soil-borne diseases caused by *Pythium* spp., *Rhizoctonia* spp. and *Fusarium* spp (De Corato *et al*., 2017;Silva *et al*., 2020).The suppressive effect of biochar, lime and compost on soil borne diseases was noted when the

amendments are applied singly (De Corato *et al*., 2016). However, research carried out by Bonanomi *et al*. (2017) reported both synergistic and antagonistic effects of organic amendments on soil borne diseases. In addition, studies on effect of soil amendment combinations on soil borne diseases have mostly been carried out between two organic amendments (Akhter *et al.* 2016) with an exception by (Cao *et al.,* 2017). Therefore, to enhance the effectiveness of organic amendments in acidic soils, the study proposes to combine organic soil amendments with lime and inorganic fertilizers.

1.3 Justification of study

Small scale holder farmers are major producers of common bean in Western Kenya and rely on the crop as a source of food and income (Otsyula *et al*., 2004). However, low soil fertility, bean pests and diseases have reduced its production. To improve soil fertility, farmers have incorporated the use of soil amendments. Among these amendments are inorganic fertilizers which have improved bean yield and intensified its production. However, continuous production of common bean and prolonged sole use of inorganic fertilizers has increased the inoculum level of bean root rot pathogens, acidified the soil, depleted soil nutrients and enhanced low soil fertility (Otsyula, 1998). Use of seed dressers and tolerant varieties as options of managing bean root rot, though effective have not been easily adopted by small scale holder farmers (Singh and Shwartz, 2010; Nzungize *et al*., 2012). Management of soil acidity by small scale farmers with agricultural lime is limited due to its cost, high labor demand and limited knowledge on its use.

Biochar and compost can be used as alternative soil amendments to manage soil acidity, bean root rot and improve soil fertility. They are organic amendments made from readily available plant materials and serve as substitute farm inputs for resource-constrained small holder farmers. Application of biochar and compost to soils with low fertility restores the biological, physical, chemical and ecological properties of soil. This is achieved by their ability to ameliorate soil acidity due to their liming effect (Boungom *et al*., 2009; Berek *et al*., 2011). They have an antagonistic effect on soil borne pathogens which would reduce buildup of inoculum and subsequent rotting in intensively cultivated bean plots (Graber *et al*., 2014; Mehta *et al*., 2014). Acting as organic fertilizers, they provide significant macro and micronutrients required for plant growth which enhances the plant's tolerance to bean root rot (Graber *et al*., 2014; Eboibi *et al*., 2018; van Zweieten, 2018). Additionally, lime decreases soil acidity by reducing the

concentration of toxic aluminium ions and increases the availability of essential macro and micronutrients required for root development (Thakuria *et al*., 2016). Therefore, use of biochar, compost and lime by small scale holder farmers provides an opportunity for increasing bean production in soils with low fertility.

However, the supply of macro and micronutrients by organic amendments is regulated by the rate of mineralization and may not provide a balanced or adequate nutrient dosage (van Zweieten, 2018). Thus, these amendments require to be applied in combination with mineral fertilizers. Therefore, the study aimed at assessing the effect of biochar, lime, compost and DAP when applied individually or in combination on soil acidity and bean root rot.

1.4 Study objectives

The broad objective was to improve productivity of common bean by managing bean root rot and soil fertility through use of biochar, compost and lime as a soil amendment.

The specific objectives were:

i. To determine the effect of biochar, lime and compost on soil acidity and bean root rot
ii. To determine the effect of biochar, lime and compost on biomass and grain yield of common bean

1.5 Hypothesis

i. Application of biochar, lime, compost and their combinations significantly reduce soil acidity and bean root rot
ii. Application of biochar, lime, compost and their combinations significantly increases biomass and grain yield of common bean

CHAPTER TWO: LITERATURE REVIEW

2.1 Importance of common bean

Common bean is the most widely grown legume that occupies approximately 90% of the area planted with *Phaseolus* species and is an important crop in the tropics and sub-tropics (Morales, 2007; Oshone, 2017). It is an ideal crop for small holder production and farming systems, because it enhances nitrogen fixation, improves soil fertility, has a short life cycle and maturity of less than three months, provides income and used as an intercrop (Mukankusi *et al*., 2018).

In Eastern and Southern Africa, common bean contributes to health, food and nutrition security through its protein, vitamin, mineral and fiber content which complements the calorie content of carbohydrates (Keterew *et al*., 2018; Lobaton *et al*., 2018; de Oliveira *et al*., 2018). It aids in the reduction of cholesterol and sugar levels and alleviate and hinder cardiovascular diseases, type 2 diabetes and types of cancer (Leterme, 2002). Additionally, it allows for sustainable intensification within agricultural systems (Franke *et al*., 2016).

2.2 Production of common bean in Kenya

Production of common bean is estimated to be approximately 26.8 to 28 million tons globally while its consumption in East Africa ranges from fifty to sixty kilogram per year (Celmeli *et al*., 2018; Menge *et al.*, 2018). Approximately 38% of common bean is produced in the Eastern African highlands by small-holder farmers are the primary growers (Kimani et *al.*, 2001; Kawaka *et al.*, 2018). The production of dry bean in Kenya has been on the rise from 2010 to 2013 but with a slight decline in the year 2014 and 2016 (Figure 2.1). According to Mukankusi *et al*. (2018), a production of 615,992 tons of common beans in Kenya within an area of 1,052,408 hectares results to yield of 585.3kg/ha. Estimates made by the Kenya Agricultural and Livestock Research Organization show that 1.8 million households in Kenya contribute to 85% production of the crop (Nelson, 2016). About thirty seven common bean varieties have been listed in KEPHIS. Among these include Mwitemania (GLP92), Rosecoco (GLP2) Mwezi Moja (GLP1004), Canadian Wonder (GLP24), Miezi mbili, Red Haricot, KAT series, and for Western Kenya and root rot-prone areas Kakuma-KARI series (KK8 and KK15) are recommended (ICRISAT, 2013).

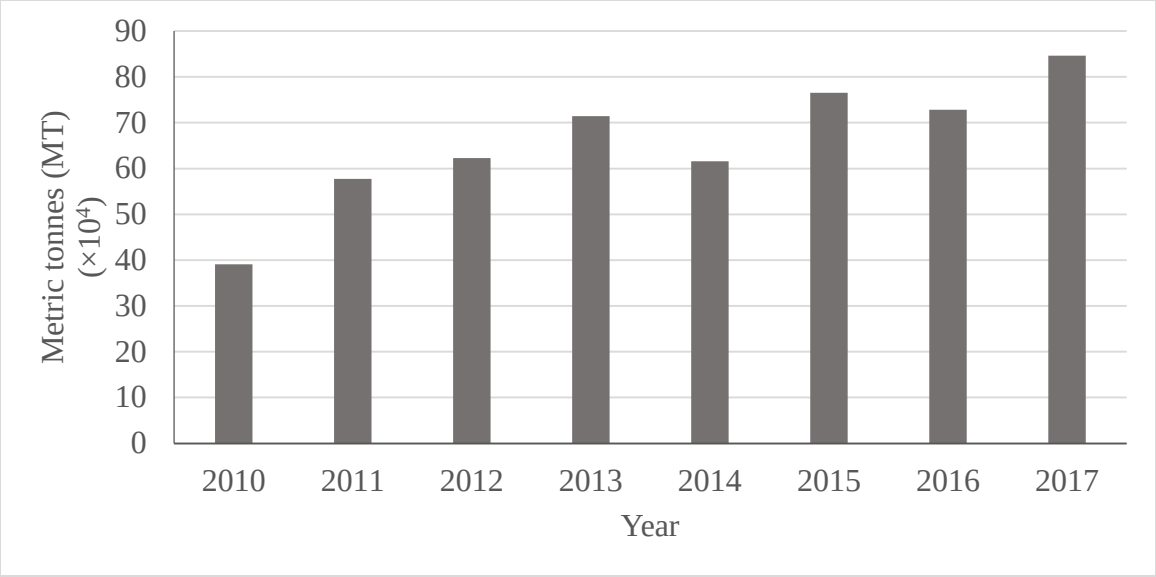

Figure 2.1: Amount of dry bean produced in Kenya from 2010 to 2017 Source: FAOSTAT (2019)

2.3 Production constraints of common bean in Kenya

The production of common beans in Kenya is not consistent with its demand due to increasing population. Abiotic constraints are wide spread and categorized into edaphic or climatic constraints (Asfaw, 2011). Low soil fertility, fertilizer costs and drought are among the abiotic factors affecting bean productivity among small-holder farmers (Chemining'wa *et al.,* 2004). Pests and diseases are the major biotic constrains. Pests of economic importance such as pod borers, bean stem maggot, foliage thrips, bean stem fly (Kiptoo *et al*., 2016) aphids (*Aphis craccivora* Koch), spider mites (*Tetranychus urticae),* white fly (*Bemisia tabaci*) have been observed to lower the productivity in beans (Wortman *et al*., 1998; Saad *et al.,* 2007). Fungal, bacterial and viral diseases of the common bean that have contributed to low bean production include Anthracnose (*Colletotrichum lindemuthianum*), Root rot (*Fusarium solani f. sp. phaseoli; Rhozoctonia solani; Pythium* spp), rust (*Uromyces appendiculatus* var. *appendiculatus*), Angular leaf spot-ALS (Phaeoisariopsis *griseola*), common bacterial blight-CBB (*Xanthomonas axopnopodis pv. phaseoli*), halo blight (*Pseudomonas syringae pv.phaseolicola*), *Bean common mosaic virus* (BCMV) and root knot nematodes (*Meloidogyne* spp) are economic important bean diseases (Wortmann *et al*., 1998; Fikre *et al*., 2011). Whereas

other constraints such as poor quality seeds, in adequate labour and poor marketing framework have been reported by (Birachi *et al.,* 2011) to affect bean production in Western Kenya.

2.4 Root rot as a biotic constraint of bean production

Root rot is caused by soil borne fungal pathogens belonging to the genera *Pythium*, *Fusarium Rhizoctonia*, *Macrophomina* and *Sclerotium* which are phytopathogenic (Gao *et al.,* 2014; Paparu *et al.,* 2016). *Fusarium oxysporum*, *Fusarium solani*, *Fusarium sporotrichioides*, *Fusarium nygamai, Macrophomina phaseolina, Rhizoctonia solani* and *Sclerotinia* sp. have been identified as the causal agent of bean root rot in various counties in Kenya (Mwang'ombe *et al*., 2007; Okoth and Siameto, 2010; Muthomi *et al*.,2014).

There is a synergistic association of *F. oxysporum, F. solani, M. phaseolina* and *R. solani* in the rhizopshere where they occur as a complex and damage the rooting system (Macedo *et al*., 2017). This leads to seed and seedling infections, damping off, poor plant stand and low grain yield (Muthomi *et al*., 2007; Naseri and Mousavi, 2015). Additionally, root rot is enhanced during stressful conditions of low soil fertility and losses of 100% may occur in susceptible varieties (Otsyula *et al*., 2004; Paparu *et al*., 2016). Pests such as bean stem maggot are found in close association with bean root rot. This is because emerging maggots from eggs laid on leaves, stems and hypocotyls, mine the root zone, where pupation and extensive feeding occurs, thus creating wounds which act as entry points for root rot pathogens (Mwang'ombe *et al*., 2007; Ochilo and Nyamasyo, 2011).

The number and type of root rot pathogens which will occur varies depending on the environmental and soil condition thus determining the incidence and severity of bean root rot (Abawi and Pastor Corrales, 1990; Rusuku *et al*., 1997). The severity of root rot is influenced by the soil structure, presence of organic matter, inadequate soil drainage and soil compactness (Abawi and Pastor Corrales, 1990). In addition, insufficient crop rotation and use susceptible bean varieties by small scale holder farmers has led to buildup of inoculum and resulted to severe bean root rot (Abawi and Pastor Corrales, 1990).

Commonly observed symptoms of root rot in the field are wilting, yellowing or chlorosis of the lower leaves, water soaked roots and stems, stunting, poor germination, death of roots, emerging

adventitious roots above dead root parts, extended brownish color to the hypocotyl region (Abawi and Pastor Corrales, 1990; Binagwa *et al*., 2016).

2.4.1 Pythium root rot of common bean

Pythium spp reduce bean yield potential by interfering with seedling emergence and establishment resulting to yield losses of up to 70% in locally available common bean varieties in East Africa (Gichuru *et al*., 2016; Binagwa *et al*., 2016). Host symptoms associated with *Pythium* root rot include browning of the root tip, chlorosis, root swelling and callus formation (Owen-Going *et al*., 2010). Common isolated species of *Pythium* that cause root rot from studies carried out in Kenya, Tanzamia and Uganda are *Pythium aphanidermatum, Pythium graminicola*, *Pythium irregurale*, *Pythium myriotylum, Pythium nodosum, Pythium oligandrum, Pythium pachycaule* and *Pythium ultimum* (Nzungize *et al*., 2012; Binagwa *et al*., 2016).

Its disease cycle begins with the direct and indirect germination of oospores into diploid mycelia which produces a zoosporangia. The sporangium is separated from the mycelium by a cross wall (Nzungize *et al*., 2012). The presence of magnesium, potassium, and calcium ions and root exudates act as a stimulus for the production of sporangia, hyphal swellings and germination of sporangia and mycelial growth (Nzungize *et al*., 2012).The zoosporangia produces a short discharge tube to form a vesicle into which the undifferentiated content within the sporangia empties its contents from which the protoplasm cleaves to form flagellated zoospores. The zoospores swim about in the soil water and encyst on adjacent roots, infect the young root tissue and develops into mycelia. The mycelia may undergo sexual reproduction to form oospores in adverse conditions or asexual reproduction to form flagellated zoospores and zoosporangia (Agrios, 2005; Nzungize *et al*., 2012)

2.4.2 Rhizoctonia root rot

Also called the ‘killer disease’ is caused by *Rhizoctonia solani* Kuhn (Lakshman *et al.*, 2016). It is considered worldly to be economically important and associated with root rot as well as web blight, seed rot and damping off hence affecting seed germination and seedling establishment (Valentin Torres *et al.*, 2016; Spedaletti *et al*., 2017). According to Mayo *et al.* (2015) *Rhizoctonia solani* penetrates the host through wounds or the cuticle of the root and the hypocotyl region forming lesions which are observed at the root-shoot interface (Martins *et al*.,

2018). However, on young seedlings, initial lesions are formed on the lower stem and tap root. These lesions are small reddish brown, sunken cankers and with delineated margins. As infection progresses, the lesions slowly enlarge, merge with each other, girdle the stem and eventually destroy the plant (Abawi and Pastor Corrales, 1990).

Rhizoctonia solani is a complex pathogen containing about 14 anastomosis groups which vary with the disease they are associated with (Valentin Torres *et al.*, 2016). Isolates of *Rhizoctonia* that cause root rots and hypocotyl rot belong to the anastomoses group (AG) 2-2 or AG 4 (Valentin Torres *et al.*, 2016). The pathogen's facultative parasitic nature enables it to survive as a saprophyte in the form of mycelia and sclerotia in crop residues and serve as primary inoculum for the subsequent season (Spedaletti *et al*., 2017). The pathogen is dispersed by wind and water, and grows in moist soils whose temperature ranges between 15-18^{o}C and pH ranges from 5-9 (Fayzalla *et al.*, 2008; Mayo *et al*., 2015; Spedaletti *et al*., 2017).

The disease cycle is characterized by the presence of inoculum in the soil in form of basidiospores, mycelium and sclerotium (Keijer, 1996). The hyphae germinates in the presence of moisture and adequate temperature and is attracted to the plant roots where it forms hyphal aggregates (Keijer, 1996). The mycelial growth is stimulated high amounts of amino acids, phenols and organic acids which are contained in the root exudates of young plants (Keijer, 1996). The mycelium grows over the plant and attaches itself to the plant cellular wall and forms T-shaped side branches whose infection structures contain infection pegs which penetrate the cuticle and epidermis and grows intracellularly (Keijer, 1996).

2.4.3 Fusarium root rot of common bean

The causal microorganism of Fusarium root rot (FRR) is *Fusarium solani* f.sp. *phaseoli* (Saremi *et al.*, 2011). *Fusarium* is a pre-dominant weak antagonistic root rot pathogen that is dependent on plant stress to initiate infection (Gossen *et al.*, 2016). Fusarium root rot occurs at the most critical stages of bean growth mainly in flowering and pod setting (Saremi *et al.*, 2011). Fusarium root rot is in close association with Fusarium *oxysporum* f.sp. *phaseoli* which causes wilting and has a wide host range among dicotyledonous species that have broad leaves (Muthomi *et al*., 2014; Burgess, 2014). *F. solani and F. oxysporum* produce three types of asexual spores namely macroconidia, microconidia and chlamydospores The macroconidia are septate, curved and have blunt ends while the chlamydospores are thick walled. The pathogen

survives in crop debri in the form of mycelia as well as on roots of non-host crops which are symptomless (Abawi and Pastor Corrales, 1990).

The pathogenicity of *Fusarium* is due to its ability to produce pectic enzymes that are able to dissolve pectin in cell walls hence reducing plant turgidity (Balaali and Iranpoor, 2006). The pathogen rarely kills its host instead weakens it and eventually the plant becomes stunted. However, when infection occurs in older mature plants, there is minimal damage (Abawi and Pastor Corrales, 1990). Plant root exudates influence the mycelial growth, development of microconidia and germination of chlamydospores (Akhter *et al*., 2016). Decayed roots disintegrate and release macroconidia, microconidia and chlamydospores which germinate on the roots of a susceptible host. The fungus colonizes the root tissue resulting to death of the infected roots while others survive by producing adventitious roots above the infected tissue.

Initial symptoms of infections by *F. oxysporum* usually appear within the first two weeks after planting and occur in localized regions (Abawi and Pastor Corrales, 1990). Common observed symptoms are wilts, stunted plants, tap roots and hypocotyls with red brown longitudinal streaks, decayed lateral roots, red discoloration on the vascular systems and adventitious roots (Abawi and Pastor Corrales, 1990; Saremi *et al.*, 2011; Gossen *et al.*, 2016).

Infection occurs through the feeder rootlets whereby, the fungus colonizes the root cortex prior to penetration into the endodermis. From the endodermis, it enters into the xylem vessels where its growth may be constrained or proliferate through the vascular bundles (Burgess, 2013). The macroconidia block the xylem vessels and prevent any uptake of water or mineral salts from the roots (Agrios, 2005). When the plant succumbs to wilting, the fungus forms chlamydospores within the root cortex and xylem vessels (Burgess, 2014).

2.4.4 Charcoal rot of common bean

Also known as Ashy stem blight is caused by *Macrophomina phaseoli* (Tassi) Goid which forms numerous miniscule black sclerotia on the stem base of the host plant (Abawi and Pastor Corrales, 1990; Sarr *et al.*, 2014). The pathogen is both seed and soil-borne, saprophytic, widely distributed and diverse due to its heterokaryotic nature and exhibits a pathogenic and saprophytic phase (Abdel-Kader *et al*., 2010; Almomani *et al*., 2013; Sarr *et al.*, 2014).

Symptoms associated with the disease as described by Almomani *et al*. (2013) show that hypocotyls of infected seedlings have a reddish brown discoloration which occur at or above the soil line. The fungus produces phaseolinone, an exotoxin, which inhibits germination and is responsible for causing wilts in seedlings (Almomani *et al*., 2013). Additionally, wilting due to *Macrophomina* is attributed to the fibrovascular infection in the roots and stem base nodes (Abdel-Kader *et al*., 2010). When infection occurs at the beginning of the season, leaflets of smaller sizes that lack vigor are produced in infected plants, whereas leaflets become chlorotic, wilt and turn into brown but remain attached to the plant when infection arises in progressive stages (Almomani *et al*., 2013). If infection arises at the flowering stage, discolorations of light grey and silver develop in the hypocotyl and taproot (Almomani *et al*., 2013).

2.5 Soil acidity as an abiotic constraint

Intensive farming in Sub-saharan Africa has significantly led to increased levels of soil acidification (Ndurumuremyi *et al*., 2013). According to Nyarko (2012), acidic soils are intoxicated, impoverished, unproductive and with poor biological, chemical and physical properties. In Africa, bean production is hindered by low soil fertility which is associated with soil acidity, low nitrogen, phosphorous and exchangeable bases (Beebe *et al.*, 2012).

According to Beebe *et al*. (2012) bean production is prevalent in areas where the soil pH is less than or equal to 5.0 and in Western Kenya, where bean production is carried out most of the soils are acidic (Opala *et al*., 2018). Soil acidity may ensue as a result of the leaching of basic cations due to excessive rainfall, production of weak organic acids from decomposing organic matter and accelerated by human activity through prolonged use of acidifying fertilizers (Buni, 2014).

2.5.1 Effect of soil acidity on soil nutrient availability

Nitrogen, phosphorous and potassium are important macronutrients required for crop growth and development. These elements are important for the functioning of different metabolic processes such as photosynthesis and osmoregulation (Hawkesford *et al.*, 2012). However, soil acidity influences their mobilization and bio-availability by having an effect on the transformation and cycling of these elements (Kunhikrishnan *et al*., 2016). Additionally, it influences the mineralization of organically bound elements, adsorption of elements and precipitation reactions of these elements (Holland *et al*., 2018).

Mineralization of organically bound elements is carried out by soil microorganisms which contribute to the nitrogen, carbon and phosphorous cycle (Kunhikrishnan *et al*., 2016). These microorganisms belong to the bacterial community whose diversity and composition is highly influenced by soil pH (Rousk *et al*., 2010). Processes such as biological nitrogen fixation are reduced in acidic soils due the adverse effect of low soil pH on *Rhizobium* thus reducing nodulation in leguminous plants (Kunhikrishnan *et al*., 2016).

Adsorption and precipitation of elements to the soil surface is influenced by the pH of the soil solution which supplies hydrogen ions for adsorption to surface bound metal oxides (Kunhikrishnan *et al*., 2016) and dissociates functional groups bound to soil organic matter. In low soil pH, the cation exchange capacity is reduced and this affects the retention and adsorption of potassium ions on soil particles hence its increase in soil solution and can be easily leached (Kunhikrishnan *et al*., 2016). Additionally, soil acidity leads to a decline in the amount calcium and magnesium ions which result to plant deficiencies (Kunhikrishnan *et al*., 2016). In acidic soils, loosely bound phosphates are made unavailable for uptake by plant because they are re-precipitated into crystalline aluminium and iron phosphates (Ch'ng *et al*., 2014).

