

**EFFECTS OF BIOCHAR AND COMPOST ON SOIL PHYSICOCHEMICAL
PROPERTIES AND MAIZE YIELD IN ACIDIC FERRALSOL IN KAMITI
SUB-CATCHMENT, KIAMBU COUNTY, KENYA**

EMMANUEL ABBAN-BAIDOO (B.Sc. Agriculture)

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DECLARATION

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

Signature: _____ Date: _____

Candidate: Emmanuel Abban-Baidoo

I56F/39373/2016

We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

Prof. Christopher A. Shisanya

Department of Geography

Kenyatta University

Post Office Box 43844-00100

Nairobi, Kenya.

Signature: _____ Date: _____

Dr. Anthony N. Macharia

Department of Geography

Kenyatta University

Post Office Box 43844-00100

Nairobi, Kenya.

Signature: _____ Date: _____

DEDICATION

This work is dedicated to my late mother Madam Margaret Simpson, father Mr. John Louis Abban and siblings Juliet Abban, Francis Abban, Wisdom Abban-Baidoo and William Abban-Baidoo.

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ABSTRACT

The rapidly increasing global population, climate change and dwindling resources have made it very difficult to meet global food demand. To address the issue of food insecurity, sustainable intensification of agriculture (SIA) has been proposed. However, the consequences of poorly managed agricultural intensification can negatively affect the ecosystem. Biochar and compost application has been widely recommended as a highly promising soil fertility replenishment option to promote sustainable agriculture. In Kenya, only relatively recent few studies have been done to assess the effect of biochar applications on the quality of poor soils. This research is therefore, intended to investigate how biochar, applied alone or with compost could improve soil quality and increase maize yield in an acidic Ferralsol in Kamiti sub-catchment, Kiambu County of Kenya. Specifically, the study sort to 1) assess the effect of biochar, compost and their combined application on soil physical properties, 2) assess the effect of biochar, compost and their combined application on soil chemical properties and 3) determine the effect of biochar, compost and their combined application on maize growth and yield. To achieve the objectives, 6-month field trial was carried out on an acidic Ferralsol with high Al and Fe contents at the Kenyatta University Research Farm using the Randomized Complete Block Design (RCBD) comprising six treatments which included; control with no amendment (C), 20 t ha⁻¹ Biochar (20B), 40 t ha⁻¹ Biochar (40B), 20 t ha⁻¹ Compost (20C), 40 t ha⁻¹ Compost (40C) and 20 ha⁻¹ Biochar + 20 ha⁻¹ Compost (BC). During the study, data on plant height, stem diameter and leaf area were taken after every 2 weeks. Plant samples taken at the tasseling stage and soil samples taken at physical maturity stage of the maize, respectively, were dried, ground and sieves (< 2 mm) before being sent to the Soil Science laboratory of the Department of Soil Science / Soil Ecology, Ruhr University Bochum for analysis. Statistical analysis of data was done using SPSS (version 25) statistical software. The study showed that single or combined application of biochar and compost reduced soil bulk density. The reduction in bulk density followed the decreasing order BC<40B<40C<20B<20C and C. The incorporation of biochar and compost singly or in combination increased soil water holding capacity as well as aggregate stability by 56.7% (in 40B) and 71.5% (in 40C) respectively. Soil chemical properties including available phosphorus (P), electrical conductivity (EC), exchangeable K and Mg, and cation exchange capacity (CEC) were significantly increased in the amended soils than the unamended control. Plant growth parameters such as plant height, stem diameter and leaf area were increased by the application of the organic amendments with BC treatments recording the highest increases. Grain yield (GY) and hundred grain weight (HGW) were significantly improved relative to the control treatment for all organic amendment, with increases in grain yield between 12.2% (in 40B and 40C) and 22.8% (in BC). The results suggest that the application of biochar and compost can reduce soil bulk density, increase aggregate stability, water holding capacity, soil nutrient status and maize yield. The study concludes that biochar-compost-base soil management approach offer the potential for soil fertility improvement, and recommend it for adoption by farmers in Kamiti sub-catchment.