Soil acidity enhances the solubility of metal cations such as aluminium and manganese which are highly toxic to plants (Kunhikrishnan *et al*., 2016). Manganese cations directly affect the plants metabolism while aluminium toxicity leads to plant malformation and malfunction (Kunhikrishnan *et al*., 2016).

2.5.2 Effect of soil acidity on root rot pathogens

Soil pH has a direct effect on soil borne pathogens and populations of soil microorganisms hence affects plant disease infection and development (Holland *et al*., 2018; Ghorbani *et* al., 2008). Acidic soils are a conducive environment for plant disease because they have low nutrient content, which indirectly causes a change in the composition of plant root exudates levels (Holland *et al*., 2018; Alhussaen, 2012). el Zahar Haichar *et al*. (2014) noted that root exudates have an influence on the growth and development of mycelia and conidia of soil borne pathogens. In addition, low microbial diversity reduces the competition of nutrients by root rot pathogens which leads to an increase in the population.

Soil pH affects the survival and growth of the pathogen and has a varying effect on the disease stages of soil borne diseases (Holland *et al*., 2018). This observation was confirmed by Tyagi and Paudel (2014) who reported that *Fusarium oxysporum* has an optimum growth at pH of 6 but form chlamydospores in pH of 4.5. Alhussaen (2012) also noted that *Pythium ultimum* had an optimum growth in pH levels of 5 while that of *Fusarium oxysporum* was between pH of 6 and 7.

2.5.3 Effect of soil acidity on plant growth

Soil pH affects plant growth through nutrient deficiencies and toxicities which affect above and below ground plant development (Omollo *et al*., 2016; Thakuria *et al*.,2016). In acidic soils, aluminium toxicities limit plant growth and interfere with effective utilization of inorganic fertilizers which have been employed to mitigate nitrogen and phosphorous deficiencies (Opala *et al*., 2018; Yuan *et al*., 2011). Plant growth in soils with high concentration of aluminium is limited because the aluminium ions impair root growth as a result of root injuries, reduced lateral root formation and stubby roots which reduce uptake to water and mineral salts (Aguilera *et al* ., 2015; Thakuria *et al*., 2016). Other effects associated with nutrient toxicities is poor seedling emergence and establishment, reduced nodule formation, plant stunting at seedling and maturity, reduced plant biomass, reduced seed weight and severe yield losses (Rao *et al*., 2016).

Soil nutrients have an indirect effect on plant tolerance to diseases by influencing the primary resistance and enhancing the inactivation of pathogens (Gupta *et al.*, 2017). Acidic soils have reduced nitrogen, phosphorous and potassium content which enhances the susceptibility of plants to diseases such as root rot (Otsyula, 1998). Reduction of nitrogen levels in the soil increases the severity of facultative parasites by altering the plant's metabolism thus inducing anatomical and physiological changes (Gupta *et al.*, 2017).

High amounts of nitrogen lower the activity of phenols, which are toxic to pathogens and increase the plants' susceptibility to diseases (Agrios, 2005; Gupta *et al.*, 2017). Forms of nitrogen such as ammonium have an influence on the activity and incidence of root-borne diseases because it affects the uptake of potassium ions, which stimulate root development (Gupta *et al.*, 2017). Additionally, plants growing in inadequate levels of phosphorous and potassium have, thin cell walls, delicate stalks and stems and reduced root systems which

increase the seedlings' susceptibility to damping off and attack by root rot pathogens (Gupta *et al.*, 2017).

2.6 Use of soil amendments in management of soil acidity

Intensive farming in Sub-saharan Africa where agriculture is pre-dominantly relied on has significantly led to increased levels of soil acidification (Ndurumuremyi *et al.,* 2013). To curb this acidity, soil amendments such as lime, organic materials, their combinations, acidic-tolerant varieties, improved agronomic, cultural and biological activities and limiting the use of acidifying fertilizers have been employed (Muindi *et al*., 2016).

Different types of lime such as crashed lime, slaked lime, dolomitic lime and quick lime have been used for alleviating soil acidity (Ndurumuremyi *et al.,* 2013; Wamalwa, 2018). Its activity is influenced by the mode of application such as spot, banding and broadcasting, type of lime, application rate, reaction time, soil type and characteristics (Nyarko, 2012; Thakuria *et al*., 2016) On dissolving in the soil moisture, lime reduces soil acidity through producing hydroxide (OH^-) and calcium ($Ca^{2+)}$ ions which are responsible for the removal of toxic Aluminium (Al^{3+}) and Hydrogen ions (H^+) (Nduwumuremyi *et al*., 2013; Opala *et al*., 2018). Incorporating lime in the soil results to an increase in soil pH, calcium and magnesium ion concentration in the 0 to 10 cm soil layer. The effect of lime to soil properties is long-lived and reduces the frequency of its application. However, monitoring is required to ensure that the exchangeable ions needed by a particular plant are in their optimum level (Nduwumuremyi *et al.,* 2013).

Organic materials such as compost may be used as alternative liming amendmnets to ameliorate soil acidity in the event that lime is unavailable (Bougnom *et al*., 2009). Compost is a humus-like material produced at temperatures of 40^0C-70^0C through aerobic decomposition. It is effective in ameliorating soil acidity and improving soil fertility (Khoi *et al*., 2010). Composts whose pH is higher than that of the soil are able to significantly increase pH. This is due to the presence of binding and buffering sites on compost surfaces which allow proton flow from the soil to the organic material (Bougom *et al*., 2009). Cattle manure has also been shown to reduce soil acidity due to the presence organic acids and calcium carbonate. The calcium carbonate in the manure may have been transferred from the animals feeds (Whalen *et al*., 2000).

Biochar is a porous, fine-grained, charcoal-like product produced from carbon-rich biomass at high temperature ranges of (250–900°C) (Graber *et al*., 2014). Various studies carried out by Berek *et al*. (2011), Chintala *et al*. (2013) and Knox *et al*., (2015) have shown that application of biochar increases soil pH and reduces exchangeable acidity in acidic soils. The ability of biochar to correct soil acidity has been linked to its alkaline nature, capacity to buffer, ash content and oxygenated surface-functional groups (Dai *et al.*, 2016; Berek and Hue, 2016). According to Dai *et al.* (2016) biochars whose pH is greater than 7 is able to raise acid soil pH by 1.5 units. The surfaces of biochar have negatively charged sites which act as binding sites for cations and facilitate cation exchange (Verrheijen *et al*., 2010). Additionally, biochar releases base cations which participate in cation exchange reactions (Chintala *et al*., 2013). However, biochar's chemical, physical properties and effectivity is influenced by the feedstock used as well as the temperature and heating ranges in the production process (Jaiswal *et al.*, 2018).

2.7 Management of soil borne diseases

Management of soil borne diseases such as bean root is challenging because they are caused by a complex of soil borne pathogens. These pathogens have a wide host range and survive in the absence of a host by producing resting structures in adverse environmental conditions (Agrios, 2005; Mihajlović *et al*., 2017). Various chemical, biological and cultural management options have employed to manage soil borne diseases (Mihajlović *et al*., 2017; Nzungize *et al*., 2012).

Among the chemical methods is by seed dressing with chemical fungicides (Nzungize *et al*., 2012). To manage *Pythium* root rot, benomyl, captafol, captan, and metalaxyl have been proven to be efficient (Nzungize *et al*., 2012). However, their activity is limited to the growing mycelium and not the resting structures. Additionally, seed dressing offers a short lived protective effect of two to three weeks after sowing after which the crop remains susceptible to attack (Nzungize *et al*., 2012). Chemical methods have been preferred because of their efficiency and quick activity (Mihajlović *et al*., 2017). However, due to their negative environmental effect through air and water pollution, use of cultural and biological options have been proposed (Mihajlović *et al*., 2017).

Biocontrol of soil borne pathogens uses antagonistic bacterial and fungal microorganisms such as *Bacillus* sp. and *Trichoderma* sp. (Nzungize *et al*., 2012; Mihajlović *et al*., 2017) The

microorganisms are introduced into the soil where they suppress soil borne pathogens through parasitism, competition for nutrients such as carbon and iron, production of secondary metabolites such as antibiotics and siderophores, promotion of plant growth in *Rhizobium* sp. and induce plant resistance (Nzungize *et al*., 2012; Mihajlović *et al*., 2017). Although use of microorganisms is effective, their suppression may be partial and inadequate due to sensitivity of the microorganism to environmental characteristics such as soil pH and moisture (Mihajlović *et al*., 2017). Additionally, their activity must be present and persist during the period when the host is susceptible (Nzungize *et al*., 2012).

For eradication and reduction in soil borne pathogen inoculum, various cultural methods such as crop rotation, soil solarization, use of tolerant varieties and soil amendments have been recommended (Agrios, 2005; Mihajlović *et al*., 2017). Crop rotation enhances soil fertility but its effect is limited in management of soil borne pathogens that occur and persist in presence of the host (Agrios, 2005). In soil solarization, thermal heat from the sun is absorbed and trapped by polyethylene sheets placed over the soil (Mihajlović *et al*., 2017). The trapped heat not only changes the soil chemical properties but also destroys propagules of soil borne pathogens and changes the diversity of microbial populations (Mihajlović *et al*., 2017).

Breeding of bean varieties against Fusarium and Pythium root rot has led to the release of resistant bean varieties (Mukankusi *et al*., 2018). Despite these efforts, the varieties are few and interactions with the environment breaks down resistance which requires assessing new resistant genes and developing tolerant varieties (Singh and Shwartz, 2010; Nzungize *et al*., 2012; Muthomi *et al*., 2014). According to Buruchura and Scheidegger (1991) cultural practices such as soil amendments may influence the bean root rot severity by reducing the inoculum of the pathogen. This is due to the creation of an unfavorable environment condition for pathogen development and proliferation as well as enhanced plant growth and vigor even in the presence of the pathogen.

2.8 Use of soil amendments in management of soil borne pathogens

Soil amendments are used in the management of soil borne pathogens because they influence the pathogen's life cycle and have an effect on soil health (Mihajlovic *et al.*, 2017; Bonilla *et al*., 2012). These amendments exhibit general and specific suppression towards these soil-borne

pathogens (Bonilla *et al*., 2012; Mehta *et al*., 2014). However, the suppressive effect of soil amendments is variable and non-specific among different soil borne pathogens (Bonanomi *et al*., 2007; Bonilla *et al*., 2012).

Soils amended with lime create a suppressive environment for the soil borne pathogens due to its liming effect (Ingemarsson, 2004). The resultant increase in soil pH and reduction in the concentration of aluminium ions allows for the uptake of calcium ions which strengthen the rooting system by increasing cellular proliferation (Ingemarsson, 2004). Lime contains calcium which has an effect on incidence and disease development of Fusarium wilt and root rot of tomato (McGovern, 2015). Different forms of calcium such as calcium hydroxide and calcium carbonate were noted by McGovern (2015) and Chittem *et al*. (2016) to reduce radial growth rate, conidia production and germination and amount of disease of *Fusarium* species.

According to Chittem *et al*. (2016) radial growth and growth rate of *Fusarium avenaceum*, *Fusarium oxysporum*, *Fusarium acuminatum*, *Fusarium gramineraum* and *Fusarium solani* increased in petridishes amended with lime when compared to the control. However, conidia production and germination was reduced at concentration of 2.2, 5.6, 11.2 and 22.5t/ha. Suppressive effect of lime arises due to change in soil pH which leads to decreased amounts of soil micronutrients essential for their development. On the other hand, pure calcium carbonate reduced the radial growth of *Rhizoctonia solani* but agricultural lime had no effect on *Fusarium graminearum* and *Rhizoctonia solani* (Peña *et al*., 2016).

Disease suppression by compost is a variable, pathogen specific and is affected by the process of decomposition (Bonanomi *et al*., 2010; Mehta *et al*., 2014). Compost is effective in the suppression of soil borne diseases caused by *Pythium*, *Phytopthora*, *Fusarium*, *Verticilium dahliae*, *Sclerotinia* and Thielaviopsis as well as *Rhizoctonia* (Mehta *et al*., 2014). Suppressive effect of compost may be attributed to microbes associated with composts such as *Trichoderma harzianum*, *Bacillus cereus*, *Bacillus subtilis* which reduce the mycelial growth of *Sclerotium rolfsii*, *Fusarium oxysporum*, *Pythium aphanidermatum*, *Helminthosporium maydis* and *Rhizoctonia solani* (Muhammad and Amusa, 2003). These microorganisms compete with *Pythium* and *Pytopthora* for carbon sources present in compost (Mehta *et al*., 2014; Bonanomi *et al*., 2010; Avilés *et al*., 2011).

Other studies carried out by Mbau *et al*. (2015) report that when compost was added into soil, it increased the soil nitrogen. This is because compost has high nitrogen and which alters the pH creating an alkaline environment in which ammonium may be produced (Lazarovits *et al*., 2005). The ammonium in alkaline environment breaks down into ammonia which is able to kill microsclerotia of *Verticilium dahliae* and sclerotia of *Sclerotinia sclerotiorum* (Lazarovits *et al*., 2005)

Biochar has been observed to be effective against foliar and soil borne pathogens (*Fusarium, Rhizoctonia* and *Phytopthora* species) (Bonanomi *et al*., 2015). This is because biochar interacts with the complex systems in the rhizosphere and thus influence the disease triangle (Graber *et al*., 2014). Disease suppression through biochar has been noted in 85% of studies carried out in a review done by (Bonanomi *et al*., 2017). However, this suppression is influenced by the biochar feedstock and concentration (Jaiswal *et al*., 2015). In that, when the concentration of biochar is low in the soil, plant disease is suppressed as opposed to high concentrations where it's ineffective and induces plant disease (Frenkel *et al*., 2017).

Suppression of soil borne pathogens by biochar is linked to the presence of toxic anti-fungal compounds such as butyric acids and benzoic acid in biochar-residual tars (Elad *et al*., 2010; Głuszek *et al*., 2016). However, Jaiswal *et al*. (2017) contradicts this and reports that biochar lacked a direct toxic effect on the mycelial growth of *Fusarium*. Secondly, biochar is able to adsorb the pathogen's extracellular enzymes and toxins which interferes with the interaction between the pathogen and host (Jaiswal *et al*., 2018).

Addition of biochar to the soil increases microbial activity and diversity because biochar acts as a short-term substrate for microorganisms and due to its high carbon content, it serves as a source of energy for microbes in the soil (Thies and Rilling, 2009; Bonanomi *et al*., 2015;Jaiswal *et al*., 2017). Another mechanism of disease suppression is through induced resistance which arises as a result of enhanced nutrient availability, increased microbial abundance, diversity and activity and enhanced soil physiochemical properties (Elad *et al*., 2011; Bonanomi *et al*., 2015).

2.9 Effect of soil amendments on bean productivity

Addition of lime to acidic soils reduces soil acidity and favors the establishment and growth of legumes. Improved growth and yield of the haricot bean was attributed to increased soil pH in

soils amended with lime (Kassa *et al*., 2014). Increased yield of cowpea in soils amended with lime was credited to increased root and shoot dry weight and increased number of root nodules (Bello *et al*., 2018). Supply of calcium ions from lime and the binding of excess aluminium and hydrogen ions also contributed to increased growth of cow pea.

Crop productivity in biochar amended soils is variable (Lehmann and Joseph, 2015). Increases in crop productivity due to biochar has been noted in rice, soybean, wheat and maize cropping systems. However, no significant effects of biochar were observed on sugarcane and beet, oats and red clover (Lehmann and Joseph, 2015). Legumes grown in soils amended with biochar have increased biomass, grain yield, nodulation, number of pods, flowers, and dry weight of grain (Rondon *et al*.,2007; Güereña *et al*., 2015; Shamim *et al*., 2015; Poormansour and Razzaghi, 2016;Castro *et al* ., 2018). Increased productivity of legumes in biochar amended soils is attributed to increased soil pH, availability of macro and micronutrients, increased biological nitrogen fixation and improved water holding capacity (Oram *et al*., 2014; van Zwieten *et al*., 2015; Poormansour and Razzaghi, 2016). Additionally, the effect of biochar on crop productivity can be enhanced when biochar is combined with a fertilizer (Castro *et al.*, 2018).

Compost is an organic fertilizer which gradually releases nutrients required for the plant growt (Duong, 2013; Eboibi *et al*., 2018; Kawaka *et al*., 2018). Increased girth, number of leaves, branches, flowers, total fresh weight, dry weight and yield in compost amended soils would be attributed to direct and indirect effects of compost (Duong, 2013; Eboibi *et al*., 2018). Indirect effects are linked to reduced acidity, reduced aluminium toxicity, increased microbial activity, soil structure, nutrient availability and water retention (Kawaka *et al*., 2018).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of study area

The study was conducted during the short rains of 2018 and long rains of 2019 at Kapkerer, Kiptaruswo and Koibem, in Nandi South sub-county, whose agro-ecological conditions are Lower midland (LM1-3), Upper midland (UM2-3) and Upper midland- UM1 respectively (Jaetzold and Schmidt, 2007). All the sites are located at latitude 0˚ N and at longitude 34.7833˚E, 34.5602˚ E and 34.9667˚E respectively (Mutai *et al*., 2019). The rainfall pattern in each site is bimodal occurring in January to August (long rains) and from September to December (short rains), the key season for growing beans (Mutai *et al*., 2019). The annual rainfall among the sites range from 1800mm to 2146 mm. An average of 386 mm and 436mm of rainfall was recorded during the short rains of 2018 and long rains of 2019 (Appendix 1). The sites have a mean annual temperature of 21^{o}C with Kapkerer, Kiptaruswo and Koibem having an annual temperature of 21^{o}C, 20^{o}C and 18^{o}C (Odundo *et al*., 2014). Soils in Kapkerer and Kiptaruswo belong to class ferralo-orthic acrisols whereas those in Koibem are humic acrisols (Odundo *et al*., 2014).

3.2 Production of biochar

Biochar was produced from sugarcane bagasse sourced from Kibos Sugar Factory. The bagasse was sun-dried and pyrolyzed in a Top lift up draft combustion stove (TLUD) in an anaerobic environment for two to three hours at temperatures between 300^{0}C to 600^{0}C (Swaminathan and Amupolo, 2014). Sun-dried sugarcane bagasse was stacked into the TLUD- stove and lit with aid of a paper (Manickam *et al*., 2015). A lid was place once the bagasse caught fire and the stove was monitored every 10 to 15 minutes to avoid complete combustion into ash. Once the charred product was removed, it was sprinkled with water to remove excess heat thus cooling it off, bulked and stored in sacks. A sample of one kilogram of the charred product was collected and its pH, nutrient content, total organic carbon and C: N ratio were analyzed at Kenya Agricultural and Livestock Research Organization- National Agricultural Research Laboratories (KALRO-NARL) using procedures described by Okalebo *et al*. (2002).

3.3 Production of compost

Compost was prepared under a shaded area in a 5 m by 2.5 m plot in which layers of sticks and twigs, dry banana leaves, water, bio stimulant, fresh leaves of *Tithonia diversifolia*, cow manure and soil were repeatedly staked to a height of 2 meters. Approximate amounts of cow manure, dry matter and green matter were 1.8 tonnes, 200 kg and 300 kg respectively. The dry banana leaves and fresh plant material were cut into pieces of 10-15 cm and 10 litres of water and 200 ml of the bio-stimulant sprinkled during layering. The stacked compost was covered with a mixture of both fresh and dry banana leaves to prevent it from overheating and drying (Pamela *et al.*, 2018). Biodegradation of compost was monitored by two diagonally placed sticks at the middle of the heap (Pamela *et al.*, 2018). Mixing of the stacked materials after 28 days and 90 days ensured that the compost was homogeneous. A sample of compost weighing one kilogram was collected and analyzed on its pH, macro and micronutrients, total organic carbon and C: N ratio using procedures described by Okalebo *et al*. (2002).

3.4 Experiment design and soil amendments

The field experiment was carried out on five farms per site, whose soil pH was less than 5.5. The farms were chosen based on previous soil analysis for their pH, soil nutrient content and soil texture at Kenya Agricultural and Livestock Research Organization, Kibos. The farm's soil pH was verified prior to selection by use of a portable-handheld ATC soil pH meter. The treatments used were biochar, compost, lime, DAP and their combinations as shown in table 3.1. The treatments were randomly assigned and incorporated into sixteen plots of 9 m^2 which were separated by one meter distances and surrounded by a one meter guard row.

The experiment was arranged in a randomized complete block design with five replications per site and carried out in the short rains of 2018 and a repeat in the long rains of 2019. GLP 2 (Rosecoco) was planted at inter and intra-row spacing's of 50 cm by 10 cm respectively. About 150 g of biochar and 300 g of compost were applied into the furrows while 1.8 kg of lime was broadcasted and thoroughly mixed with the soil. Weeding was carried out at the first and third week after emergence. Data was collected on emergence, plant stand, incidences of bean root rot and stem maggot, plant mortality yield and yield components (pods per plant, seed per pod biomass and grain yield).

Table 3.1: Soil amendments used during the experiment

Soil amendments	Rates	Soil amendments	Rates
Non-amended	-	Lime and DAP	2t/ha+67kg/ha
Biochar	1t/ha	Lime and compost	2t/ha+2t/ha
DAP	67kg/ha	Compost and DAP	2t/ha+67kg/ha
Compost	2t/ha	Biochar + compost +lime	2t/ha+2t/ha +2t/ha
Lime	2t/ha	Biochar + compost + DAP	1t/ha+2t/ha+67kg/ha
Biochar and lime	2t/ha+2t/ha	Biochar+ lime + DAP	1t/ha+2t/ha+67kg/ha
Biochar and compost	2t/ha+2t/ha	Compost +lime+ DAP	2t/ha+2t/ha+67kg/ha
Biochar and DAP	1t/ha+67kg/ha	Biochar + compost +lime + DAP	1t/ha+2t/ha+2t/ha+67kg/ha

3.5 Soil sampling and analysis

In each farm, prior to planting, soils within the 0 to 15 cm depth were sampled in a zigzag pattern. Five samples per farm were, pooled together and a composite sample of 1kg was drawn and placed in khaki bags. The soil samples were analyzed for soil pH, total C, total N, K and P, total Mg and exchangeable cation bases at Kenya Agricultural and Livestock Research Organization- National Agricultural Research Laboratories (KALRO- NARL).