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LIST OF UNITS

cmol kg^{-1} centimol charge per kilogram

g cm^{-3} gram per cubic centimetres

mg kg^{-1} milligram per kilogram

g kg^{-1} gram per kilogram

t ha^{-1} tons per hectare

$\mu\text{s cm}^{-1}$ microseconds per centimeter

LIST OF ABBREVIATIONS AND ACRONYMS

BD	Bulk Density
CEC	Cation Exchange Capacity
CRD	Completely Randomized Design
EC	Electrical conductivity
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GY	Grain yield
HGW	Hundred grain weight
KARI	Kenya Agricultural Research Institute
LA	Leaf Area
LSD	Least Significant Difference
NAAIAP	National Accelerated Agricultural Inputs Access Programme
NEMA	National Environment Management Authority
SSA	Sub Sahara Africa
TN	Total Nitrogen
TOC	Total Organic Carbon
WHC	Water Holding Capacity

CHAPTER ONE

1 INTRODUCTION

1.1 Background to the study

The World's soils are under threat from erosion, acidification, salinization, nutrient imbalances, biodiversity losses and contamination, among many others, which has resulted in a decline in productivity across many parts of the world (Montanarella *et al.*, 2016). In addition, the rapidly increasing global population, climate change and dwindling resources have made it very difficult to meet global food demand (Kang *et al.*, 2017; Bass *et al.*, 2016). Meeting this increasing demand for food in the context of declining resources and changing climatic conditions, brings to fore the urgency of innovative techniques required for agricultural intensification (Burrell *et al.*, 2016). Thus, increasing the size of land under cultivation, increasing application of chemical fertilizers and increasing crop area under irrigation.

To address the issue of food insecurity, sustainable intensification of agriculture (SIA) has been proposed. However, the consequences of poorly managed agricultural intensification can negatively affect the ecosystem (Agegnehu *et al.*, 2015; Kang *et al.*, 2017). In most sub-Saharan African (SSA) countries, agriculture is the backbone of their economies (Davis *et al.*, 2017), but declining soil fertility and reliance on rain-fed agriculture represent major constraints to agricultural productivity. In Kenya for example, agriculture has contributed significantly to the economic growth and employs more than half of the country's population (Wandaka *et al.*, 2017). Given poor land practices and

continuous cropping, fertility of most soils in Kenya has been depleted (Wandaka *et al.*, 2017).

This situation has led to excessive use of chemical fertilizers on many commercial agricultural fields, with attendant negative environmental consequences (Agegnehu *et al.*, 2016). According to Ahmad *et al.* (2016), agriculture is the major nonpoint source polluter of both surface and groundwater, and this has been attributed to the way in which agriculture has been practised over the years (Boulding and Ginn, 2016). Sustainable practices to increase food production are urgently needed to reduce pressure on agricultural soils (Burrell *et al.*, 2016) and to reduce its negative impact on the environment.

Various soil fertility improvement technologies have been tried (Agegnehu *et al.*, 2017; Trupiano *et al.*, 2017; Cao *et al.*, 2018; Mensah and frimpong, 2018; Manolikaki and Diamadopoulos, 2019). For example, the use of organic resources such as biochar has been recommended as an alternative options for improving soil quality to promote sustainable agriculture (Rawat *et al.*, 2019). Biochar is produced by burning biomass under very little or no oxygen environment, a process known as pyrolysis (Bonanomi *et al.*, 2017).

Effect of organic amendments such as biochar, compost or their combination on soil properties and yield have been reported for maize (Agegnehu *et al.*, 2016; Mensah and Frimpong 2018; Shareef *et al.*, 2018; Manolikaki and Diamadopoulos, 2019), cabbage (Kiran *et al.*, 2017), cucumber (Cao *et al.*, 2018), lettuce (Bonanomi *et al.*, 2017), banana and papaya (Bass *et al.*, 2016). Positive, and to a lesser extent negative effect of biochar

application on crop yield have also been reported (Bass *et al.*, 2016). The porous nature, large surface area and high recalcitrant carbon content of biochar makes it more preferable than other organic resources (Rawat *et al.*, 2019). For instance, biochar applied to soil can increase the soil water holding capacity (WHC), pH and cation exchange capacity (CEC), which in turn reduce the leaching of exchangeable cation (Agegnehu *et al.*, 2016), and reduce fertilizer requirements and its associated negative environmental consequences (Cao *et al.*, 2018).

Biochar study is recent in Kenya, therefore there is limited evidence on its effects on soils quality and crop yield. Furthermore, previous studies have focused minimally on potentials of combined application of biochar and compost to improve soil properties and increase crop yields. This research is therefore, intended to investigate how biochar, applied alone or with compost could improve the physicochemical properties of acidic soils and maize yield in Kamiti sub-catchment, Kiambu County of Kenya.

1.2 Statement of the problem

Soil fertility depletion had been identified as one of the major problems accounting for low crop yield in Kenya. The National Accelerated Agricultural Inputs Access Programme (NAAIAP) and Kenya Agricultural Research Institute (KARI) report in 2014 categorized the soil of the Kamiti sub-catchment as low nutrient soil with high aluminum toxicity. The report recommended fertilizer applications to replenish the fertility of the soil. However, various studies indicated that agricultural practices such as chemical fertilizer application, pesticide and herbicide use are major sources of water pollution from agricultural fields.