Soil pH was determined by use of a soil-water suspension ratio of 1:2.5 in which 50 milliliter of water was added to 10 ± 0.1 grams of soil. The soil suspension was stirred for 10 minutes, allowed to stand for 30 minutes and stirred for 2 minutes. The pH was measured by immersing a PL-600 lab pH meter into the soil suspension as described by (Okalebo *et al*., 2002). Organic carbon was determined using the Walkley and Black chromic wet oxidation method as described by (Okalebo *et al*., 2002) in which 5 milliliter of potassium dichromate and 7.5 milliliter of dihydrogen sulphate was added to 0.1 to 0.5g of soil. The mixture was heated at 145 to 155^0C for 30 minutes and allowed to cool. The digest was transferred into a 100 ml conical flask and 0.3 milliliter of the indicator solution was added into the conical flask. The resultant digest was stirred and titrated with ferrous ammonium sulphate until a change in color from greenish to brownish was noted.

Total nitrogen was analyzed using wet digestion techniques through the Kjeldahl methodin which two grams of soil was digested with concentrated sulphuric acid in the presence of a catalyst and the resulting solution was subjected to distillation and titration as described by (Pansu and Gautheyrou, 2006). Phosphorus was extracted as described by Okalebo *et al*. (2002) whereby soil samples were treated with a combination of hydrogen peroxide, sulphuric acid, selenium and salicylic acid. The resulting digest was subjected to colorimetric analysis. Potassium was determined by use of a flame photometer as described by Okalebo et al. (2002) in which an excess of 100 milliliter of 1 M NH_4OAc (ammonium acetate) solution was added to five grams of air-dried soil. This was followed by an addition of one ml of 26.8% lanthanum chloride solution. The resulting solution was then sprayed to the flame photometer.

3.6 Determination of the population of root rot pathogens

3.6.1 Isolation of soil borne fungi

Isolations were carried out on soils sampled at six weeks after emergence. Soil borne fungi were isolated by serial dilution as described by Belete *et al*. (2015) in which, one gram of soil was added to nine milliliters of sterile distilled water and thoroughly mixed in a mechanical shaker for 30 minutes. One ml of the soil suspension was serially diluted into a ten-fold dilution of up to 10^3. From the third dilution (10^{-3}), one ml of the soil suspension was drawn using a sterile micropipette and plated into three replicate petridishes containing molten potato dextrose agar (PDA) amended with 50 ppm and 40 ppm of streptomycin and tetracycline to inhibit bacterial growth. The petridishes were incubated at 25^0C for 5 to 7 days.

3.6.2 Identification of bean root rot pathogens

After 5 to 7 days of incubation, the developed fungal colonies were sub-cultured on fresh molten potato dextrose agar through the hyphal tip transfer method for identification of root rot pathogens. Identification of root rot pathogens was done on isolates that were 5 to 12 days old (Ali et al., 2019) by use of cultural and morphological features. Morphological characteristics of the mycelium and spores were examined under magnification of ×100 and ×400 by use of a light microscope.

Identification of the genera *Fusarium* on PDA was based on above and reverse colors of (white, cream, orange, tan, brown, reddish brown, carmine red, pink, purple, blue and blue green) of mycelia (Nelson *et al*., 1983). Suspected isolates belonging to the *Fusarium* genera were further

sub-cultured onto molten Spezieller Nährstoffarmer Agar (SNA) for identification to the species level by use morphological characteristics based on the presence of macro and microconidia, mono and polyphialides, sporodochium and chlamydospores using a manual described by (Leslie and Summerell, 2006 and Nelson *et al*., 1983). Identification of *Pythium* species on PDA was based on presence of submerged, radial or arachnoid patterned or chrysanthemum-patterned colonies. Presence of coenocytic hyaline mycelia, filamentous or sickle-shaped or intercalary sporangium, smooth-walled, globose, elongated or dumbbell shaped oogonium, thick walled oospore were the morphological features used to identify *Pythium* species as described by (Zitnick-Anderson, 2013). Homogenous black cultures were used to identify *Macrophomina* species whereas, isolates belonging to *Rhizoctonia* genera were identified morphologically by presence of monilioid cells, and pale brown, septate, angular branched hyphae with constrictions at the site of branching as described by (Watanabe, 2010).

3.6.3 Quantification of population of root rot pathogens

Isolations of root rot pathogens were carried out on soils sampled at six weeks after emergence (57days after application) by serial dilution as described by Belete *et al*. (2015) in section 3.6.1. After 5 to 7 days of incubation at 25^0C, colonies of root rot pathogens were counted and used to determine the colony forming units per gram (CFU/g) of soil using a formulae described by Chandini and Rajeshwari (2017) shown below:

$$\text{CFU/g} = \frac{\text{Number of colonies} \times \text{volume plated} \times \text{dilution factor}}{\text{weight of dry soil}}$$

3.7 Determination of plant emergence, plant stand and plant mortality

Bean emergence was assessed after seven to eight days after sowing by counting the number emerged plants and expressing it as a percentage of the seeds that were planted in each plot (Mutai *et al*., 2019). While the plant stand count was determined at the second, fourth and sixth week by counting the number of plants standing (healthy and unhealthy) per treatment plot and expressed as a percentage of the seeds planted. Plant mortality was derived from the plant stand by getting the difference between the total number of plants that survived at the second, fourth and sixth week after emergence. This was expressed as a percentage of the survived plants at each week as shown below:

$$\text{Percentage plant mortality (\%)} = \frac{\text{Previous plant stand count} - \text{Current plant stand count}}{\text{Previous plant stand count}} \times 100$$

3.8 Determination of incidences of bean root rot and stem maggot

Root rot incidence was assessed at the second, fourth and sixth week after emergence by counting the number of plants per plots that had expressed above ground symptoms of stunted growth, yellowing, stem base rotting and wilting (Saremi et al., 2011) Root rot incidence was calculated as a percentage using the formulae as described by (Liton et al., 2019):

$$\text{Percentage root rot incidence (\%)} = \frac{\text{Number of plants with root rot symptoms}}{\text{Total number of plants per plot}} \times 100$$

The incidence of bean stem maggot was determined by counting the number of plants exhibiting split stems above the soil line, yellow leaves and unusual thick stems and premature defoliation at the 4^{th} and 6^{th} week after emergence (Ochilo and Nyamasyo, 2011). The incidence of bean stem maggot was expressed as a percentage of the total number of plants per plot (Ochilo and Nyamasyo, 2011).

3.9 Determination of yield and yield components

The number of pods per plant, seeds per pod, biomass and grain yield were the yield and yield components assessed at the final harvest. Additionally, the number of plants per plot were counted and used in determining the grain yield and biomass per plot (Gicharu *et al*., 2013). Grain yield was determined as described by Nassary et al. (2020) in which all the plants within the $9m^2$ experimental plot in each treatment were hand-harvested, threshed, cleaned and weighed. A kilogram of the field-weighed grain was air-dried until a moisture content of 10% was attained. The air-dried grain was weighed and the field grain weight per plot was adjusted. The resulting weight was converted to kg/ha using the formula shown below as described by Liton *et al*. (2019):

$$\text{Yield (kg/ha)} = \frac{\text{Field weight per plot (kg)}}{\text{Area of plot } (m^2)} \times 10000\ m^2$$

From the harvested plants, prior to threshing, ten plants were sampled and used to determine the number of pods per plant and number of seeds per pod as described by Nachigera *et al*. (2016). The ten plant samples (shoot and roots) were weighed and dried at 60^0C for 48 hours until a

constant weight was obtained (Mweetwa *et al*., 2016). The resulting weight per plot was converted to hectare by a formulae described by Lusweti (2009):

Biomass (kg/ha) = (Initial fresh weight– Dry weight)/ Initial fresh weight) × Total number of plants per plot × Harvested area in hectares

3.10 Evaluation of farmers on use of soil amendments in management of soil acidity and bean root rot

3.10.1 Purpose of farmers evaluating soil amendments

In July 2019, after the long-rain field-experiment, farmers were evaluated on observations that they made in different experimental plots applied with biochar, compost, lime, DAP and their combinations. These evaluations were carried out to determine their prior knowledge and use of soil amendments, observations made on growth, performance, pests, diseases and yield of common bean during the course of the experiment, ratings of the amendments and their willingness for adopting the soil amendments.

3.10.2 Selection of farmers and administration of questionnaires

The farmers' selected were among 93 participants of an on-going soil fertility on-farm trial carried out by researchers from Kenya Agricultural and Livestock Research Organization- Kibos and whose farms were used to conduct the current study. On the basis of soil fertility gradients, each study site formed a sampling stratum (Odendo *et al*., 2010) from which 10 farmers were selected. Among the 10 farmers selected, five of farmers' farms were used to conduct field experiments for this study.

One-on-one interviews were conducted using a semi-structured questionnaire (Appendix 2) that was divided into four main sections labelled as Section A to Section D which covered a range of topics. The topics included prior knowledge on use of soil amendments, farmer involvement in the trial, major observations on growth and performance of common bean in the soil amendments, ratings of the soil amendments and willingness of adopting the soil amendments.

3.11 Data analysis

Data on pathogen population was transformed using ($\log_{10}$+1) prior to analysis and data on plant mortality and bean stem maggot incidence was square-root transformed by use of ($\sqrt{x}$+0.5) for normalization. The data was subjected to an analysis of variance (ANOVA) and means were

separated using Fisher's protected LSD at a significance level of 5%. Relationships among soil characteristics, root rot pathogens, root rot incidence and grain yield were assessed by carrying out a correlation analysis. The analysis was carried out using Genstat Inc. 15th edition 9 (Lawes Agricultural Trust, Rothamsted Experimental Station, UK). Qualitative data collected using the questionnaires on use of soil amendments, observations made and willingness to adopt the soil amendments from the interviews was coded and subjected to descriptive analysis using IBM Statistical Package for Social Sciences Version 20 (Buthelezi-Dube *et al*., 2020).

CHAPTER FOUR: RESULTS

4.1 Effect of soil amendments on soil pH and soil macronutrients

Biochar and compost used in the experiment was alkaline with a pH 9.1 and 7.1 respectively. However, biochar had higher carbon, potassium, calcium, magnesium, iron content and carbon to nitrogen (C/N) ratio than compost which had a slightly higher amount of nitrogen (Table 4.1).

Table 4.1: pH and nutrient content of biochar and compost prepared by small holder farmers in Nandi South for soil fertility management in the short rains of 2018

Properties	**Units**	**Biochar**	**Compost**
pH	Units	9.1	7.1
Nitrogen (N)	%	0.4	0.5
Carbon(C)	%	21.8	5.5
C/N ratio	-	62.3	11.6
Phosphorous (P)	%	0.3	0.3
Potassium (K)	%	0.7	0.2
Calcium (Ca)	%	493.0	143.0
Magnesium (Mg)	mg/kg	689.0	250.0
Iron (Fe)	mg/kg	14650.0	2800.0

At Kapkerer, relative to non- amended soils, significant ($P \leq 0.05$) increases on soil pH by 0.6 to 0.8 was noted in soils amended with sole application of lime and combined application of biochar with lime and compost and biochar with lime. Whereas at Koibem, combined application of biochar with lime and compost increased soil pH by 0.9 compared to non-amended soils (Table 4.2). Total organic carbon and phosphorous content significantly ($P \leq 0.05$) differed among sites, whereby soils at Koibem had significantly higher total organic carbon while soils at Kiptaruswo had more phosphorous content. (Tables 4.2). However, interactions between sites and treatments only had a significant on total organic carbon (Table 4.2).

Table 4.2: pH and macronutrient content of soils incorporated with different treatments across Kapkerer, Kiptaruswo and Koibem in Nandi South

Site/Treatments	soil pH	Total organic carbon (%)	Total Nitrogen %	Phosphorous (ppm)	Potassium (me)
Kapkerer					
Biochar	5.4 [bc]	1.7 [a]	0.2 [a]	39.5 [a]	0.4 [a]
Compost	5.7 [abc]	1.6 [a]	0.4 [a]	17.6 [a]	0.4 [a]
DAP	5.5 [abc]	2.1 [a]	0.2 [a]	44.8 [a]	0.4 [a]
Lime	5.8 [ab]	1.8 [a]	0.2 [a]	26.3 [a]	0.4 [a]
Biochar+compost	5.3 [bc]	1.3 [a]	0.2 [a]	27.5 [a]	0.4 [a]
Biochar+lime	5.8 [ab]	2.1 [a]	0.2 [a]	14.9 [a]	0.4 [a]
Biochar+lime + compost	6.0 [a]	2.4 [a]	0.2 [a]	19.5 [a]	0.5 [a]
Non-amended	5.2 [c]	1.7 [a]	0.2 [a]	27.7 [a]	0.5 [a]
Mean	**5.6 [a]**	**1.8 [c]**	**0.2 [a]**	**27.2 [b]**	**0.4 [a]**
LSD-treatment	0.5	1.3	0.3	35.3	0.2
P-value treatment	0.04	0.801	0.66	0.61	0.98
CV%	5.7	44.6	82.2	81.3	34
Kiptaruswo					
Biochar	5.2 [a]	2.3 [a]	0.2 [a]	26.3 [a]	0.5 [a]
Compost	5.4 [a]	3.3 [a]	0.3 [a]	41.4 [a]	0.6 [a]
DAP	5.2 [a]	2.5 [a]	0.3 [a]	46.7 [a]	0.6 [a]
Lime	5.6 [a]	2.7 [a]	0.3 [a]	49.6 [a]	0.6 [a]
Biochar+compost	5.7 [a]	2.8 [a]	0.3 [a]	46.1 [a]	0.7 [a]
Biochar+lime	5.7 [a]	4.0 [a]	0.4 [a]	83.5 [a]	0.8 [a]
Biochar+lime + compost	6.0 [a]	2.7 [a]	0.3 [a]	36.0 [a]	0.8 [a]
Non-amended	5.3 [a]	2.5 [a]	0.2 [a]	40.7 [a]	0.6 [a]
Mean	**5.5 [a]**	**2.9 [b]**	**0.3 [a]**	**46.3 [a]**	**0.6 [a]**
LSD-treatment	1.0	2.0	0.2	63.6	0.7
P-value treatment	0.665	0.729	0.46	0.79	0.97
CV%	11.3	44.8	42.6	40.8	66.1
Koibem					
Biochar	5.3 [b]	4.0 [a]	0.3 [a]	27.1 [a]	0.7 [a]
Compost	5.4 [ab]	3.6 [a]	0.4 [a]	18.6 [a]	0.7 [a]
DAP	5.2 [b]	4.6 [a]	0.4 [a]	30.2 [a]	0.8 [a]
Lime	5.4 [ab]	4.3 [a]	0.4 [a]	28.6 [a]	0.7 [a]
Biochar+compost	5.6 [ab]	4.3 [a]	0.4 [a]	23.7 [a]	1.0 [a]
Biochar+lime	5.5 [ab]	4.8 [a]	0.4 [a]	24.8 [a]	0.6 [a]
Biochar+lime + compost	6.0 [a]	4.4 [a]	0.4 [a]	21.9 [a]	0.8 [a]
Non-amended	5.1 [b]	4.1 [a]	0.4 [a]	25.1 [a]	0.6 [a]
Mean	**5.4 [a]**	**4.3 [a]**	**0.3 [a]**	**25.0 [b]**	**0.7 [a]**
LSD-treatment	0.6	1.2	0.2	14.5	0.4
LSD-site	**0.2**	**0.5**	**0.7**	**14.4**	**0.4**
P-value site*treatment	0.946	<.001	0.073	0.564	0.525
CV%	6.8	17.7	29.1	37.0	36.5

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means in bold were assigned superscripts after comparison with site LSD per parameter per column; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

4.2 Effect of soil amendments on the population of root rot pathogens

The root rot pathogens isolated were *Fusarium oxysporum*, *Fusarium solani* and *Rhizoctonia solani* (Figures 4.1, 4.2 and 4.3).

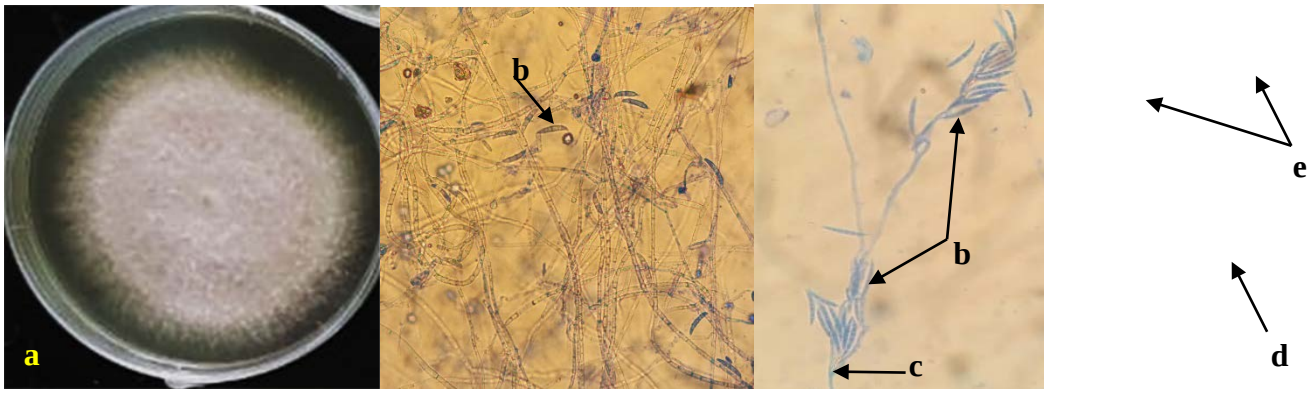

Figure 4.1: Pure culture of *Fusarium oxysporum* (**a**) Morphology features of *F.oxysporum:* Slender, sickle-cell shaped macroconidia with a tapered apical cell and foot shaped-basal cell (**b**), macroconidia borne on a monophiliade (**c**), microconidia borne on false-heads (**d**) intercalary chlamydospores (**e)** Magnification: ×400

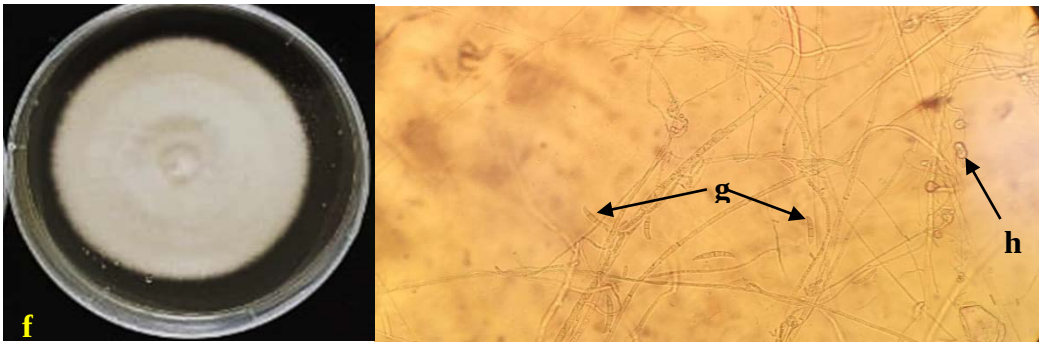

Figure 4.2: Pure culture of *Fusarium solani* (**f**) Morphology features of *F. solani:* wide, straight macroconidia with a blunt apical cell and notched basal cell (**g**), paired chlamydospores (**e)** Magnification: ×400

Figure 4.3: Pure culture of *Rhizoctonia solani* (**i**) Morphology features of *R. solani:* basal constriction at the hyphal branch (**j)** Magnification: ×400

Population of *Rhizoctonia solani* significantly (P≤0.05) differed among the treatments in both seasons and varied in site (Table 4.3). In the short rains of 2018, all the treatments used in Koibem had significantly higher population of *R. solani* compared to non-amended soils while the reverse was noted in the long rains of 2019 (Table 4.3).

Table 4.3: Population (cfu/g×10^3) of *Rhizoctonia solani* in soils incorporated with different soil amendments at three sites in Nandi South in the short rains of 2018 and long rains of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	0.0 [a]	1.2 [a]	4.8 [efg]	11.7 [a]	10.0[a]	3.3[a]
Biochar	1.2 [a]	1.2 [a]	2.4 [fg]	1.7 [cd]	0.0 [c]	0.0[a]
Compost	2.4 [a]	2.4 [a]	0.0 [g]	1.7 [cd]	1.7 [bc]	0.0 [a]
Lime	0.0 [a]	2.4 [a]	12.0 [abc]	5.0 [bcd]	0.0 [c]	5.0 [a]
Lime+ compost	0.0 [a]	0.0 [a]	14.4 [ab]	0.0 [d]	5.0 [abc]	6.7 [a]
Biochar+ compost	2.4 [a]	0.0 [a]	6.0 [def]	10.0 [ab]	5.0 [abc]	3.3 [a]
Biochar+ lime	0.0 [a]	0.0 [a]	3.6 [fg]	1.7 [cd]	1.7 [bc]	0.0 [a]
Biochar+ lime+ compost	0.0 [a]	9.6 [a]	10.8 [bcd]	1.7 [cd]	3.3 [bc]	8.3[a]
DAP	0.0 [a]	1.2 [a]	6.0 [def]	6.7 [abc]	0.0 [c]	3.3 [a]
Biochar +DAP	0.0 [a]	1.2 [a]	9.6 [bcde]	1.7 [cd]	6.7 [ab]	3.3 [a]
Lime+ DAP	2.4 [a]	1.2 [a]	13.2[ab]	3.3 [cd]	0.0 [c]	6.7 [a]
Compost+ DAP	0.0 [a]	1.2 [a]	9.6 [bcde]	0.0 [d]	3.3 [bc]	3.3 [a]
Biochar+ compost+ DAP	3.6 [a]	0.0 [a]	16.8 [a]	3.3[cd]	1.7 [bc]	6.7[a]
Biochar+ lime+ DAP	1.2 [a]	0.0 [a]	3.6 [fg]	0.0[d]	3.3 [bc]	1.7 [a]
Compost+ lime+ DAP	1.2 [a]	0.0 [a]	7.2 [cdef]	1.7 [cd]	3.3 [bc]	5.0[a]
Biochar+ compost+ lime+ DAP	1.2 [a]	3.6 [a]	9.6 [bcde]	1.7 [cd]	1.7 [bc]	5.0[a]
Mean	1.0 [b]	1.6 [b]	8.1 [a]	3.2 [c]	2.9[b]	4.3 [a]
P-value (treatment)	0.224	0.105	≤.001	0.002	0.048	0.144
P-value (site* treatment per season)	<.001			0.011		
CV%	415.3	357.6	98.6	184.8	201.1	167.0

Analysis was carried out on log-transformed values log (x+1) means were separated using Fisher's LSD at (p≤0.05). Treatment means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per season are not significantly different at p≤0.05;CV%=Coefficient of Variation; LSD=Least Significant Difference

Treatments with DAP such as biochar + compost+ DAP had the highest population of 16.8×10^3 cfu/g of *R.solani* than those without DAP with an exception of lime and combinations of lime +compost (Table 4.3). In the long rains of 2019, treatments with DAP in Kapkerer and Kiptaruswo had significantly lower populations of *R.solani* with an exception of DAP and combinations of biochar + DAP. Among treatments without DAP, combined treatments of biochar + compost had higher populations than sole treatments.