Organic waste management also represents a major challenge in the study area. Solid waste production in Kenya is 4 million tons per year. About 50% of the total solid wastes produced (1.9 million tons) are food wastes. Improper disposal of these organic wastes has led to various kinds of nuisance with serious environmental and health implications. These organic wastes can be converted into biochar and compost, and be used as an organic amendment to improve soil quality, and at the same time to reduce the negative impact on the environment and public health.

Given the potential benefits reported with the use of biochar and compost on soil quality and crop yield improvements, its adoption on a large scale into policy remains a major challenge due to insufficient scientific evidence. This is because, biochar research is still a new research area in most sub-Saharan African (SSA) countries and information on its effects on soil quality and crop yield remains scanty. Additionally, most previous studies carried out on biochar and or compost (for example, Akça and Namli, 2015; Frimpong *et al.*, 2016; Cao *et al.*, 2018; Mensah and Frimpong, 2018; Manolikaki and Diamadopoulou, 2019) have been done in greenhouses and pot experiments. Few scientific studies have detailed the effects of biochar applied alone or in combination with compost at field scale. More scientific studies are needed at the field scale to better understand how sole application of biochar or in combination with compost could influence soil quality and crop yield in an acidic Ferralsol soil in Kenya.

1.3 Justification and significance of the study

This study was conducted within Kamiti sub-catchment in Kiambu County of Kenya. The study area was selected because majority of the populations are farmers growing food

crops such as maize, beans and assorted vegetables (Musa and Odera, 2015). The livelihood of the inhabitants in this sub-catchment depends on these subsistence farming activities. However, due to low crop output and sometimes crop failure, farming can no longer support the livelihood of these farmers. Therefore alternative and innovative agricultural practices that have the potential to increase crop production may eventually result in improved livelihood.

The study also offers an alternative use for organic wastes which are in abundance in the catchment. Among the most common organic waste found in the catchment are corn cob and vegetable wastes. This is because maize is a staple food in Kenya and is mostly consumed together with vegetables in a meal. Improper disposal of these organic wastes could clog waterways and serve as breeding ground for pests and diseases resulting in health implications.

The findings of this study will make contribution to existing knowledge to facilitate the monitoring and evaluation of sustainable agricultural technologies regarding their effects on soil properties and crop yield in the sub-catchment.

1.4 Research questions

The following are the research questions:

- i. How do the application of biochar, compost and their combination on Ferralsol soil affect its physical properties (bulk density, aggregate stability and water holding capacity)?
- ii. How do the application of biochar, compost and their combination on Ferralsol soil affect its chemical properties (pH, EC, TC, TN, available P, exchangeable

bases (Mg^{+2} , Ca^{+2} , K^+ and Na^+), CEC and total elements (Mg, Na, K, P, Ca, Al and Fe))?

- iii. Do biochar and compost application on Ferralsol soil have an effect on maize growth and yield?

1.5 Research hypotheses

Ho:

- i. Biochar, compost and their combined applications have no significant effects on the soil bulk density, aggregate stability and water holding capacity of an acidic Ferralsol.
- ii. Biochar, compost and their combined applications have no significant effects on the chemical properties (pH, EC, TC, TN, available P, exchangeable bases (Mg^{+2} , Ca^{+2} , K^+ and Na^+), CEC and total elements (Mg, Na, K, P, Ca, Al and Fe)) of an acidic Ferralsol.
- iii. Biochar and compost applications do not significantly affect maize growth and yield.

1.6 Objectives of the study

1.6.1 General objective

The general objective of the study was to investigate the effects of biochar, compost and their combined application on soil physicochemical properties and maize yield in Kamiti sub-catchment, Kenya.

1.6.2 Specific objectives

The study addressed the following specific objectives:

- i. To assess the effect of biochar, compost and their combined application on soil physical properties (bulk density, aggregate stability and water holding capacity)
- ii. To assess the effect of biochar, compost and their combined application on soil chemical properties (pH, EC, TC, TN, available P, exchangeable bases (Mg^{+2} , Ca^{+2} , K^+ and Na^+), CEC and total elements (Mg, Na, K, P, Ca, Al and Fe))
- iii. To determine the effect of biochar, compost and their combined application on maize growth and yield.

1.7 Scope and limitations of the study

The study primarily focused on the Kamiti sub-catchment located in Kiambu County of Kenya. Major limitations are that although the catchment has the same soil type (Ferralsols), and under the same agro-climatic zone (semi-arid), the study only considered one location and one growing season (March to July) due to logistical constraints and time. Collecting data for at least two seasons and at different locations could have generated enough data to make concrete predictions on the effect of biochar and compost applications on soil quality and crop yield for the entire sub-catchment. Therefore in future studies, it is recommended that different locations within the watershed and different growing seasons should be considered.