Application of biochar+ lime + DAP and compost + DAP in Kapkerer, and application of lime + DAP in Kiptaruswo had the least population of *R. solani* (Table 4.3). Population of *R. solani* significantly ($p\leq0.05$) differed among the sites. Soils of Koibem had significantly higher populations of *R. solani* compared to other sites. Additionally, there was a significant ($p\leq0.05$) interaction of the site and treatments in both seasons (Table 4.3).

The population of *Fusarium oxysporum* significantly ($p\leq0.05$) differed among the treatments in both seasons and this effect varied among the sites (Table 4.4). In the short rains of 2018, all the treatments used in Koibem had significantly higher population of *F. oxysporum* compared to non-amended soils. Treatments combined with DAP had significantly higher populations of *F. oxysporum* with an exception in combinations of lime + DAP, biochar + DAP and biochar + compost + DAP.

Among the treatments, compost and two way combination of compost + DAP had the highest populations of 98.4×10^3 and 103×10^3 cfu/g of *F. oxysporum* respectively (Table 4.4). Population of *F. oxysporum* varied per site whereby, soils from Koibem and Kapkerer had the highest population of *F. oxysporum* in the short rains of 2018 and long rains of 2019 respectively. There were no significant interaction between site and treatment in both seasons (Table 4.4).

Table 4.4: Population (cfu/g×10^3) of *Fusarium oxysporum* in soils incorporated with different soil amendments at three sites in Nandi South in the short rains of 2018 and long rains of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	16.8 [a]	18.0[a]	30.0[e]	48.0[a]	48.3 [a]	21.7 [a]
Biochar	25.2 [a]	21.6[a]	52.8 [bcde]	75.0 [a]	25.0 [a]	18.3 [a]
Compost	40.8 [a]	54.0[a]	98.4 [a]	48.0[a]	25.0 [a]	35.0 [a]
Lime	34.8 [a]	61.2 [a]	51.6 [bcde]	75.0 [a]	15.0 [a]	16.7 [a]
Lime+compost	50.4 [a]	44.4 [a]	52.8 [bcde]	97.0 [a]	40.0 [a]	46.7 [a]
Biochar+compost	34.8 [a]	45.6 [a]	43.2 [cde]	65.0 [a]	10.0 [a]	28.3 [a]
Biochar+lime	36.0 [a]	31.2[a]	55.2[bcde]	120.0 [a]	25.0 [a]	16.7 [a]
Biochar+ lime+compost	34.8 [a]	55.2[a]	42.0 [cde]	38.0[a]	36.7 [a]	28.3 [a]
DAP	28.8 [a]	32.4 [a]	34.8[de]	160.0[a]	30.0 [a]	21.7 [a]
Biochar +DAP	39.6 [a]	34.8[a]	44.4[cde]	48.0[a]	51.7 [a]	35.0 [a]
Lime+DAP	34.8 [a]	46.8 [a]	40.8 [cde]	92.0 [a]	58.3 [a]	65.0 [a]
Compost+DAP	28.8 [a]	14.4[a]	102.0[a]	53.0[a]	33.3 [a]	26.7 [a]
Biochar+compost+DAP	37.2 [a]	50.4 [a]	30.0[e]	78.0 [a]	38.3 [a]	35.0 [a]
Biochar+lime+DAP	44.4 [a]	42.0 [a]	84.0 [ab]	90.0 [a]	16.7 [a]	23.3 [a]
Compost+lime+DAP	30.0 [a]	49.2 [a]	73.2 [abc]	65.0 [a]	33.3 [a]	18.3 [a]
Biochar+compost+ lime+ DAP	27.6 [a]	64.8[a]	69.6 [abc]	72.0 [a]	20.0 [a]	51.7 [a]
Mean	34.1[c]	41.6 [b]	56.6 [a]	76.3 [a]	31.7 [b]	30.5 [b]
P-value (treatment)	0.472	0.096	0.041	0.331	0.898	0.1
P-value (site* treatment per season)	0.507			0.719		
CV%	56.3	54.9	39.1	39.7	69.8	52.9

Analysis was carried out on log-transformed values log (x+1) and means were separated using Fisher's LSD at ($p \leq 0.05$). Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference

There were significant ($P \leq 0.05$) effects of the soil amendments on the population of *Fusarium solani* in both seasons (Table 4.5). However, these effects varied among the three sites in each season. All the treatments used in Koibem in the short rains of 2018 and in Kapkerer and Kiptaruswo during the long rains of 2019 with an exception of biochar in Kiptaruswo, had significantly lower population of *F. solani* compared to non-amended soils. Treatments with DAP had significantly lower populations of *F. solani* in Koibem during the short rains of 2018 and in Kiptaruswo during the long rains of 2019. Among treatments without DAP, biochar and lime had significantly higher population of *F. solani* than combined treatments with an exception of biochar + compost combinations. The sites had a significant ($P \leq 0.05$) effect on the population

of *F. solani* whereby, soils from Kiptaruswo and Kapkerer had the highest population *F. solani* in the short rains of 2018 and long rains of 2019 respectively. In both seasons, significant ($P \leq 0.05$) effects of site by treatment interaction were noted (Table 4.5).

Table 4.5: Population (cfu/g×10^3) of *Fusarium solani* in soils incorporated with different soil amendments at three sites in Nandi South in the short rains of 2018 and long rains of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	1.2 ^{a}	1.2 ^{a}	37.2^{a}	18.3 ^{ab}	6.7 ^{a}	0.0 ^{a}
Biochar	3.6 ^{a}	9.6 ^{a}	13.2 ^{bcd}	8.3 ^{b}	20.0 ^{a}	3.3 ^{a}
Compost	0.0 ^{a}	9.6 ^{a}	2.4^{ef}	5.0 ^{abc}	1.7 ^{a}	1.7 ^{a}
Lime	2.4 ^{a}	1.2 ^{a}	1.2^{ef}	56.7^{ab}	0.0 ^{a}	5.0 ^{a}
Lime+compost	3.6 ^{a}	13.2 ^{a}	13.2 ^{bcd}	5.0 ^{abc}	0.0 ^{a}	1.7 ^{a}
Biochar+compost	0.0 ^{a}	4.8 ^{a}	16.8 ^{b}	1.7 ^{bc}	0.0 ^{a}	3.3 ^{a}
Biochar+lime	4.8 ^{a}	13.2 ^{a}	4.8^{ef}	21.7 ^{ab}	5.0 ^{a}	1.7 ^{a}
Biochar+ lime+compost	2.4 ^{a}	8.4 ^{a}	3.6^{ef}	0.0 ^{c}	0.0 ^{a}	8.3 ^{a}
DAP	2.4 ^{a}	13.2 ^{a}	4.8^{def}	18.3 ^{a}	1.7 ^{a}	3.3 ^{a}
Biochar +DAP	1.2 ^{a}	4.8 ^{a}	2.4^{ef}	6.7 ^{b}	0.0 ^{a}	10.0 ^{a}
Lime+DAP	0.0 ^{a}	4.8 ^{a}	14.4 ^{bc}	0.0 ^{c}	3.3 ^{a}	1.7 ^{a}
Compost+DAP	2.4 ^{a}	15.6 ^{a}	3.6^{ef}	5.0 ^{abc}	0.0 ^{a}	3.3 ^{a}
Biochar+compost+DAP	4.8 ^{a}	4.8 ^{a}	9.6 ^{bcde}	18.3 ^{a}	3.3 ^{a}	0.0 ^{a}
Biochar+lime+DAP	0.0 ^{a}	8.4 ^{a}	6.0^{cde}	8.3 ^{b}	0.0 ^{a}	1.7 ^{a}
Compost+lime+DAP	4.8 ^{a}	16.8 ^{a}	0.0^{f}	0.0 ^{c}	0.0 ^{a}	1.7 ^{a}
Biochar+compost+ lime+ DAP	2.4 ^{a}	9.6 ^{a}	0.0^{f}	3.3 ^{abc}	0.0 ^{a}	21.7 ^{a}
Mean	2.3^{c}	8.7 ^{a}	8.0 ^{b}	11.0 ^{a}	2.6^{b}	4.3 ^{c}
P-value (treatment)	0.426	0.611	<.001	0.047	0.192	0.089
P-value (site* treatment per season)	<.001			0.008		
CV%	293.8	170.9	127.7	164.9	362.1	203.1

Analysis was carried out on log-transformed values log (x+1) and means were separated using Fisher's LSD at ($p \leq 0.05$). Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference

4.3 Effect of soil amendments on bean root rot

4.3.1 Effect of soil amendments on plant emergence

Percentage emergence of common bean significantly ($p \leq 0.05$) differed among the seasons, sites and treatments. (Table 4.6). In both seasons, non-amended plots had significantly higher emergence than amended plots. *Among the treatments, those with DAP had significantly low plant emergence in both seasons.* In the short rains of 2018, significantly low plant emergence of 79.3 to 79.9% was noted in treatments of biochar + compost+ lime + DAP, compost+ lime + DAP and

Table 4.6: Plant emergence (%) of common bean in plots incorporated with different soil amendments at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	Short rains-2018			Long rains-2018		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	90.5 ^{a}	86.9 ^{a}	79.2 ^{a}	60.4 ^{a}	83.0 ^{a}	58.8 ^{abc}
Biochar	90.1 ^{a}	84.7 ^{a}	79.6 ^{a}	56.0 ^{a}	69.6 ^{abc}	39.1 ^{cde}
Compost	89.6 ^{ab}	81.3 ^{a}	77.9 ^{a}	64.3 ^{a}	74.8 ^{ab}	60.5 ^{abc}
Lime	89.5 ^{ab}	79.7 ^{a}	79.5 ^{a}	64.7 ^{a}	80.4 ^{ab}	62.6 ^{ab}
Biochar and lime	89.3 ^{ab}	79.3 ^{a}	78.4 ^{a}	58.1 ^{a}	56.4 ^{cd}	52.8 ^{abc}
Lime and compost	84.0 ^{abcde}	77.2 ^{a}	78.4 ^{a}	55.0 ^{a}	68.1 ^{abc}	57.2 ^{abc}
Biochar and compost	88.5 ^{abc}	78.5 ^{a}	82.8 ^{a}	53.4 ^{a}	74.7 ^{ab}	65.1 ^{a}
Biochar + compost +lime	82.7 ^{bcde}	75.7 ^{a}	75.9 ^{a}	61.5 ^{a}	78.7 ^{ab}	51.8 ^{abcd}
DAP	90.1 ^{a}	82.0 ^{a}	71.6 ^{a}	58.4 ^{a}	72.9 ^{abc}	52.7 ^{abc}
Biochar and DAP	88.1 ^{abc}	78.0 ^{a}	75.2 ^{a}	42.5 ^{a}	49.3 ^{d}	39.1 ^{cde}
Lime and DAP	86.5 ^{abcd}	77.7 ^{a}	79.2 ^{a}	57.2 ^{a}	77.9 ^{ab}	54.4 ^{abc}
Compost and DAP	83.1 ^{bcde}	75.9 ^{a}	79.3 ^{a}	53.1 ^{a}	69.6 ^{abc}	39.4 ^{cde}
Biochar + compost + DAP	82.1 ^{cde}	75.1 ^{a}	71.9 ^{a}	50.6 ^{a}	67.9 ^{abc}	41.4 ^{bcde}
Biochar+ lime + DAP	79.9 ^{de}	74.3 ^{a}	79.7 ^{a}	53.1 ^{a}	77.7 ^{ab}	29.8 ^{de}
Compost +lime+ DAP	79.5 ^{e}	73.3 ^{a}	77.1 ^{a}	71.0 ^{a}	65.1 ^{bcd}	43.4 ^{abcde}
Biochar + compost +lime +DAP	79.3 ^{e}	73.1 ^{a}	81.9 ^{a}	59.7 ^{a}	68.6 ^{abc}	26.7 ^{e}
Mean	85.8 ^{a}	78.3 ^{b}	78.0 ^{b}	57.4 ^{b}	70.9 ^{a}	48.4 ^{c}
LSD (treatment per site)	7.0	11.5	9.4	17.3	17.7	9.4
P-value (treatment)	0.002	0.527	0.615	0.331	0.032	0.023
LSD (site per season)	4.9			6.4		
LSD (site*treatment per season)	9.4			19.4		
CV%	0.9	4.2	5.8	20.5	22.5	5.8

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

biochar + lime + DAP at Kapkerer (Table 4.6) . In the long rains, significantly low emergence of 49% to 65% in Kipatruswo was noted in plots amended with compost+ lime + DAP and biochar + DAP whereas low emergence of 26% to 30% was noted in application of biochar + compost+ lime + DAP and biochar + lime + DAP in Koibem (Table 4.6).

4.3.2 Effect of soil amendments on plant stand count

The effect of the treatments on percentage plant stand count and mortality significantly varied in site and season (Table 4.7).

Table 4.7: Plant stand count (%) of common bean in plots amended with different treatments during the short rains of 2018 and long rains of 2019 at Kapkerer, Kiptaruswo and Koibem in Nandi South

	Short rains-2018			Longrains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	86.0 ^{ab}	72.3 ^{abc}	66.3 ^{bcde}	48.5 ^{abcd}	62.8 ^{a}	51.9 ^{ab}
Biochar	86.0 ^{ab}	74.4 ^{ab}	68.9 ^{abc}	37.9 ^{cdefg}	51.9 ^{a}	36.5 ^{de}
Compost	88.3 ^{a}	72.0 ^{abcd}	68.1 ^{abcd}	42.2 ^{bcdefg}	56.6 ^{a}	54.2 ^{ab}
Lime	84.5 ^{abc}	67.7 ^{abcdef}	68.7 ^{abc}	46.2 ^{abcde}	57.6 ^{a}	59.5 ^{a}
Biochar and compost	87.2 ^{ab}	73.1 ^{abc}	68.9 ^{abc}	50.6 ^{ab}	57.6 ^{a}	57.0 ^{a}
Biochar and lime	84.5 ^{abc}	60.6 ^{f}	60.6 ^{e}	48.8 ^{abc}	50.0 ^{a}	45.0 ^{cde}
Lime and compost	85.2 ^{abc}	65.8 ^{cdef}	65.8 ^{bcde}	44.3 ^{abcdef}	52.0 ^{a}	45.8 ^{bcd}
Biochar + compost +lime	83.8 ^{abc}	69.5 ^{abcde}	67.8 ^{abcd}	56.1 ^{a}	54.5 ^{a}	49.0 ^{abc}
DAP	82.9 ^{bcd}	64.0 ^{def}	61.4 ^{de}	54.2 ^{ab}	54.8 ^{a}	45.5 ^{bcd}
Biochar + DAP	78.6 ^{de}	75.7 ^{a}	64.1 ^{cde}	30.5 ^{g}	45.4 ^{a}	38.4 ^{cde}
Compost + DAP	75.9 ^{e}	71.5 ^{abcde}	66.2 ^{bcde}	36.1 ^{efg}	48.5 ^{a}	37.8 ^{de}
Lime + DAP	77.3 ^{e}	66.8 ^{bcdef}	71.9 ^{ab}	48.3 ^{abcde}	63.7 ^{a}	50.6 ^{ab}
Biochar+ lime + DAP	77.5 ^{e}	67.5 ^{abcdef}	63.9 ^{cde}	31.6 ^{g}	56.6 ^{a}	32.5 ^{e}
Compost +lime+ DAP	77.6 ^{e}	69.6 ^{abcde}	64.0 ^{cde}	51.3 ^{ab}	52.6 ^{a}	45.2 ^{bcd}
Biochar + compost + DAP	80.8 ^{cde}	63.6 ^{ef}	63.5 ^{cde}	33.8 ^{fg}	51.6 ^{a}	35.8 ^{de}
Biochar + compost +lime + DAP	76.3 ^{e}	65.0 ^{cdef}	74.4 ^{a}	36.4 ^{defg}	54.2 ^{a}	28.3 ^{e}
Mean	82.1 ^{a}	68.9 ^{b}	66.5 ^{c}	43.5 ^{b}	54.4 ^{b}	44.6 ^{b}
P-value (treatment per site)	<.001	0.012	0.009	<.001	0.078	<.001
LSD (treatment per site)	5.1	8.3	7.0	12.3	10.6	10.9
LSD (site per season)	1.9			4.2		
LSD (site*treatment per season)	7.7			16.3		
C.V (%)	2.4	13.5	13.9	41.7	39	30.4

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

This effect was mostly noted in Kapkerer and Koibem. The percentage plant stand count of common bean was significantly ($p \leq 0.05$) lower in amended plots compared to non-amended plots with an exception in Koibem during the short rains of 2018 (Table 4.7). Among the treatments, the percentage plant stand count was significantly lower in treatments containing DAP compared to non-amended especially in Kapkerer whereby, application of biochar +compost + lime+ DAP and biochar + DAP significantly reduced the plant stand count by 13% and 33% respectively in the short rains of 2018 and long rains of 2019.

Percentage plant stand of common bean significantly differed among the treatments in both seasons. However, this effect varied by week in each site (Tables 4.8 and 4.9). Among the treatments, application of biochar+ compost+ lime + DAP and lime + DAP had significantly low plant stand of 78.4% and 79.2% at two weeks after emergence whereas application of biochar+ lime + DAP and compost + DAP had lower percentage plant stand of 75.7% and 75.2% at four weeks after emergence compared to non-amended plots in Kapkerer (Table 4.8).

In the long rain season of 2019, application of biochar + DAP and biochar+ lime + DAP had significantly lower plant stand of 23.6% and 27.3% at the second week after emergence whereas application of biochar+ compost+ lime+ DAP and biochar+ lime + DAP had the least percentage plant stand of 25.3% and 26.7% at the fourth week after emergence compared to non-amended plots in Koibem. At the sixth week after emergence, application of biochar + compost+ lime and DAP and compost + DAP had significantly low plant stand of 35.9 and 39.3%. Although combined application of biochar+ compost+ lime + DAP had the least plant stand it was increasing from the second week to the sixth week after emergence (Table 4.9).

The percentage plant stand of common bean significantly ($p \leq 0.05$) differed among the sites whereby high percentage plant stand was noted in Kapkerer and Kiptaruswo in the short and long rain respectively (Tables 4.8 and 4.9). However, there was no significant ($p \leq 0.05$) interaction between the sites and treatments.

Table 4.8: Plant stand count (%) at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the short rain growing season of 2018

	2 weeks			4weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	89.2 ^{abc}	75.6 ^{a}	75.3 ^{a}	87.1 ^{ab}	71.5 ^{a}	64.4 ^{a}	81.9 ^{a}	69.7 ^{a}	59.1 ^{a}
Biochar	88.0 ^{abcd}	80.7^{a}	74.7 ^{a}	87.2 ^{ab}	73.2^{a}	67.9 ^{a}	82.9 ^{a}	69.5 ^{a}	64.1 ^{a}
Compost	92.0 ^{a}	79.9 ^{a}	74.7 ^{a}	90.3^{a}	74.8 ^{a}	70.9 ^{a}	82.7 ^{a}	61.5 ^{a}	58.8 ^{a}
Lime	86.8 ^{abcde}	70.1 ^{a}	76.4 ^{a}	85.9 ^{abc}	66.7 ^{a}	64.4 ^{a}	80.9 ^{a}	66.3 ^{a}	65.3 ^{a}
Biochar+lime	88.7 ^{abc}	68.3 ^{a}	67.7 ^{a}	81.9 ^{abcd}	59.3 ^{a}	58.7 ^{a}	82.9 ^{a}	54.1 ^{a}	55.3 ^{a}
Biochar+compost	90.4 ^{ab}	79.7 ^{a}	74.1 ^{a}	87.1 ^{ab}	75.6^{a}	69.9 ^{a}	84.3 ^{a}	63.9 ^{a}	62.7 ^{a}
Lime+compost	88.9 ^{abc}	74.3^{a}	72.5 ^{a}	87.3 ^{ab}	65.8^{a}	63.9 ^{a}	79.2 ^{a}	57.3 ^{a}	60.9 ^{a}
Biochar+lime+compost	84.5^{bcdef}	73.2 ^{a}	72.3 ^{a}	84.5^{abcd}	71.3 ^{a}	67.1 ^{a}	82.4 ^{a}	64.0 ^{a}	64.0 ^{a}
DAP	86.7 ^{abcde}	67.5 ^{a}	70.0 ^{a}	80.9 ^{abcd}	64.0 ^{a}	59.7 ^{a}	81.1 ^{a}	60.0 ^{a}	54.5 ^{a}
Biochar+DAP	82.4 ^{cdef}	80.1 ^{a}	68.1 ^{a}	76.8 ^{cd}	71.1 ^{a}	64.8 ^{a}	76.7 ^{a}	75.9 ^{a}	59.3 ^{a}
Lime+DAP	79.2^{f}	73.9 ^{a}	74.0 ^{a}	78.1^{bcd}	68.1 ^{a}	74.7 ^{a}	74.5 ^{a}	58.3 ^{a}	67.1 ^{a}
Compost+DAP	79.6^{ef}	73.3 ^{a}	74.8 ^{a}	75.2 ^{d}	71.9 ^{a}	63.1 ^{a}	72.9 ^{a}	69.3 ^{a}	60.8 ^{a}
Biochar+lime+DAP	81.2^{def}	73.5 ^{a}	74.0 ^{a}	75.7^{d}	65.7 ^{a}	64.9 ^{a}	75.5 ^{a}	63.3 ^{a}	52.8 ^{a}
Biochar+compost+ DAP	82.5^{cdef}	72.5 ^{a}	67.7 ^{a}	82.5 ^{abcd}	61.9 ^{a}	59.1 ^{a}	77.2 ^{a}	56.3 ^{a}	63.6 ^{a}
Compost+lime+DAP	82.0 ^{cdef}	71.5 ^{a}	71.3 ^{a}	76.3 ^{cd}	67.7 ^{a}	62.4 ^{a}	74.4 ^{a}	69.7 ^{a}	58.1 ^{a}
Biochar+compost+lime+DAP	78.4^{f}	68.9 ^{a}	80.8 ^{a}	76.9^{cd}	65.1 ^{a}	73.3 ^{a}	73.9 ^{a}	61.1 ^{a}	69.2 ^{a}
Mean	85.0 ^{a}	65.2 ^{c}	73.0 ^{b}	82.1 ^{a}	68.4 ^{b}	65.6 ^{b}	78.9 ^{a}	63.8 ^{b}	61.0 ^{b}
LSD (treatment per site)	7.4	13.6	9.7	10.1	13.3	13.5	7.7	13.6	11.6
P-value (treatment per site)	0.003	0.67	0.433	0.03	0.48	0.451	0.104	0.295	0.276
LSD (site per WAE)	2.8			3.5			5.7		
LSD (site*treatment per WAE)	10.4			12.2			16.9		
P-value (site*treatment per WAE)	0.379			0.713			0.100		
CV%	2.1	8.6	8.3	4.6	16.0	16.3	2.2	18.6	19.5

Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Site means followed by the same letter(s) in each row per week are not significantly different at p≤0.05; CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05) WAE: week after emergence

Table 4.9: Plant stand count (%) of common bean at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the long rain growing season of 2019

	2 weeks			4weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	50.4 [a]	68.9 [a]	53.3 [abcd]	51.3 [a]	71.4 [a]	51.1 [ab]	43.8 [abcd]	48.1 [a]	51.3 [ab]
Biochar	42.5 [a]	63.6 [a]	33.1 [defg]	41.5 [a]	56.9 [a]	35.3 [bcd]	29.8 [cd]	35.1 [a]	41.2 [bc]
Compost	48.5 [a]	64.6 [a]	61.4 [a]	43.3 [a]	61.8 [a]	53.9 [ab]	34.7 [bcd]	43.3 [a]	58.9 [a]
Lime	51.5 [a]	67.8 [a]	58.7 [ab]	49.5 [a]	65.6 [a]	62.7 [a]	37.5 [bcd]	39.4 [a]	57.1 [a]
Biochar+compost	50.9 [a]	67.1 [a]	53.5 [abc]	47.5 [a]	66.5 [a]	59.9 [a]	53.5 [ab]	39.2 [a]	57.5 [a]
Biochar+lime	42.6 [a]	63.8 [a]	43.9 [abcdefg]	48.8 [a]	54.1 [a]	43.3 [abcd]	55.0 [ab]	32.1 [a]	47.9 [abc]
Lime+ compost	52.5 [a]	61.9 [a]	48.4 [abcde]	44.8 [a]	58.4 [a]	45.6 [abcd]	35.7 [bcd]	35.7 [a]	43.5 [bc]
Biochar+lime+ compost	52.4 [a]	63.9 [a]	50.1 [abcde]	57.3 [a]	63.3 [a]	48.7 [abc]	58.7 [a]	36.2 [a]	48.1 [abc]
DAP	52.8 [a]	61.8 [a]	42.4 [abcdefg]	61.8 [a]	64.3 [a]	47.1 [abcd]	48.0 [ab]	38.3 [a]	46.9 [abc]
Biochar+DAP	33.1 [a]	55.6 [a]	36.1 [cdefg]	31.5 [a]	52.3 [a]	37.5 [bcd]	26.8 [d]	28.1 [a]	41.7 [bc]
Lime+ DAP	44.1 [a]	70.4 [a]	48.1 [abcde]	45.8 [a]	76.2 [a]	56.5 [ab]	54.8 [ab]	44.6 [a]	47.2 [abc]
Compost+ DAP	39.0 [a]	58.2 [a]	39.6 [bcdefg]	34.0 [a]	57.3 [a]	34.4 [bcd]	35.2 [bcd]	29.9 [a]	39.3 [bc]
Biochar+lime+ DAP	34.4 [a]	66.4 [a]	27.3 [fg]	36.3 [a]	64.6 [a]	26.7 [cd]	24.0 [d]	38.7 [a]	43.5 [bc]
Compost+ lime+ DAP	55.7 [a]	56.6 [a]	45.4 [abcdef]	50.3 [a]	62.3 [a]	43.6 [abcd]	47.7 [abc]	39.0 [a]	46.5 [abc]
Biochar+compost+DAP	36.2 [a]	58.4 [a]	32.4 [efg]	39.2 [a]	59.9 [a]	34.4 [bcd]	25.2 [d]	36.5 [a]	40.5 [bc]
Biochar+compost+lime+DAP	35.4 [a]	64.5 [a]	23.6 [g]	37.7 [a]	62.2 [a]	25.3 [d]	36.0 [bcd]	35.8 [a]	35.9 [c]
Site mean per week	45.1 [b]	63.3 [a]	42.8 [b]	45.0 [b]	62.3 [a]	44.1 [b]	40.4 [b]	37.5 [b]	46.7 [a]
LSD (treatment per site)	17.0	15.2	20.4	19.9	19.0	22.3	20.6	14.9	13.5
P-value (treatment per site)	0.1	0.81	0.037	0.184	0.649	0.027	0.01	0.295	0.03
LSD (site per WAE)	5.7			8.2			5.7		
LSD (site*treatment per WAE)	17.5			20.2			16.0		
P-value (site*treatment per WAE)	0.809			0.849			0.233		
CV%	40.2	35.4	29.4	46.3	46.4	38.4	40.5	35.1	24.4

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per week are not significantly different at $p \leq 0.05$;CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$); WAE: week after emergence

4.3.3 Effect of soil amendments on plant mortality

Significant ($p \leq 0.05$) effects of the treatments on percentage plant mortality varied per treatment in each season and were only noted in Kapkerer. In the short rains, amended plots had significantly higher plant mortality compared to non-amended plots. Additionally, plots amended with compost or DAP had significantly higher plant mortality whereby, application of biochar + compost +DAP and compost + DAP significantly increased bean mortality by 48% and 43% with an exception of biochar + lime+ compost. But in the long rains, plots amended with biochar + lime + compost and biochar + compost significantly reduced plant mortality by 59% and 43% respectively (Table 4.10).

Table 4.10: Plant mortality (%) of common bean in plots with different treatments during the short rains of 2018 and long rains of 2019 at Kapkerer, Kiptaruswo and Koibem in Nandi South

	Short rains-2018			Longrains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	4.5^{de}	8.2^{a}	12.9^{a}	20.5^{abc}	16.1^{a}	20.9^{a}
Biochar	6.0^{bcde}	11.4^{a}	7.5^{a}	19.6^{abc}	14.7^{a}	21.8^{a}
Compost	5.8^{bcde}	10.3^{a}	9.7^{a}	31.0^{a}	15.7^{a}	14.5^{a}
Lime	6.2^{bcde}	11.4^{a}	8.5^{a}	24.8^{ab}	18.0^{a}	15.6^{a}
Biochar and compost	4.0^{de}	12.5^{a}	9.8^{a}	11.7^{cd}	17.1^{a}	16.2^{a}
Biochar and lime	6.1^{bcde}	14.8^{a}	8.6^{a}	15.9^{bcd}	19.1^{a}	10.0^{a}
Lime and compost	5.6^{bcde}	11.9^{a}	8.0^{a}	22.3^{abc}	22.9^{a}	24.9^{a}
Biochar + compost +lime	10.3^{a}	10.9^{a}	7.4^{a}	8.5^{d}	26.1^{a}	14.4^{a}
DAP	7.0^{abcd}	13.1^{a}	10.7^{a}	23.6^{abc}	18.1^{a}	18.4^{a}
Biochar + DAP	7.1^{abcd}	10.7^{a}	9.0^{a}	25.8^{ab}	18.2^{a}	15.5^{a}
Compost + DAP	7.9^{abc}	9.1^{a}	8.2^{a}	19.6^{abc}	23.1^{a}	12.8^{a}
Lime + DAP	6.6^{abcde}	9.4^{a}	9.0^{a}	14.5^{bcd}	16.3^{a}	13.0^{a}
Biochar+ lime + DAP	6.3^{bcde}	10.5^{a}	12.2^{a}	31.6^{a}	22.4^{a}	10.6^{a}
Compost +lime+ DAP	4.8^{cde}	12.0^{a}	10.8^{a}	22.9^{abc}	19.7^{a}	8.3^{a}
Biochar + compost + DAP	8.7^{ab}	11.2^{a}	7.5^{a}	24.1^{ab}	16.2^{a}	15.1^{a}
Biochar + compost +lime + DAP	3.8^{e}	11.7^{a}	5.4^{a}	22.2^{abc}	20.0^{a}	19.6^{a}
Mean	6.3^{b}	38.0^{a}	3.0^{c}	20.7^{a}	18.0^{a}	14.7^{b}
P-value (treatment per site)	0.022	0.942	0.551	0.031	0.843	0.07
P-value (site per season)	<0.001			0.006		
P-value (site*treatment per season)	0.536			0.776		
CV%	17.1	24.4	23.6	15.1	17.6	12.0

Analysis on plant mortality was carried out on square-root transformed ($\sqrt{x+0.5}$) data. Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row are not significantly different at $p \leq 0.05$ CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

Percentage mortality of common bean significantly ($P \leq 0.05$) differed among the treatments on the second week after emergence during the short rains of 2018 and at the sixth week in both seasons (Tables 4.11 and 4.12). However, this effect varied by week in each site

In the short rains of 2018, at two weeks after emergence, plots with combined treatments had significantly higher plant mortality compared to non-amended plots. Treatments with DAP had significantly higher plant mortality in Kapkerer compared to other non-DAP treatments which had higher plant mortality in Kiptaruswo. Among these, application of lime + DAP at Kapkerer and combined application of biochar +compost +lime+ DAP at Kiptaruswo significantly increased bean mortality by more than 100% compared to non-amended plots. However, combined application of biochar + lime+ compost had significantly high plant mortality in both Kapkerer and Kiptaruswo. Similarly, in Kapkerer at the sixth week after emergence, combined application of biochar + compost + DAP significantly increased bean mortality by 100% compared to non-amended plots (Table 4.11).

However in the long rains of 2019, at the sixth week after emergence, combined treatments had significantly lower plant mortality than non-amended plots. Among the combined treatments lower percentages of plant mortality were noted in treatments with DAP. Application of biochar + lime, biochar + compost + DAP, biochar + lime + DAP and compost +lime +DAP significantly reduced bean mortality by 90%, 84%, 77% and 68% compared to non-amended plots at Kapkerer. (Table 4.12).

Mortality of common bean significantly ($P \leq 0.05$) differed among the sites in the long rains of 2019 whereby, the highest mortality was noted in Kapkerer and Kiptaruswo at the second and sixth week after emergence respectively (Table 4.12). On the other hand, significant ($P \leq 0.05$) effects of site by treatment interaction were noted at the second week after emergence in the short rains of 2018 and at the second and sixth week after emergence in the long rains of 2019 (Tables 4.11 and 4.12).

Table 4.11: Plant mortality (%) of common bean at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the short rain growing season of 2018

	2 weeks			4 weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	5.0 ^{def}	8.3 ^{abcd}	11.2 ^{a}	6.0 ^{a}	4.8 ^{a}	13.4 ^{a}	8.0 ^{bcdef}	5.3 ^{a}	13.5 ^{a}
Biochar	8.6 ^{cdef}	5.0 ^{bcd}	9.0 ^{a}	5.3 ^{a}	9.3 ^{a}	6.6 ^{a}	10.9 ^{abcdef}	13.7 ^{a}	5.4 ^{a}
Compost	3.4 ^{f}	6.4 ^{bcd}	5.5 ^{a}	8.4 ^{a}	5.7 ^{a}	4.9 ^{a}	14.4 ^{ab}	13.3 ^{a}	21.6 ^{a}
Lime	7.1 ^{cdef}	10.3 ^{abc}	5.5 ^{a}	7.7 ^{a}	5.9 ^{a}	11.5 ^{a}	12.8 ^{abcd}	9.4 ^{a}	7.4 ^{a}
Biochar and lime	10.9 ^{abc}	14.1 ^{ab}	11.7 ^{a}	8.9 ^{a}	15.3 ^{a}	7.0 ^{a}	4.8 ^{ef}	8.5 ^{a}	5.4 ^{a}
Lime and compost	7.3 ^{cdef}	7.7 ^{abcd}	9.7 ^{a}	5.1 ^{a}	9.0 ^{a}	7.4 ^{a}	11.5 ^{abcde}	11.0 ^{a}	5.2 ^{a}
Biochar and compost	4.2 ^{ef}	14.8 ^{ab}	9.9 ^{a}	8.5 ^{a}	6.3 ^{a}	6.9 ^{a}	6.6 ^{cdef}	6.5 ^{a}	10.3 ^{a}
Biochar + compost +lime	15.0 ^{ab}	17.7 ^{a}	7.1 ^{a}	12.6 ^{a}	4.1 ^{a}	5.8 ^{a}	12.3 ^{abcd}	7.4 ^{a}	7.2 ^{a}
DAP	9.9 ^{bcd}	10.5 ^{abc}	7.1 ^{a}	11.2	6.4 ^{a}	14.8 ^{a}	9.3 ^{abcdef}	12.1 ^{a}	8.9 ^{a}
Biochar and DAP	9.4 ^{bcd}	1.9 ^{d}	10.3 ^{a}	11.0 ^{a}	9.6 ^{a}	3.5 ^{a}	6.1 ^{cdef}	12.0 ^{a}	11.3 ^{a}
Biochar + compost + DAP	8.9 ^{bcde}	3.2 ^{cd}	7.0 ^{a}	7.2 ^{a}	13.0 ^{a}	8.5 ^{a}	16.0 ^{a}	10.0 ^{a}	5.4 ^{a}
Biochar + compost +lime + DAP	4.4 ^{ef}	17.8 ^{a}	2.8 ^{a}	5.2 ^{a}	4.7 ^{a}	5.5 ^{a}	5.8 ^{def}	4.8 ^{a}	6.2 ^{a}
Biochar+ lime + DAP	10.6 ^{abc}	5.6 ^{bcd}	9.9 ^{a}	8.0 ^{a}	8.0 ^{a}	11.3 ^{a}	7.6 ^{bcdef}	10.5 ^{a}	13.3 ^{a}
Compost +lime+ DAP	5.3 ^{def}	9.9 ^{abc}	8.4 ^{a}	8.7 ^{a}	7.6 ^{a}	12.0 ^{a}	5.2 ^{def}	7.2 ^{a}	10.8 ^{a}
Compost and DAP	10.8 ^{abc}	6.9 ^{abcd}	8.1 ^{a}	5.8 ^{a}	7.7 ^{a}	8.7 ^{a}	14.0 ^{abc}	5.2 ^{a}	5.4 ^{a}
Lime and DAP	17.1 ^{a}	2.5 ^{cd}	11.9 ^{a}	5.5 ^{a}	9.1 ^{a}	1.5 ^{a}	4.1 ^{f}	10.4 ^{a}	13.4 ^{a}
Mean	8.6 ^{a}	8.9 ^{a}	8.4 ^{a}	7.8 ^{a}	7.9 ^{a}	8.1 ^{a}	9.3 ^{a}	9.2 ^{a}	9.4 ^{a}
P-value (treatment per site)	≤0.01	0.026	0.381	0.528	0.505	0.28	0.032	0.898	0.358
P-value (site*treatment per WAE)	<0.001			0.344			0.477		
CV%	16.1	18.8	14.6	24.6	33.7	34.5	18.4	31.6	25.7

Analysis was carried out on square-root transformed to ($\sqrt{x}$+0.5) Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per week are not significantly different at p≤0.05CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05); WAE: week after emergence

Table 4.12: Plant mortality (%) of common bean at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the long rain growing season of 2019

	2 weeks			4 weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	7.1 [a]	18.8 [a]	25.4 [a]	14.3 [a]	10.1 [a]	15.2 [a]	31.6 [a]	14.6 [a]	30.6 [abc]
Biochar	13.6 [a]	6.2 [a]	36.2 [a]	13.6 [a]	22.4 [a]	5.7 [a]	22.5 [a]	13.7 [a]	44.1 [a]
Compost	21.8 [a]	12.9 [a]	11.1 [a]	22.8 [a]	5.6 [a]	18.2 [a]	27.6 [a]	11.5 [a]	12.5 [efgh]
Lime	18.2 [a]	13.9 [a]	10.5 [a]	13.9 [a]	18.6 [a]	17.7 [a]	27.8 [a]	17.8 [a]	28.7 [abcd]
Biochar and lime	15.6 [a]	10.6 [a]	17.2 [a]	13.1 [a]	19.3 [a]	14.3 [a]	8.1 [a]	21.2 [a]	3.2 [h]
Lime and compost	14.2 [a]	20.3 [a]	13.6 [a]	21.2 [a]	19.4 [a]	24.6 [a]	15.5 [a]	19.1 [a]	38.5 [ab]
Biochar and compost	6.6 [a]	8.9 [a]	21.4 [a]	15.1 [a]	11.8 [a]	10.9 [a]	8.0 [a]	26.4 [a]	19.9 [cdef]
Biochar + compost +lime	7.7 [a]	24.4 [a]	11.5 [a]	5.1 [a]	18.5 [a]	15.7 [a]	3.5 [a]	22.7 [a]	19.4 [cdef]
DAP	14.6 [a]	16.1 [a]	17.6 [a]	14.2 [a]	11.5 [a]	18.6 [a]	30.2 [a]	22.8 [a]	19.8 [cdef]
Biochar and DAP	19.4 [a]	11.8 [a]	12.0 [a]	13.6 [a]	19.0 [a]	13.4 [a]	26.3 [a]	19.2 [a]	30.2 [abcd]
Biochar + compost + DAP	17.4 [a]	15.7 [a]	21.1 [a]	11.0 [a]	10.6 [a]	19.7 [a]	34.6 [a]	17.2 [a]	5.0 [gh]
Biochar + compost +lime + DAP	25.4 [a]	8.3 [a]	27.5 [a]	13.0 [a]	27.3 [a]	28.0 [a]	28.3 [a]	20.0 [a]	14.4 [defg]
Biochar+ lime + DAP	19.0 [a]	23.8 [a]	12.3 [a]	36.5 [a]	21.4 [a]	17.6 [a]	26.3 [a]	18.7 [a]	7.0 [gh]
Compost +lime+ DAP	27.5 [a]	20.0 [a]	2.9 [a]	18.8 [a]	25.4 [a]	16.0 [a]	8.2 [a]	18.9 [a]	9.8 [fgh]
Compost and DAP	15.1 [a]	22.8 [a]	5.6 [a]	22.5 [a]	18.9 [a]	20.6 [a]	15.0 [a]	24.7 [a]	24.0 [bcde]
Lime and DAP	6.9 [a]	13.8 [a]	10.6 [a]	17.7 [a]	7.1 [a]	7.2 [a]	15.3 [a]	21.3 [a]	28.7 [abcd]
Mean	27.9 [a]	9.3 [c]	14.7 [b]	19.7 [a]	12.7 [c]	18.1 [b]	14.6 [b]	35.8 [a]	13.2 [b]
P-value (treatment per site)	0.419	0.199	0.112	0.058	0.766 [ns]	0.491	0.081	0.627	<.001
P-value (site*treatment per WAE)	0.006			0.822			<0.001		
CV%	26.0	34.0	17.4	24.1	45.4	17.6	31.8	17.0	23.6

Analysis was carried out on square-root transformed to (√x+0.5) Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per week are not significantly different at p≤0.05CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05); WAE: week after emergence

4.3.4 Effect of soil amendments on root rot and stem maggot incidences of common bean

Percentage root rot incidence significantly ($p \leq 0.05$) varied per treatment in each season and was only noted in Kapkerer during the long rains of 2019. The treatments had no significant effect of on incidence of bean stem maggot. (Table 4). The percentage root rot incidence was significantly lower in amended plots, compared to non-amended plots. This effect was noted in treatments were combined. Sole application of biochar had significantly ($P \leq 0.05$) higher root rot incidence compared to combined treatments with an exception of combinations of lime + compost, biochar + DAP and compost +lime+ DAP

Table 4.13: Root rot incidence (%) of common bean in soils amended with different treatments during the short rains of 2018 and long rains of 2019 at three sites in Nandi South

	Short-rains-2018			Longrains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	16.9 [a]	13.0 [a]	8.8 [a]	14.6 [abc]	11.3 [a]	7.7 [a]
Biochar	13.4 [a]	12.8 [a]	9.7 [a]	20.3 [a]	7.8 [a]	6.7 [a]
Compost	10.6 [a]	10.5 [a]	10.7 [a]	12.6 [bcd]	15.2 [a]	8.5 [a]
Lime	11.3 [a]	11.8 [a]	8.9 [a]	13.9 [abc]	13.8 [a]	7.2 [a]
Biochar + compost	10.6 [a]	12.8 [a]	10.3 [a]	8.2 [cd]	24.6 [a]	7.3 [a]
Biochar + lime	10.6 [a]	10.8 [a]	10.9 [a]	6.4 [d]	15.5 [a]	9.9 [a]
Lime + compost	8.9 [a]	13.2 [a]	10.5 [a]	13.8 [abc]	9.9 [a]	11.1 [a]
Biochar + compost +lime	9.1 [a]	13.1 [a]	10.2 [a]	10.7 [bcd]	14.9 [a]	8.1 [a]
DAP	13.2 [a]	17.0 [a]	8.7 [a]	8.7 [cd]	8.5 [a]	7.0 [a]
Biochar + DAP	14.3 [a]	12.6 [a]	8.1 [a]	16.7 [ab]	11.6 [a]	7.3 [a]
Compost + DAP	14.1 [a]	9.3 [a]	10.1 [a]	9.5 [cd]	13.4 [a]	6.8 [a]
Lime + DAP	12.3 [a]	12.4 [a]	7.7 [a]	12.0 [bcd]	6.0 [a]	7.9 [a]
Biochar+ lime + DAP	10.6 [a]	12.5 [a]	10.7 [a]	11.8 [bcd]	12.2 [a]	6.1 [a]
Compost +lime+ DAP	12.4 [a]	10.0 [a]	8.2 [a]	13.9 [abc]	9.1 [a]	5.4 [a]
Biochar + compost + DAP	11.5 [a]	13.5 [a]	10.8 [a]	13.2 [bc]	10.4 [a]	7.0 [a]
Biochar + compost +lime + DAP	8.4 [a]	11.8 [a]	8.4 [a]	10.9 [bcd]	9.8 [a]	8.0 [a]
Mean	11.8 [a]	12.3 [a]	9.5 [b]	12.3 [a]	12.1 [a]	7.6 [b]
P-value (treatment per site)	0.14	0.824	0.979	0.016	0.536	0.597
LSD (site per season)	1.5			2.4		
LSD (treatment per site)	5.3	6.0	4.9	6.7	12.5	4.1
LSD (site*treatment per season)	6.0			9.0		
CV%	41.1	26.5	49.2	24.0	45.7	11.6

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

Plots amended with combinations of biochar + lime significantly reduced the root rot incidence by 56% relative to non-amended plots and had no significant differences with DAP-amended plots (Table 4.13). Percentage root rot incidence significantly ($p \leq 0.05$) differed among the soil amendments at the second and fourth week after emergence in the short rains of 2018 and at fourth and sixth week after emergence in the long rains of 2019. But, these differences were only noted in Kapkerer (Tables 4.14 and 4.15).

In the short rains of 2018, most of the treatments had significantly lower root rot incidence compared to non-amended plots with an exception in combination of biochar + lime + compost + DAP, lime + compost +DAP and compost + DAP at the second week after emergence, and compost +DAP and DAP at the fourth week after emergence. Application of lime, biochar +lime, biochar +lime+ DAP and biochar + lime + compost significantly reduced root rot incidence by 83% to 89% compared to non-amended plots at the second week after emergence. At the fourth week after emergence, application of biochar + compost +lime + DAP, biochar + lime + compost, lime + DAP and biochar + DAP significantly reduced root rot incidence by 63% to 72% compared to non-amended plots and by 60% to 72% compared to soils amended with DAP (Table 4.14).

In the long rain season of 2019, at the fourth week after emergence, significant increases of 45% to 90% in root rot incidence was noted where biochar and combinations of biochar +DAP and biochar + lime +compost+ DAP were used compared to non-amended plots. However, at six weeks after emergence, most treatments had significantly low root rot incidence compared to non-amended plots with an exception of biochar which had increased the incidence by 59%. Treatments of biochar + compost +lime + DAP and biochar + lime significantly reduced root rot incidence by 77% and 64% compared to non-amended plots (Table 4.15).

Percentage root rot incidence significantly ($p \leq 0.05$) differed among the sites in both seasons. However this effect varied by weeks (Tables 4.14 and 4.15). In the short rains of 2018, high root rot incidences were noted in Kapkerer whereas in the long rain of 2019, high root rot incidences were noted in Kapkerer at the second and fourth week after emergence and in Kiptaruswo at the six week (Tables 4.14 and 4.15). The interaction between sites and soil amendments only had a significant effect at the second week after emergence in the short rains of 2018 (Table 4.14).

Table 4.14: Root rot incidence (%) of common bean at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the short rain growing season of 2018

	2 weeks			4 weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	1.8 [ab]	3.7 [a]	3.4 [a]	20.3 [a]	13.6 [a]	6.3 [a]	28.6 [a]	21.8 [a]	16.5 [a]
Biochar	0.9 [bc]	3.6 [a]	2.1 [a]	12.1 [bcd]	11.7 [a]	7.1 [a]	27.2 [a]	23.3 [a]	19.8 [a]
Compost	1.2 [abc]	2.5 [a]	0.5 [a]	7.7 [cd]	6.0 [a]	8.7 [a]	22.9 [a]	23.0 [a]	22.9 [a]
Lime	0.3 [c]	4.5 [a]	3.2 [a]	11.0 [bcd]	13.9 [a]	9.5 [a]	25.6 [a]	16.9 [a]	14.0 [a]
Biochar+lime	0.2 [c]	5.7 [a]	2.8 [a]	9.5 [bcd]	7.9 [a]	5.4 [a]	22.2 [a]	20.0 [a]	24.5 [a]
Lime+compost	1.2 [abc]	2.5 [a]	2.8 [a]	9.7 [bcd]	11.4 [a]	12.2 [a]	23.0 [a]	25.5 [a]	16.4 [a]
Biochar+compost	1.3 [abc]	3.2 [a]	1.0 [a]	9.4 [bcd]	9.2 [a]	6.6 [a]	21.1 [a]	25.8 [a]	23.3 [a]
Biochar+lime+compost	0.5 [c]	4.4 [a]	2.4 [a]	7.6 [d]	8.9 [a]	7.9 [a]	19.2 [a]	26.0 [a]	20.3 [a]
DAP	1.2 [abc]	3.3 [a]	3.4 [a]	19.2 [a]	16.9 [a]	7.5 [a]	19.2 [a]	30.8 [a]	15.2 [a]
Biochar+compost+DAP	1.0 [bc]	2.4 [a]	4.5 [a]	8.5 [bcd]	12.8 [a]	7.7 [a]	25.0 [a]	25.2 [a]	20.4 [a]
Biochar+DAP	1.1 [abd]	2.8 [a]	2.3 [a]	5.7 [d]	9.2 [a]	5.6 [a]	26.1 [a]	18.7 [a]	16.4 [a]
Lime+DAP	0.8 [bc]	1.5 [a]	1.5 [a]	6.4 [d]	12.0 [a]	5.9 [a]	19.6 [a]	23.6 [a]	15.9 [a]
Biochar+lime+DAP	0.3 [c]	2.5 [a]	3.6 [a]	9.7 [bcd]	15.0 [a]	7.5 [a]	21.6 [a]	20.0 [a]	20.8 [a]
Compost+DAP	1.8 [ab]	3.2 [a]	2.4 [a]	15.0 [abc]	7.1 [a]	5.7 [a]	25.5 [a]	17.6 [a]	22.1 [a]
Lime+compost+DAP	1.8 [ab]	3.1 [a]	2.0 [a]	11.5 [bcd]	6.9 [a]	6.7 [a]	23.9 [a]	20.0 [a]	16.1 [a]
Biochar+lime+compost+DAP	2.4 [a]	2.8 [a]	0.9 [a]	5.4 [d]	9.4 [a]	6.1 [a]	17.3 [a]	23.1 [a]	18.3 [a]
Mean	1.1 [b]	3.2 [a]	2.4 [a]	11.2 [a]	10.7 [a]	7.3 [a]	23.0 [a]	22.9 [a]	18.9 [a]
LSD(treatment per site)	1.2	2.2	2.6	6.8	8.8	5.1	10.0	13.9	8.8
P-value (treatment per site)	0.024	0.079	0.217	≤.001	0.430	0.514	0.641	0.87	0.391
LSD (site per WAE)	1.2			7.8			16.1		
LSD (site*treatment per WAE)	2.3			10.0			11.0		
P-value (site*treatment per WAE)	0.012			0.076			0.622		
CV%	38.3	30.7	50.1	66.7	36.7	68.8	40.0	34.2	28.4

Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per week are not significantly different at p≤0.05; CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05); WAE: week after emergence

Table 4.15: Root rot incidence (%) of common bean at the second, fourth and sixth week after emergence (WAE) at three sites in Nandi South during the long rain growing season of 2019

	2 weeks			4 weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	7.9 [a]	1.1 [a]	1.9 [a]	14.1 [bcd]	4.8 [a]	7.6 [a]	21.9 [ab]	28.1 [a]	13.6
Biochar	5.5 [a]	0.7 [a]	0.8 [a]	20.5 [abc]	4.9 [a]	5.9 [a]	34.8 [a]	17.7 [a]	13.5
Compost	6.0 [a]	4.0 [a]	2.7 [a]	12.0 [cd]	7.6 [a]	6.6 [a]	19.9 [bc]	36.0 [a]	16.2
Lime	4.7 [a]	1.6 [a]	2.1 [a]	16.3 [abcd]	5.1 [a]	6.1 [a]	20.8 [b]	34.5 [a]	13.3
Biochar+compost	3.8 [a]	1.7 [a]	1.6 [a]	10.4 [cd]	4.2 [a]	6.0 [a]	10.5 [bcd]	25.8 [a]	14.3
++	4.3 [a]	1.9 [a]	3.0 [a]	7.2 [d]	5.3 [a]	8.2 [a]	7.8 [cd]	39.4 [a]	18.4
Lime+compost	4.8 [a]	0.8 [a]	1.4 [a]	17.1 [abcd]	4.9 [a]	7.0 [a]	19.5 [bc]	23.8 [a]	25.0
Biochar+lime+compost	7.2 [a]	3.1 [a]	2.8 [a]	13.3 [bcd]	7.9 [a]	7.4 [a]	11.5 [bcd]	33.5 [a]	14.0
DAP	7.3 [a]	3.4 [a]	3.6 [a]	7.7 [d]	5.0 [a]	5.7 [a]	11.1 [bcd]	17.0 [a]	11.7
Biochar+DAP	8.0 [a]	0.8 [a]	2.0 [a]	26.8 [a]	2.8 [a]	6.9 [a]	15.5 [bcd]	31.0 [a]	12.9
Lime+DAP	4.5 [a]	0.8 [a]	3.6 [a]	15.5 [bcd]	5.5 [a]	5.4 [a]	16.1 [bcd]	11.7 [a]	14.7
Compost+DAP	2.4 [a]	1.0 [a]	2.0 [a]	11.3 [cd]	3.3 [a]	3.7 [a]	14.9 [bcd]	17.0 [a]	14.7
Biochar+lime+DAP	6.6 [a]	2.9 [a]	1.1 [a]	12.0 [cd]	7.9 [a]	6.0 [a]	16.9 [bcd]	25.9 [a]	11.1
Biochar+compost+DAP	6.6 [a]	1.6 [a]	1.3 [a]	11.5 [cd]	4.6 [a]	6.7 [a]	21.4 [b]	25.0 [a]	12.9
Lime+compost+DAP	4.5 [a]	0.4 [a]	2.4 [a]	14.6 [bcd]	4.9 [a]	2.3 [a]	22.6 [ab]	28.1 [a]	11.6
Biochar+lime+compost +DAP	4.4 [a]	0.6 [a]	4.0 [a]	23.4 [ab]	7.2 [a]	5.4 [a]	5.0 [d]	21.7 [a]	14.5
Mean	5.5 [a]	1.7 [b]	2.2 [b]	14.6 [a]	5.4 [b]	6.1 [b]	16.9 [b]	29.3 [a]	14.5 [b]
LSD(treatment per site)	5.0	3.0	2.8	10.6	4.8	4.4	12.9	34.2	11.1
P-value (treatment per site)	0.626	0.387	0.56	0.032	0.658	0.570	0.010	0.361	0.769
LSD (site per WAE)	0.98			2.09			6.7	25	25
LSD (site*treatment per WAE)	3.8			7.05			23.8		
P-value (site*treatment per WAE)	0.763			0.210			0.010		
CV%	22.5	76.9	32.7	34.9	35.3	13.7	28.5	54.8	19.4

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per week and season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$); WAE: week after emergence

Percentage bean stem maggot significantly differed among the soil amendments in the long rains of 2019 (Table 4.16). However this effect was noted in Kapkerer. Application of biochar + compost + lime +DAP and biochar + lime had the least bean stem maggot incidence of 5.6 and 5.1% compared to non-amended plots (Table 4.16). Among the sites, Koibem had the highest incidence of 8.3% in the short rains of 2018 while Kapkerer had the highest percentage bean stem maggot incidence of 10.5% in the long rains of 2019 (Table 4.16).

Percentage bean stem maggot significantly differed among the soil amendments at the sixth week after emergence in the long rains of 2019 (Table 4.17). However this effect was noted in Kapkerer. Application of biochar + compost + lime +DAP, biochar + lime and biochar + compost significantly reduced stem maggot incidence by 77%, 64% and 52% respectively in Kapkerer compared to non-amended plots (Table 4.17).

Table 4.16: Bean stem maggot incidence (%) of common bean in soils amended with different treatments during the short rains of 2018 and long rains of 2019 at three sites in Nandi South

	Short rains-2018			Long rains- 2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	0.1 [a]	4.5 [a]	9.0 [a]	13.6 [ab]	3.7 [a]	8.6 [a]
Biochar	0.2 [a]	3.3 [a]	7.9 [a]	19.5 [a]	6.7 [a]	8.0 [a]
Compost	0.3 [a]	2.8 [a]	7.7 [a]	12.7 [abc]	3.5 [a]	9.1 [a]
Lime	0.4 [a]	3.4 [a]	8.3 [a]	11.3 [abc]	5.3 [a]	7.1 [a]
Lime + compost	0.3 [a]	3.5 [a]	8.6 [a]	13.1 [ab]	7.7 [a]	14.7 [a]
Biochar + lime	0.2 [a]	3.0 [a]	6.5 [a]	5.1 [c]	6.2 [a]	11.2 [a]
Biochar + compost	0.2 [a]	3.1 [a]	9.1 [a]	7.0 [bc]	6.1 [a]	8.0 [a]
Biochar + compost +lime	0.2 [a]	4.3 [a]	8.6 [a]	7.8 [bc]	6.3 [a]	8.3 [a]
DAP	0.5 [a]	2.7 [a]	8.8 [a]	6.4 [bc]	4.3 [a]	7.7 [a]
Biochar + DAP	0.2 [a]	3.5 [a]	8.2 [a]	11.3 [abc]	5.0 [a]	7.9 [a]
Compost + DAP	0.2 [a]	2.8 [a]	8.4 [a]	9.8 [abc]	5.7 [a]	9.4 [a]
Lime + DAP	0.7 [a]	3.1 [a]	8.8 [a]	9.2 [abc]	4.1 [a]	8.3 [a]
Biochar + compost + DAP	0.3 [a]	3.2 [a]	8.6 [a]	12.2 [abc]	6.6 [a]	8.2 [a]
Biochar+ lime + DAP	0.4 [a]	3.3 [a]	11.2 [a]	9.6 [ac]	4.6 [a]	6.2 [a]
Compost +lime+ DAP	0.4 [a]	2.6 [a]	8.1 [a]	14.3 [bc]	5.7 [a]	6.9 [a]
Biochar + compost +lime + DAP	0.3 [a]	3.5 [a]	5.6 [a]	5.6 [c]	6.2 [a]	9.3 [a]
Mean	0.3 [c]	3.3 [b]	8.3 [a]	10.5 [a]	5.5 [c]	8.7 [b]
P value (treatment per site)	0.856	0.993	0.788	0.024	0.470	0.534
P value (site *treatment per season)	0.995			0.167		
CV%	12.8	39.2	23.3	33.4	31.8	32.7

Analysis was carried out on square-root transformed ($\sqrt{x} + 0.5$); Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$); WAE: week after emergence

Table 4.17: Bean stem maggot incidence (%) at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	4 weeks			6 weeks		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Short rains -2018						
Non-amended	0.1 [a]	5.5 [a]	2.2 [a]	0.0 [a]	5.5 [a]	14.8 [a]
Biochar	0.1 [a]	2.9 [a]	2.9 [a]	0.1 [a]	4.4 [a]	12.2 [a]
Compost	0.0 [a]	3.5 [a]	2.4 [a]	0.4 [a]	2.7 [a]	11.7 [a]
Lime	0.3 [a]	3.5 [a]	4.3 [a]	0.3 [a]	3.8 [a]	9.6 [a]
Lime+compost	0.2 [a]	3.5 [a]	4.1 [a]	0.3 [a]	3.0 [a]	12.0 [a]
Biochar+lime	0.0 [a]	2.5 [a]	1.9 [a]	0.3 [a]	6.9 [a]	8.1 [a]
Biochar+compost	0.1 [a]	4.2 [a]	2.4 [a]	0.1 [a]	4.7 [a]	14.1 [a]
Biochar+lime+compost	0.0 [a]	3.8 [a]	3.2 [a]	0.3 [a]	3.1 [a]	13.0 [a]
DAP	0.3 [a]	1.9 [a]	2.9 [a]	0.5 [a]	3.9 [a]	13.6 [a]
Biochar+DAP	0.1 [a]	3.6 [a]	2.4 [a]	0.1 [a]	3.8 [a]	13.2 [a]
Compost+DAP	0.2 [a]	3.5 [a]	2.2 [a]	0.1 [a]	2.3 [a]	13.5 [a]
Lime+DAP	0.5 [a]	3.3 [a]	1.9 [a]	0.6 [a]	3.9 [a]	12.6 [a]
Biochar+compost+DAP	0.0 [a]	2.6 [a]	4.3 [a]	0.4 [a]	4.5 [a]	11.6 [a]
Biochar+lime+DAP	0.6 [a]	4.5 [a]	3.6 [a]	0.0 [a]	1.9 [a]	16.2 [a]
Compost +lime+ DAP	0.2 [a]	2.5 [a]	1.7 [a]	0.3 [a]	3.1 [a]	12.0 [a]
Biochar+lime+compost+DAP	0.2 [a]	3.9 [a]	2.8 [a]	0.2 [a]	2.5 [a]	6.2 [a]
Mean	0.2 [b]	3.5 [a]	2.8 [a]	0.2 [c]	3.7 [b]	12.2 [a]
P-value (treatment per site)	0.676	0.484	0.519	0.864	0.356	0.411
CV%	20.3	34.8	19.1	9.7	40.1	29.5
Long rains-2019						
Non-amended	5.2 [a]	1.8 [a]	3.8 [a]	21.8 [ab]	5.8 [a]	13.6 [a]
Biochar	4.0 [a]	2.5 [a]	2.5 [a]	34.8 [a]	10.9 [a]	13.5 [a]
Compost	5.3 [a]	1.5 [a]	2.1 [a]	19.9 [bc]	5.6 [a]	16.2 [a]
DAP	1.5 [a]	1.7 [a]	3.7 [a]	11.1 [bcd]	7.0 [a]	11.7 [a]
Lime	1.7 [a]	2.6 [a]	0.9 [a]	20.8 [b]	8.1 [a]	13.3 [a]
Biochar+compost	3.4 [a]	0.7 [a]	1.7 [a]	10.5 [cd]	11.6 [a]	14.3 [a]
Biochar+compost+DAP	2.9[a]	3.5 [a]	3.6 [a]	21.4 [ab]	9.7 [a]	12.9 [a]
Biochar+DAP	7.0 [a]	1.6 [a]	2.9 [a]	15.5 [bcd]	8.4 [a]	12.9 [a]
Biochar+lime	2.2 [a]	2.0 [a]	4.0 [a]	7.8 [cd]	10.4 [a]	18.4 [a]
Biochar+lime+compost	3.9 [a]	2.8 [a]	2.7 [a]	11.5 [bcd]	9.8 [a]	14.0 [a]
Biochar+lime+compost+DAP	6.0 [a]	3.3 [a]	4.2 [a]	5.0 [d]	9.2 [a]	14.5 [a]
Biochar+lime+DAP	2.2 [a]	1.9 [a]	1.2 [a]	16.9 [bcd]	7.4 [a]	11.1 [a]
Compost+DAP	4.6 [a]	2.3 [a]	4.1 [a]	14.9 [bcd]	9.3 [a]	14.7 [a]
Lime+compost	6.5 [a]	4.3 [a]	4.6 [a]	18.0 [abc]	11.2 [a]	25.0 [a]
Lime+compost+DAP	5.8 [a]	2.8 [a]	2.2 [a]	22.6 [ab]	8.7 [a]	11.6 [a]
Lime+DAP	2.2 [a]	1.9 [a]	2.0 [a]	16.1 [bcd]	6.4 [a]	14.7 [a]
Mean	3.6 [a]	2.3[a]	2.9[a]	16.9 [a]	8.7 [c]	14.5 [b]
P-value (treatment per site)	0.091	0.373	0.752	0.01	0.909	0.796
CV%	24.5	48.5	36.9	28.5	28.1	19.4

Analysis was carried out on square-root transformed ($\sqrt{x} + 0.5$); Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$); WAE: week after emergence

Additionally, the percentage incidence of bean stem maggot significantly varied among the sites whereby, high percentage bean stem maggot incidences were noted Koibem and Kapkerer at the fourth and sixth week after emergence respectively (Tables 4.17). However, there was no significant interaction between the sites and soil amendments.

4.4 Effect of soil amendments on yield and yield components

The number of pods per plant significantly ($p \leq 0.05$) differed among the soil amendments in the long rains of 2019 and this effect was noted in Kapkerer (Table 4.18) Compared to non-amended plots, application of biochar+ lime + DAP, biochar + lime, biochar+ lime + compost, compost+

Table 4.18: Number of pods per plant in various treatments at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	5.4 [a]	10.4 [a]	7.4 [a]	4.8 [de]	1.6 [a]	1.9 [a]
Biochar	5.2 [a]	9.2 [a]	6.7 [a]	6.3 [abcd]	2.6 [a]	1.9 [a]
Compost	5.7 [a]	8.0 [a]	5.9 [a]	5.9 [bcde]	1.9 [a]	2.1 [a]
Lime	5.5 [a]	9.6 [a]	7.0 [a]	4.4 [e]	1.6 [a]	2.0 [a]
Biochar + lime	6.3 [a]	7.8 [a]	7.5 [a]	7.1 [ab]	1.7 [a]	2.2 [a]
Biochar + compost	6.3 [a]	9.2 [a]	5.6 [a]	4.7 [de]	2.5 [a]	2.0 [a]
Lime +compost	6.4 [a]	9.8 [a]	6.9 [a]	6.3 [abcd]	2.1 [a]	2.0 [a]
Biochar + compost +lime	6.5 [a]	10.1 [a]	6.5 [a]	7.0 [ab]	2.2 [a]	2.2 [a]
DAP	7.9 [a]	9.6 [a]	7.9 [a]	5.8 [bcde]	2.4 [a]	2.1 [a]
Compost + DAP	5.5 [a]	7.6 [a]	8.4 [a]	5.7 [bcde]	2.9 [a]	2.0 [a]
Lime + DAP	6.2 [a]	9.6 [a]	6.8 [a]	6.2 [abcd]	3.1	2.0 [a]
Biochar + compost + DAP	5.6 [a]	8.8 [a]	6.3 [a]	6.5 [abc]	2.8 [a]	2.0 [a]
Biochar + DAP	6.3 [a]	8.3 [a]	7.1 [a]	4.8 [cde]	3.2 [a]	2.0 [a]
Biochar+ lime + DAP	4.9 [a]	9.1 [a]	7.1 [a]	7.8 [a]	2.5 [a]	2.0 [a]
Compost +lime+ DAP	7.2 [a]	9.0 [a]	7.7 [a]	6.7 [ab]	3.3 [a]	1.5 [a]
Biochar + compost +lime + DAP	6.9 [a]	9.0 [a]	6.8 [a]	5.9 [bcde]	2.2 [a]	1.1 [a]
Mean	6.1 [c]	9.1 [a]	7.0 [b]	6.0 [a]	2.4 [b]	2.0 [b]
LSD (treatment per site)	2.3	3.3	1.9	1.9	2.4	0.6
P-value (treatment per site)	0.494	0.929	0.285	0.012	0.074	0.075
LSD(site per season)	0.7			0.5		
LSD (site*treatment per season)	2.5			1.2		
P-value(site*treatment per season)	0.847			0.011		
CV%	46.9	32.6	7.7	24.4	22.8	8.5

Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

lime +DAP and biochar+ compost + DAP significantly increased the number of pods per plant by 35% to 63% respectively in Kapkerer (Table 4.18). Whereas application of biochar + lime + DAP significantly increased the number of pods per plant by 35% relative to plots amended with DAP alone. The number of pods per plant significantly ($p \leq 0.05$) differed among the sites in both seasons whereby, Kiptaruswo and Kapkerer had the highest number of pods per plant in both seasons (Table 4.19). A significant ($p \leq 0.05$) interaction between the sites and soil amendments was only noted in the long rains of 2019 (Table 4.18). The number of seeds per pod significantly ($p \leq 0.05$)

Table 4.19: Number of seeds per pod in plots incorporated with different soil amendments at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	3.5^{bcd}	3.7^{a}	2.7^{a}	2.2^{e}	1.6^{a}	3.9^{a}
Biochar	3.0^{d}	3.5^{a}	2.8^{a}	3.1^{abcd}	2.8^{a}	2.6^{a}
Compost	3.2^{d}	3.1^{a}	2.6^{a}	2.9^{bcde}	1.5^{a}	2.9^{a}
Lime	4.6^{a}	4.2^{a}	2.5^{a}	3.1^{abcd}	1.5^{a}	3.4^{a}
Biochar +lime	4.6^{a}	5.1^{a}	3.3^{a}	3.6^{ab}	1.7^{a}	3.7^{a}
Biochar + compost	4.4^{ab}	3.5^{a}	2.6^{a}	2.4^{bcde}	2.2^{a}	3.5^{a}
Lime + compost	3.6^{bcd}	4.4^{a}	3.4^{a}	3.1^{abcd}	2.9^{a}	3.2^{a}
Biochar + compost +lime	3.7^{abcd}	3.8^{a}	3.5^{a}	3.5^{ab}	2.2^{a}	3.5^{a}
DAP	3.6^{bcd}	3.8^{a}	2.6^{a}	3.1^{abcd}	3.1^{a}	2.8^{a}
Biochar +DAP	3.4^{cd}	3.6^{a}	2.8^{a}	2.4^{de}	3.5^{a}	3.0^{a}
Compost + DAP	2.9^{d}	4.7^{a}	2.8^{a}	2.9^{bcde}	2.6^{a}	3.3^{a}
Lime + DAP	4.2^{abc}	3.6^{a}	3.0^{a}	3.0^{bcde}	1.7^{a}	3.1^{a}
Biochar+ lime + DAP	3.6^{bcd}	3.6^{a}	3.0^{a}	3.9^{a}	1.9^{a}	3.8^{a}
Biochar + compost + DAP	3.4^{cd}	3.9^{a}	2.9^{a}	3.2^{abc}	2.8^{a}	3.0^{a}
Compost +lime+ DAP	3.7^{abcd}	3.8^{a}	2.5^{a}	2.4^{cde}	3.1^{a}	2.0^{a}
Biochar + compost +lime + DAP	3.3^{d}	4.3^{a}	3.1^{a}	3.0^{bcde}	2.2^{a}	3.0^{a}
Mean	3.7^{a}	3.9^{a}	2.9^{b}	3.0^{a}	2.3^{b}	3.2^{a}
LSD (treatment per site)	0.9	1.2	0.7	1.3	1.5	1.1
P-value (treatment per site)	0.003	0.118	0.12	0.012	0.771	0.1
LSD(site per season)	0.9			0.5		
LSD (site*treatment per season)	0.9			1.3		
P-value(site*treatment per season)	0.06			0.007		
CV%	25.9	17.0	3.5	24.4	29.5	43.5

Means were separated using Fisher's LSD at Means followed by the same letter(s) in each column are not significantly different at $p \leq 0.05$; Means followed by the same letter(s) in each row per season are not significantly different at $p \leq 0.05$; CV%=Coefficient of Variation; LSD=Least Significant Difference at ($p \leq 0.05$)

differed among the soil amendments in both seasons but this effect was noted in Kapkerer (Table 4.19). Compared to non-amended plots, plots amended with lime and application of biochar + lime significantly increased the number of seeds per pods by 31% in the short rains while in the long rains, application of biochar+ lime+ DAP increased it by 77% (Table 4.18). Additionally, a significant ($p \leq 0.05$) interaction between the sites and soil amendments was noted in both seasons (Table 4.19). Biomass of common bean significantly ($p \leq 0.05$) differed among the treatments in the long rains of 2019 but this effect varied in sites (Table 4.20). Plots amended with application of biochar+ lime + compost and biochar+ lime + DAP significantly increased plant biomass by 30% and 25% in Kapkerer and Koibem compared to non-amended plots (Table 4.20).

Table 4.20 Biomass (kg/ha) of common bean in different soil amendments at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	Short rains-2018			Long rains-2019		
Treatments	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Non-amended	625.3 [a]	650.1 [a]	353.1 [a]	691.8 [abc]	418.0 [a]	796.2 [abc]
Biochar	518.7 [a]	705.6 [a]	524.5 [a]	760.6 [ab]	473.6 [a]	984.4 [ab]
Compost	567.2 [a]	717.5 [a]	402.9 [a]	477.9 [abc]	361.9 [a]	423.2 [cde]
Lime	506.0 [a]	509.2 [a]	331.6 [a]	669.7 [abc]	269.2 [a]	632.5 [abcde]
Lime+compost	513.4 [a]	598.6 [a]	386.6 [a]	592.8 [abc]	377.3 [a]	467.1 [cde]
Biochar+lime	500.8 [a]	422.5 [a]	253.3 [a]	319.1 [bc]	226.5 [a]	168.8 [e]
Biochar+compost	487.3 [a]	647.3 [a]	409.9 [a]	236.6 [c]	503.7 [a]	487.5 [abcde]
Biochar+lime+compost	611.3 [a]	579.0 [a]	285.7 [a]	901.5 [a]	341.2 [a]	477.5 [bcde]
DAP	434.3 [a]	768.1 [a]	338.6 [a]	456.4 [abc]	324.5 [a]	928.8 [ab]
Biochar+DAP	606.6 [a]	691.9 [a]	331.1 [a]	316.1 [bc]	485.8 [a]	300.7 [de]
Lime+DAP	384.5 [a]	964.7 [a]	474.1 [a]	485.4 [abc]	846.9 [a]	929.9 [ab]
Compost+DAP	396.4 [a]	823.2 [a]	372.5 [a]	771.3 [ab]	165.2 [a]	645.5 [abcde]
Biochar+compost+DAP	550.3 [a]	623.8 [a]	278.9 [a]	333.4 [bc]	463.1 [a]	454.7 [cde]
Biochar+lime+DAP	506.7 [a]	826.3 [a]	433.4 [a]	666.9 [abc]	454.2 [a]	995.2 [a]
Compost+lime+DAP	565.9 [a]	816.4 [a]	308.4 [a]	461.7 [abc]	526.0 [a]	238.5 [e]
Biochar+compost+ lime+DAP	582.8 [a]	663.6 [a]	439.1 [a]	263.4 [c]	462.6 [a]	134.0 [e]
Mean	527.2 [a]	687.8 [a]	573.5 [a]	525.3 [a]	418.7 [a]	566.5 [a]
LSD (treatment per site)	341.8	295.0	155.8	253.6	376.7	512.9
P-value (treatment per site)	0.941	0.094	0.05	<.001	0.209	0.017
LSD(site per season)	295.7			284.1		
LSD (site*treatment per season)	249.8			363.0		
P-value(site*treatment per season)	0.209			0.003		
CV%	32.0	37.6	37.6	13.8	36.7	48.0

Means were separated using Fisher's LSD at Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per season are not significantly different at p≤0.05; CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05)

However, application of biochar+ lime +compost and biochar + compost had the least biomass of 263.4 and 236.6 kg/ha within Kapkerer and application of biochar +lime+ compost +DAP and compost+ lime + DAP had the least biomass of 134.0 and 238.5 kg/ha in Koibem compared to non-amended plots (Table 4.20). Grain yield of common bean significantly (p≤0.05) differed among the soil amendments in the long rains of 2019 in the long rains of 2019 but this effect was noted in Kapkerer (Table 4.21). Amended plots had significantly higher grain yield relative to non-amended plots. Compared to non-amended plots, plots amended with either lime or DAP had significantly higher grain yield (Table 4.21).

Table 4:21 Grain yield (kg/ha) of common bean in plots incorporated with different soil amendments at three sites in Nandi South during the short rain growing season of 2018 and long rain growing season of 2019

	Short rains-2018			Long rains-2019		
Treatmentts	Kapkerer	Kiptaruswo	Koibem	Kapkerer	Kiptaruswo	Koibem
Biochar	421.4 [a]	816.3 [a]	491.0 [a]	469.7 [abcd]	862.2[a]	227.3[a]
Compost	950.1 [a]	1144.6 [a]	655.2 [a]	724.7 [abcd]	652.5[a]	328.2[a]
DAP	587.6 [a]	974.2 [a]	835.3 [a]	782.9 [abc]	703.5[a]	517.7[a]
Lime	400.4 [a]	831.7 [a]	538.3 [a]	324.7[cd]	344.6[a]	414.9[a]
Biochar+compost	384.9 [a]	942.9 [a]	482.7 [a]	420.4 [abcd]	698.7[a]	503.6[a]
Biochar+compost+ lime+DAP	483.5 [a]	830.0 [a]	688.7 [a]	146.5[d]	578.6[a]	260.8[a]
Biochar+compost+DAP	608.5 [a]	623.7 [a]	565.2 [a]	372.5[bcd]	681.6[a]	679.5[a]
Biochar+DAP	600.7 [a]	864.6 [a]	655.2 [a]	144.6[d]	1073[a]	470.5[a]
Biochar+lime	548.2 [a]	776.2 [a]	564.7 [a]	943.9 [ab]	582.3[a]	415.6[a]
Biochar+lime+compost	645.4 [a]	690.4 [a]	751.2 [a]	203.5[cd]	654.5[a]	429.8[a]
Biochar+lime+DAP	677.4 [a]	992.1 [a]	694.2 [a]	937.1 [ab]	802.2[a]	450.6[a]
Compost+DAP	567.8 [a]	818.3 [a]	915.1 [a]	458.7 [abcd]	731.0[a]	815.7[a]
Compost+lime+DAP	489.7 [a]	1061.7 [a]	573.6 [a]	452.7 [abcd]	559.4[a]	410.8[a]
Lime+compost	507.2 [a]	956.7 [a]	747.7 [a]	342.2 [cd]	714.5[a]	396.2[a]
Lime+DAP	520.7 [a]	1007.5 [a]	704.3 [a]	988.2[a]	977.5[a]	581.1[a]
Non-amended	602.9 [a]	841.2 [a]	686.5 [a]	310.9[cd]	676.3[a]	412.7[a]
Mean	562.3 [a]	850.9[a]	659.3[a]	501.4 [b]	705.8[a]	457.2 [b]
LSD (treatment per site)	423.5	313.3	659.3	331.1	357.4	387.3
P-value (treatment per site)	0.364	0.681	0.696	<.001	0.066	0.291
LSD(site per season)	334.8			229.2		
LSD (site*treatment per season)	480.3			334.8		
P-value(site*treatment per season)	0.448			0.001		
CV%	40.5	26.9	5.6	50.6	16.2	21.5

Means were separated using Fisher's LSD at Means followed by the same letter(s) in each column are not significantly different at p≤0.05; Means followed by the same letter(s) in each row per season are not significantly different at p≤0.05; CV%=Coefficient of Variation; LSD=Least Significant Difference at (p≤0.05)

This was noted in application of lime + DAP, biochar+ lime+ DAP and biochar + lime which significantly increased grain yield by 217%, 201% and 204%. (Table 4.20). However, application of biochar + DAP and biochar + compost+ lime + DAP had the least grain yield of 144.6 kg/ha and 146.5 kg/ha (Table 4.20). The sites only had a significant (p≤0.05) effect on grain yield in the long rain season of 2019 whereby, Koibem and Kapkerer had higher grain yield compared to Kiptaruswo. Additionally, a significant (p≤0.05) interaction between the sites and soil amendments was noted in the long rains of 2019 (Table 4.21).

4.5 Correlation of soil characteristics, root rot pathogens and bean root rot to grain yield

Soil pH had a varying effect on individual root rot pathogens in whereby, soil pH was highly positively correlated to *Fusarium oxysporum* and *Rhizoctonia solani* (r=0.4201, p≤0.01) but negatively correlated to *Fusarium solani* (r=-0.4615, p≤0.05). (Table 4.21). A direct effect of root rot pathogens on bean root rot and grain yield was noted in *F. oxysporum* (Table 4.22). The effect of soil pH on bean root rot and grain yield varied among the assessed parameters whereby, a high positive correlation was noted between soil pH and plant mortality (r=0.527, p≤0.001) (Table 4.22). The effect of macronutrients on bean root rot was varied among the assessed parameters (Table 4.22)

Table 4:22: Correlation of soil pH and macronutrients, root rot pathogens, bean root rot, biomass and grain yield

Parameter	soilpH	Total N	Total P	Total K	Total O.C	*F.oxy*	*F.sol*	*R.sol*
soilpH	-							
totalN	0.317	-						
totalP	0.163	0.063	-					
totalK	0.401	0.774***	0.205	-				
totalorgC	0.243	0.853***	0.061	0.826***	-			
F.oxy	0.420**	-0.003	0.022	0.066	-0.035	-		
F.sol	-0.462	-0.257	-0.091	-0.377	-0.26	-0.215	-	
R.sol	0.047	0.114	-0.159	0.125	0.079	0.285	0.016	-
emerge	-0.463	-0.515***	0.170	-0.474	-0.572***	-0.524***	0.408	-0.168
p_stand	-0.523***	-0.559***	0.085	-0.522***	-0.527***	-0.570***	0.443	-0.176
p_mortality	0.527***	0.499	0.124	0.453**	0.371	0.547***	-0.384	0.067
rr_incidence	0.001	-0.347	0.372	-0.258	-0.425**	-0.034	0.041	-0.117
bsm_incidence	0.287	0.453	-0.19	0.37	0.386	0.524***	-0.138	0.249
biomass	-0.068	-0.198	-0.307	-0.03	-0.13	-0.015	0.014	-0.015

grain_yield	-0.366	-0.081	0.097	-0.074	-0.19	-0.152	0.223	-0.073

Significance levels ******* to show significance at p≤0.001, ******to show significance at p≤0.01,*to show significance at p≤0.05: *F.sol- Fusarium solani, F.oxy -Fusarium oxysporum, R.sol -Rhizoctonia solani*

Total K had a positive correlation with plant mortality (r=0.453, p≤0.01) and a highly negative correlation with plant stand (r=-0.522, p≤0.001). Whereas, total organic carbon had a negative correlation with plant emergence, plant stand and bean root rot incidence (Table 4.22).The effect of bean root rot on biomass and grain yield varied in parameter. Bean stem maggot incidence was negatively correlated to grain yield (r=-0.400, p≤0.01) as a result of its positive correlation with plant mortality (r=0.514, p≤0.001) and high negative correlation with emergence and plant stand (r=-0.687, r=-0787, p≤0.001) (Table 4.23).

Table 4:23: Correlation of bean root rot, biomass and grain yield

	emerge	p_stand	p_mortality	rr_incidence	bsm_incidence	biomass	grain_yield
emerge	-						
p_stand	0.889***	-					
p_mortality	-0.576***	-0.785***	-				
rr_incidence	0.347	0.141	0.032	-			
bsm_incidence	-0.687***	-0.787***	0.514***	-0.015	-		
biomass	0.028	0.028	-0.127	0.232	0.083	-	
grain_yield	0.473	0.300	-0.088	0.139	-0.400**	-0.023	-

Significance levels ******* to show significance at p≤0.001, ******to show significance at p≤0.01,*to show significance at p≤0.05: *F.sol- Fusarium solani, F.oxy -Fusarium oxysporum, R.sol -Rhizoctonia solani*

4.6 Use of soil amendments by small scale holder farmers in management of soil acidity and bean root rot

Different types of soil amendments were used by farmers in Nandi South to manage fields with low soil fertility. Among the amendments, DAP (13.6%) and manure (12.3%) are the most used amendments by farmers in the three sites whereas lime and biochar was the least used amendment. (Table 4.24). Majority of the farmers who use soil amendments were from Kapkerer compared to Koibem and Kiptaruswo (Table 4.4).

Table 4.24: Percentage of farmers who use different soil amendments at Kapkerer, Kiptaruswo and Koibem in Nandi South

	Kapkerer	Kiptaruswo	Koibem	Mean
DAP	11.1	7.4	22.2	13.6
Manure	14.8	14.8	7.4	12.3
Compost	14.8	3.7	0.0	6.2
Lime	0.0	3.7	0.0	1.2
Biochar	0.0	0.0	0.0	0.0
Mean	8.1	5.9	5.9	6.7

Observations made by farmers on various bean growth stages and disease symptoms varied among the sites and soil amendments (Table 4.25). All the amendments had an effect on emergence, podding and flowering. Majority of the farmers observed that DAP and lime amended plots had poor emergence when compared to biochar and compost plots. More than 30% of farmers in Kapkerer and Koibem noted that biochar and compost amended plots had high bean emergence (Table 4.25).

The effect of biochar on flowering and podding varied among the three sites whereby, more than 5% of the farmers in Kapkerer and Koibem observed poor, average and increased flowering and podding. Only farmers in Kapkerer were able to observe a change on the leaf color, size and number. Plants in plots amended with biochar and compost had darker shades of green while only plants in biochar amended plots were broader and many (Table 4.25)

Wilting and yellowing of leaves were observed by farmers in the three site and their occurrence varied among the sites and the soil amendments (Table 4.25). Plants in lime-amended soils were noted to have more wilts by more than 30% of farmers in Kapkerer and Kiptaruswo. Whereas 27% and 33% of farmers observed that plants in compost amended plots had more yellowing (Table 4.25). There was no yellowing or wilting observed in biochar amended plots in all the sites.

Table 4.25: Percentage of farmers who made observations on different growth stages and disease symptoms of common bean in plots amended with various soil amendments at Kapkerer, Kiptaruswo and Koibem in Nandi South

Observation	Soil amendment	Site			Observation	Soil amendment	Site		
		Kapkerer	Kiptaruswo	Koibem			Kapkerer	Kiptaruswo	Koibem
Poor emergence	DAP	0.0	33.3	16.7	Dark green leaves	DAP	0.0	0.0	0.0
	Biochar	0.0	0.0	0.0		Biochar	5.9	5.9	0.0
	Compost	0.0	0.0	0.0		Compost	16.7	0.0	0.0
	Lime	0.0	0.0	20.0		Lime	0.0	0.0	0.0
High emergence	DAP	16.7	0.0	0.0	Broad and many leaves	DAP	0.0	0.0	0.0
	Biochar	33.3	16.7	33.3		Biochar	5.9	0.0	0.0
	Compost	33.3	16.7	33.3		Compost	0.0	0.0	0.0
	Lime	0.0	0.0	0.0		Lime	0.0	0.0	0.0
Less than average podding and flowering	DAP	0.0	0.0	0.0	Increased growth	DAP	0.0	0.0	0.0
	Biochar	0.0	0.0	5.9		Biochar	0.0	0.0	0.0
	Compost	0.0	0.0	0.0		Compost	0.0	0.0	0.0
	Lime	20.0	0.0	0.0		Lime	0.0	40.0	0.0
Average podding and flowering	DAP	16.7	0.0	0.0	Poor growth	DAP	16.7	0.0	0.0
	Biochar	5.9	0.0	0.0		Biochar	0.0	0.0	0.0
	Compost					Compost	0.0	0.0	0.0
	Lime	20.0	0.0	0.0		Lime	0.0	0.0	0.0
More than average flowering and podding	DAP	0.0	0.0	0.0	Yellowing	DAP	0.0	12.5	0.0
	Biochar	0.0	0.0	0.0		Compost	28.6	0.0	0.0
	Compost	0.0	0.0	0.0		Biochar	0.0	0.0	0.0
	Lime	0.0	0.0	0.0		Lime	0.0	33.3	0.0
Wilting	DAP	0.0	25.0	12.5	Wilting	Lime	33.3	33.3	0.0
	Biochar	0.0	0.0	0.0		Compost	0.0	0.0	14.3

CHAPTER FIVE: DISCUSSION

5.1 Effect of soil amendments on soil acidity

The current study shows that the effect of the soil amendments on soil acidity was influenced by site and application of lime, biochar + lime and biochar+ lime + compost had the highest increase in soil pH. The effect of the sites would be attributed to their varying environmental conditions (Odundo *et al*., 2010). Kapkerer is characterized by dry and warm temperatures, low soil fertility and low elevation while Koibem is wet and cooler, has higher soil fertility and high elevation (Odundo *et al*., 2010). Moreover, farms in Koibem have been under cultivation for a shorter period of time of 5 to 60 years whereas those in Kapkerer have experienced intensive nutrient loses due to crop cultivation for 80-105 years (Odundo *et al*., 2010).

Studies by Chintala *et al*. (2014), Qayyum *et al*. (2015), Berek and Hue (2016) and Mensah and Frimpong (2018) also noted that sole application of lime and combined application of biochar with either lime or both compost and lime reduced soil acidity. Application of lime leads to a change in the soil chemical balance through the displacement of hydrogen ions in the soil solution by calcium and magnesium cations present in lime (Holland *et al*., 2018). Increase of soil pH in combined applications could be attributed to the synergistic effect of both biochar and lime. Biochar used in the experiment had an alkaline pH of 9.1 and according to Dai *et al.* (2016) addition of biochar whose pH is greater than seven, increases the pH of acidic soils by 1.5 units.

The alkalinity of biochar determines its liming effect and is influenced by the feedstock and pyrolysis conditions (Shi *et al*., 2019). This alkalinity is inherited from the feedstock in form of carbonates and organic anions after pyrolysis (Shi *et al*., 2019). Biochar's porosity and high surface area enhances cation exchange capacity in the soil by releasing base cations (Yuan *et al*., 2011; Nigussie *et al*., 2012). These base cations occupy exchangeable sites in the soil and bind with aluminium ions thus decreasing their concentration and soil acidity (Yuan *et al*., 2011a; Nigussie *et al*., 2012). Biochar contains organic anions and inorganic carbonates which are conjugate bases that react with hydrogen ions and displaces them from the soil solution (Yuan *et al*., 2011; Dai *et al*., 2016).The presence of calcium in its elemental or carbonate form in both lime and biochar also has a neutralizing effect on soil acidity. Although the compost used in the study had a neutral pH of 7.1 it may have enhanced a reduction in soil acidity due to its calcium content.

In contrast to soil pH, the soil amendments in the current study did not increase soil organic carbon, nitrogen, phosphorous and potassium content compared to non-amended soils. These findings contradict those of Mensah and Frimpong (2018), Yao *et al*. (2018), and Teshome *et al*. (2017) who reported that combined application of biochar with lime or compost or both and sole application of biochar, lime and compost increased soil organic carbon and macronutrients compared to non-amended soils. This variation may be attributed to low organic carbon and nutrient content of biochar and compost than the other studies.

In the current study, the amount of nitrogen, phosphorous and potassium in biochar was 0.3, 0.4 and 0.7 and that of compost was 0.3, 0.5 and 0.3 which was similar to that of non-amended soils. The availability of soil nutrients results from the interaction of nutrients available in biochar and compost and their capacity to retain and release nutrients (Dai *et al*., 2016; Wang *et al*., 2016). The nutrient content and concentration of biochar and compost is influenced by their feedstocks and processing conditions (Dai *et al*., 2016; Adugna, 2016). Additionally, biochar and compost release their nutrients slowly (Wang *et al*., 2016). High C/N ratio of biochar reduced the availability of soil macronutrients which would be due to increased nutrient immobilization low nutrient mineralization (Le and Marschner, 2018).

5.2 Effect of soil amendments on root rot pathogens

The main root rot pathogens isolated from both amended and non-amended soils were *Fusarium oxysporum, Fusarium solani* and *Rhizoctonia solani*. Among the root rot pathogens, *F. oxysporum* was the most dominant species followed by *F. solani* and *R. solani* respectively. These findings are consistent to those of (Okumu, 2018) in Nandi South, (Were, 2019) in Western Kenya and (Naseri *et al*., 2020) who observed that *Fusarium solani* and *Fusarium oxysporum* were the most predominant root rot pathogens isolated from field soils. Contrary to findings of Naseri *et al*. (2020), Were, (2019) Okumu, (2018), this study did not isolate *Pythium* and *Macrophomina* species.

Prevalence of *Fusarium oxysporum* would be attributed to its ubiquitous nature, and its existence in form of pathogenic and non-pathogenic strains in the soil (Naseri and Mousavi, 2015). The absence of *Pythium* species would be attributed to the high acidity of the soil which impairs the growth of the pathogen. Moreover, according to Alhussaen (2012) the optimum growth of

Pythium species is at pH of 6 to 7 where it was observed to be pathogenic. Additionally, dry soils as those in Kapkerer characterized by low soil moisture content inhibit production and motility of zoospores (Agrios, 2005). *Pythium* species are more pronounced in the seedling stage of the crop where it is responsible for causing damping off because it affects younger tissues than older ones (Agrios, 2005) hence low pathogen population would be expected in soils sampled with crops at the pod-setting stage.

Population of *Fusarium oxysporum, Fusarium solani* and *Rhizoctonia solani* varied among the soil amendments, sites and seasons. In the long rains, high populations of *F. oxysporum* and *F. solani* were noted in Kapkerer and in the short rains high populations of *F. oxysporum* and *R. solani* were noted in Koibem. These findings are similar those of Naseri and Mousavi (2015) who noted that the composition of root rot pathogens varied in species and locations of fields. This would be attributed to varying amount of rainfall between the seasons (Appendix 1) and varying soil nutrient content and environmental conditions among the sites. According to You *et al*. (2019) and Keijer (1996) the inoculum of soil-borne pathogens and their development is influenced by nutrient and moisture content.

In this study, the soil amendments increased the population of *Fusarium oxysporum* across the study sites. Similarly, an increase in *Fusarium* spp. was noted by Okoth and Siameto (2010) and Höper *et al*. (1995) who amended their soils with manure and lime respectively. Increased population *F. oxysporum* in compost and compost plus DAP treatments would be attributed to the presence of *Fusarium oxysporum* in compost (Mehta *et al*., 2014). *Fusarium oxysporum* is a decomposer in the composting process and occurs at the cooling and late maturation phase (Mehta *et al*., 2014). Additionally, members of *F. oxysporum* exist as non-pathogenic endophytes or saprophytic colonizers on symptomless roots and on senescing and diseased roots (Bugress, 2013). Due to its alkaline nature compost reduces soil acidity which creates a favorable environment for growth of *F. oxysporum*. This is supported by a positive correlation between soil pH and *F. oxysporum* noted in the study. Furthermore, Tyagi and Paudel (2014) noted that optimum growth of *Fusarium oxysporum* occurs at pH levels of 6.

Contrary to *Fusarium oxysporum,* the soil amendments had both an increasing and decreasing effect on population of *R. solani* whereby application of compost, biochar with lime and DAP, compost with DAP, compost with lime decreased the population of *R. solani* compared to non-

amended soils. Whereas application of biochar with compost and DAP and lime with DAP increased the population of *R. solani*. These findings are in line with those of Jaiswal *et al*. (2014) who noted lower populations of *R. solani* in biochar amended soils compared to non-amended soils. However, this effect varied with the type of biochars used. Therefore, reduction in population of *R .solani* in the study would be attributed to the presence of compost and biochar. Suppression of *R. solani* by compost is enhanced by production of extracellular lytic enzymes by antagonistic microbes such as *Pseudomonas* and *Bacillus* (Pane *et al.*, 2011; Mehta *et al.*, 2014). On the other hand pathogen suppression by biochar would be due to the presence of lactic and glycolic acids which are anti-fungal compounds (Jaiswal *et al*., 2014). Although organic soil amendments have been reported to have an antagonistic effect on soil borne pathogens, their application may result to increase in disease and severity of soil borne pathogens due to an increase in pathogen population (Bonanomi *et al*., 2007).

A reduction in the population of *F. solani* was noted in soils amended with combined application of lime with DAP; biochar, lime and compost and lime with compost and DAP. A reduction in the population of *F. solani* would be due to increase in soil pH (Berek and Hue, 2016) by a synergistic liming effect of lime and biochar. This is supported by the negative correlation between soil pH and *F. solani* and increased soil pH in combinations of biochar with lime and biochar with lime and compost. Increased soil pH modifies the rhizosphere environment to stimulate the occurrence of *Pseudomonas, Rhizobium, Streptomyces, Bacillus* which are associated with pathogen suppression (Jaiswal *et al*., 2017).

Reduced soil acidity increases microbial diversity and activities of biocontrol and plant growth agents (Jaiswal *et al*., 2017). Biochar has been noted to adsorb signal molecules released during seed germination which induce germination of macro and microconidia of *Fusarium solani* (Were, 2019). Additionally, these soil amendments may alter the content and concentration of bean root exudate leading to production of phenolic compounds which delay pathogen development and interfere with mycelial growth or germination of chlamydospores and sclerotia (Akhter *et al*., 2016).

5.3 Effect of soil amendments on bean root rot

The effect of the soil amendments on percentage emergence, plant stand, plant mortality and incidences of bean root rot and stem maggot varied in site. The effect of the amendments was mostly noted in Kapkerer and Koibem. Variation among the sites would be due to their varying environmental conditions and agro-ecological zones (Odundo *et al*., 2010). Kapkerer belongs to the lower midland (LM1-3) zone and is characterized by dry and warm temperatures which favor higher plant emergence and stand counts (Odundo *et al.*, 2010). The sites also had varying amounts of organic carbon and phosphorous in the soils whereby Kapkerer had the least amount of organic carbon and macronutrient content whereas Koibem had the least soil pH (Mutai *et al.*, 2019).

Most of the amended plots had lower plant emergence and plant stand compared to non-amended plots. This effect was noted in plots where the amendments were combined and contained DAP such as biochar +compost+ lime+ DAP. Contrary to these results, Schulz and Glaser (2012) noted an increase in the growth of oats in amended plots especially those with combinations of biochar with a fertilizer. Other studies carried out by Wang *et al*. (2016) report that combinations of biochar with compost increased plant growth of mung bean. Low emergence and plant stand in plots amended with combined treatments which contain DAP would be attributed to the minimal nutrient content of the amendments used in the study. Moreover, farmers noted that plots amended with DAP had poor emergence.

Biochar and compost used in the study had low nitrogen, phosphorus and potassium content. Biochar and compost are organic amendments whose nutrient availability is low and is influenced by its feed stock and production processes (Dai *et al*., 2016; Adugna, 2016). Additionally, although organic amendments supply macro and micronutrients, the supply is regulated by the rate of mineralization hence it is neither sufficient nor balanced (van Zweiten, 2018). Mineral fertilizers such as DAP, though preferred due to their ease of application and availability of inorganic nutrients, lack essential micronutrients for plant growth and development (Kanton *et al*., 2016). Furthermore, DAP contains ammonium ions which acidifies the soil through nitrification thus influencing mineralization, mobilization and bio-availability of macro and micro-nutrients by having an effect on the nutrient transformation and cycling (Kunhikrishnan *et al*., 2016; Holland *et al*., 2018).

In the current study, the soil amendments had a varying effect on plant mortality. Plant mortality increased and decreased in combined treatments during the short rains of 2018 and long rains of 2019 respectively. Among the combined treatments, those with DAP had higher plant mortality during the short rains of 2018 and low plant mortality during the long rains of 2019. Increased plant mortality in treatments of lime + DAP, biochar +compost +lime+ DAP, biochar + lime+ compost and biochar + compost + DAP. These findings are contrary to those of Jaiswal *et al*. (2017) and Jaiswal *et al*. (2018) who noted that in biochar amended plots there was a delay in the collapsing of plants than in non-amended plots. The differences could be attributed to the presence of lime and DAP which is supported by observations made by farmers who noted that plots amended with lime or DAP had more wilted plants.

Bean mortality due to lime may be attributed to an indirect effect due to reduced soil acidity which increased the population of *Fusarium oxysporum* and whose optimum growth occurs at pH of 6 (Hoper *et al.*, 1994; Tyagi and Paudel, 2014). This is supported by a positive correlation between soil pH and *F. oxysporum* which was noted in the study. *Fusarium oxysporum* is responsible for causing wilting in common bean and is associated with *Fusarium solani* f.sp. *phaseoli* (Muthomi *et al*., 2014). Additionally, positive correlation between bean mortality and incidence of bean stem maggot may have resulted to an increase in wilted plants in amended plots. Plants infested with bean stem maggot usually wilt due to the feeding of the maggot at the stem bases which interferes with water and mineral uptake (Ochilo and Nyamasyo, 2011). Through wounds created by the maggot, *Fusarium oxysporum* species gain entry into the plant, produces macroconidia which block the xylem vessels and consequently leads to wilting (Mwang'ombe *et al*., 2008; Agrios, 2005).

Reduced root rot incidence of common bean was noted in amended plots relative to non-amended plots. Among the amended plots, lower root rot incidences were noted where the treatments were applied in combinations. The effect of the combined amendments would be attributed to biochar and lime which was a common component in all the combinations. Khalifa and Thabet (2015) observed a reduction in disease incidence and severities of *Fusarium oxysporum* and *Rhizoctonia solani* on tomato plants grown in soils amended with biochar. Jaiswal *et al*. (2017) also noted that biochar suppressed Fusarium crown and root rot of tomato through a reduction in *Fusarium* root colonization.

Reduction in incidence of bean root rot in amended plots compared to non-amended plots would be due to the synergistic effect of the amendments on population of soil borne pathogens due to changes in soil acidity. This is supported by a negative correlation of *Fusarium solani* to soil pH and incidence of root rot. Furthermore, in the current study, biochar and lime had lower population of *R. solani* while combined application of biochar with lime and compost had reduced population of *Fusarium solani*. Both biochar and lime contain calcium which was noted by Höper *et al.* (1995) to suppress Fusarium wilts. Calcium affects the rate of growth, conidia production and germination of *Fusarium* and *Rhizoctonia* species thus may lower pathogen inoculum level (McGovern, 2015; Chittem *et al*., 2016).

5.4 Effect of soil amendments on yield and yield components

In the current study, amended plots had higher number of seeds per pod, number of pods per plant, biomass and grain yield compared to non-amended plots. This effect was mostly noted where the organic amendments were combined with both lime and an inorganic fertilizer and where lime was combined with an inorganic fertilizer. These findings are consistent to those of Yao *et al.* (2019) who noted an increase in biomass of rice bean in combined application of lime with biochar. Shanka *et al*. (2018) also noted an increase in dry matter yield of common bean in combined application of lime with manure and lime with a phosphorous fertilizer. Mete et al. (2015) also reported an increase in biomass and seed yield of soybean in combined application of biochar with NPK fertilizer. Thus, increased grain yield would be attributed to the indirect effect of reduced soil acidity.

From the current study, populations of *Fusarium solani* were reduced in non-amended soils which are acidic compared to amended soils. This is supported by a negative correlation between soil pH and *F. solani*. The presence of Inorganic fertilizers such as DAP may have increased the supply of readily available nitrogen and phosphorus leading to an extensive root system (Osoro *et al*., 2014; Medvecky and Ketterings, 2009). Additionally, farmers also observed that plants in biochar and compost amended plots had darker green leaves indicating an increased potential for photosynthesis. Studies carried out by Agegnehu *et al*. (2015) similarly reported that combined application of biochar or compost with an inorganic fertilizer enhanced the chlorophyll content of maize. An increase of chlorophyll content would indicate that there is increased nutrient availability thus leading to vigorous and healthy crops (Agegenehu *et al*., 2015).

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study shows that biochar, lime and compost have an effect on soil acidity and this effect was consistent among the study sites. Sole application of lime and combined application of biochar with lime and biochar with lime and compost reduced soil acidity. The effect of the amendments on population of root rot pathogens, varied per pathogen and site. Both an increase and a decrease in population of *Rhizoctonia solani* was noted whereas, only an increase and decrease was noted in populations of *Fusarium oxysporum* and *Fusarium solani* respectively. The effect of the amendments on bean root rot varied on assessed parameters in site and season. Most effects were noted in Kapkerer which is characterized by low soil fertility.

The soil amendments had low emergence and plant stand compared to non-amended acidic soils. This effect was noted where the amendments were combined and contained DAP. Both high and low plant mortality was noted where the treatments were combined during the short rains of 2018 and long rains of 2019 respectively. Among the combined treatments, those with DAP had higher plant mortality during the short rains of 2018 and low plant mortality during the long rains of 2019. The soil amendments had lower incidences of bean root rot and increased seeds per pod, pods per plant, biomass and grain yield. This effect was noted where the amendments were combined and contained DAP and lime.

The study shows that liming improves bean productivity. The study shows that combining soil amendments with an inorganic fertilizer leads to an increase in yield in acidic soils. The study confirms that soil pH has a direct effect on soil borne pathogens and indirect effect on bean root rot and crop productivity. Therefore, biochar, lime and compost can be used as liming amendments in acidic soils and combined with an inorganic fertilizer to improve biomass and grain yield of common bean.

6.2 Recommendations

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

i. Application of lime, two-way combination of biochar with lime and three-way ombination of biochar with lime and compost to reduce soil acidity

ii. Combined application of biochar with lime to reduce bean root rot and application of either lime with an inorganic fertilizer, biochar with lime and compost, biochar with lime and biochar with lime and an inorganic fertilizer to increase biomass and grain yield of common bean in acidic soils

iii. Further research should be carried on the effect of combining biochar, lime and compost with other inorganic fertilizers such as NPK and Mavuno on bean root rot.

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APPENDICES

Appendix I: Rainfall data (mm) for experimental sites

	Kapkerer	Total number of Rain days	Kiptaruswo	Total number of Rain days	Koibem	Total number of Rain days	Total amount of rainfall per month
Short Rains 2018							
August	138.3	31	162.5	31	101.5	31	402.3
September	34.8	31	56.5	31	75.5	31	166.8
October	185.3	31	197.5	31	118.0	31	500.8
November	61.3	31	101.0	31	108.5	31	270.8
December	176.3	31	277.5	31	135.9	31	589.6
Mean	119.2	31	159.0	31	107.9	31	386.0
Long rains 2019							
January	97.0	31	25.0	31	83.8	31	205.8
February	96.5	31	61.0	31	92.8	31	250.3
March	74.0	31	51.0	31	86.3	31	211.3
April	145.5	31	149.5	31	113.1	31	408.1
May	189.4	31	292.0	31	410.5	31	891.9
June	213.3	31	208.0	31	312.0	31	733.3
July	81.3	31	98.0	31	173.8	31	353.0
Mean	128.1	31	126.4	31	181.7	31	436.2

Appendix II: Semi structure questionnaire for evaluating farmers on use of biochar, compost, lime and DAP during on-farm trials

FARMER EVALUATION ON THE USE OF BIOCHAR, COMPOST, LIME AND DAP DURING ON-FARM TRIAL TO IMPROVE BEAN PRODUCTIVITY

Root rot of common bean is a major constraint to bean productivity in areas with low soil fertility. Biochar, lime, compost and DAP were assessed on their effectiveness to manage bean root rot and improve bean production. These amendments were applied at 1t/ha, 2t/ha and 67kg/ha respectively. This was determined by carrying out on-farm trials within Kapkerer, Kiptaruswo and Koibem in Nandi South. During the trial, various observations were made by the farmer. Ten to thirteen farmers from each site will be interviewed on the observations made on the growth, performance, pests, diseases and yield of the common bean.

Farmer information

Name: _____

Gender: _____

Site/Village: _____

Date: _____

SECTION A: Prior knowledge on the use of soil amendments

1. How do you manage fields with low soil fertility? Or fields with low plant productivity within your farm?

2. Have you used any soil amendments before?
   Yes ☐ No ☐

   a) If yes:

What amendment do you use, what amount do you apply, and why do you prefer it?

Type of soil amendment	Quantity applied and frequency	Preference
_____	_____	
_____	_____	
_____	_____	
_____	_____	

b) If no, why not?

SECTION B: Farmer involvement in the trial

What observations did you make during the bean growing season?(planting, emergence, pest and disease incidence, flowering, podding, maturity and harvesting)

SECTION C: How the amendments affected the growth (emergence, plant stand), performance (plant height, leaf color, number of branches, flowering, podding), pest and disease incidence and quality and quantity of grain yield

1. According to you, how was the growth of the bean plants among the soil amendments? How would you rank the soil amendments based on the growth of the crop and why?

2. What was the performance of the bean plants among the soil amendments used?How would you rank these amendments on the basis of performance and why?

3. What were the pests, plant diseases and symptoms observed among the soil amendments? In which amendment were these diseases and symptoms observed? How would you rank these soil amendments on the basis of disease and pest incidence?

4. Was there any difference in the quantity and quality of grain yield harvested among the soil amendments?

5. Did the amendments address the problems that hinder bean production in your farm? If yes, which specific soil amendments did and for which problems? If No, why not?

How would you rate the treatment (Best to worst) and why?

Biochar _____
Lime _____
Compost _____
DAP _____

SECTION D: Individual soil amendments versus combined soil amendments

What observations did you make between plots with individual soil amendments and combined soil amendments on:

a. Growth of the crop

_____
_____
_____
_____
_____
_____

b. Performance of the crop, pest and disease incidence, grain yield (quality and quantity)

_____
_____
_____
_____
_____

SECTION D: Adoption of Biochar, compost and lime by farmers

Would you adopt any of these soil amendments?

If Yes, which treatment?_____ And why?

_____

If No, which treatment? _____ And why?

_____

Would you use these amendments individually or in their combinations?

i. If individual, which soil amendment and why?

_____

ii. If combination, which combination and why?

_____

Thank you for your time!