1.8 Operational definition of key terms and concepts

Biochar: Charcoal produced by burning biomass (plant or animal residues) under little or no oxygen condition.

Cation Exchange Capacity: Measure of the total amount of cations (Mg^{+2} , Ca^{+2} , Na^{+} , K^{+}) that can be retained on the surfaces of the soil particle. The cation exchange capacity is an important soil quality parameter that influences soil management practices and the suitability of soils for agriculture.

Compost: Mixture of decomposed or decomposing organic materials (plant or animal residues) produced by initiating microbial activities under favourable conditions to aid further decomposition. Due to its inherent properties, application of compost has been found to improve soil fertility through mineralization of organic matter.

Feedstock: Biomass (plant or animal residues) that is to be pyrolysed in order to produce biochar. Both the feedstock type and the pyrolysis temperature affects the physicochemical properties of the biochar.

Ferralsols: Highly weathered and strongly leached mineral soils with “Oxic” B-horizon.

Maize Growth: The physiological changes in the maize plant from germination to maturity.

Maize Yield: The quantity (grain weight) and quality (nutritional composition) of maize plant at maturity.

Pyrolysis: The process of burning biomass in the absence of oxygen or very little oxygen leading to the production of biochar.

Recalcitrant Carbon Content: The carbon content of the biochar which makes it resistant to decomposition and therefore persists in soils for hundreds to thousands of years.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Biochar production and its properties

The chemical composition of biochar includes carbon, hydrogen, sulfur, nitrogen, oxygen and minerals (Ca, Na, K, and Cl) in the ash fraction (Rawat *et al.*, 2019). Biochar is a product of thermochemical decomposition of biomass (plant or animal) under limited oxygen from 250°C to > 900°C in a process known as pyrolysis (Bonanomi *et al.*, 2017). According to Lehmann and Joseph (2015), the chemical properties of the organic carbon structure of the biochar are fundamentally different from those of the materials from which the biochar was produced.

Biochar is highly porous, black in colour, lightweight, have a large surface area and has high pH. All these characteristics have positive effects on its application to soils (Rawat *et al.*, 2019). Biochar has a higher specific surface area, and when applied to the soil will result in an increase in soil surface area (Lehmann and Joseph, 2015). A wide range of biomass such as maize cob, maize straw, rice husk, wheat straw, animal manure and other agricultural residues can be used as a feedstock for biochar production (Blanco-canqui, 2017; Kiran *et al.*, 2017). However, the nutrient composition of the biochar produced depend on the type of feedstock and the pyrolysis conditions (Shareef *et al.*, 2018).

For example, Sharref *et al.* (2018) found out that the pH of biochar produced from maize straw pyrolysed at 300°C (9.42) was higher than the biochar produced from maize cob pyrolysed at 300°C (8.63). They also reported an increase in biochar pH and ash content with increasing pyrolysis temperature. Due to the different properties of biochar as

influenced by feedstock type and pyrolysis conditions, both positive and negative effect on soil quality and crop yield have been reported (Bass *et al.*, 2016; Burrell *et al.*, 2016).

Biochar can be produced on a large scale (cost-intensive) using large pyrolysis plants and higher amount of feedstock or on a small scale (low-cost) using locally modified stoves or kilns (Rawat *et al.*, 2019). During pyrolysis, oil and gases are generated as by-products (Zhu *et al.*, 2018). Pyrolysis is classified as fast pyrolysis or slow pyrolysis depending on the temperature and time duration of heating. In fast pyrolysis, the feedstock is heated at temperatures above 500°C within a shorter time (heating rates $\geq 1000^{\circ}\text{C mm}^{-1}$). Slow pyrolysis uses temperatures of less than 500°C and takes more time to fully pyrolyze (heating rates $\leq 100^{\circ}\text{C mm}^{-1}$). The bio-oils produced during fast pyrolysis are more than the bio-oils produced from slow pyrolysis (Rawat *et al.*, 2019).

2.2 Effect of biochar and compost application on soil physical properties

The effect of biochar and/or compost application on soil physical properties has been widely studied (Burrell *et al.*, 2016; Glab *et al.*, 2016; Liu, *et al.*, 2016a; Liu *et al.*, 2016b; Obia *et al.*, 2016; Zheng *et al.*, 2016; Blanco-Canqui, 2017; Trupiano *et al.*, 2017). Both positive and negative effect of biochar application on soils physical properties have also been reported (Blanco-Canqui, 2017). The soil physical properties directly or indirectly influence the soil chemical and biological processes. For example, the physical property of soil can be used as an indicator for plant root growth, aeration, erosion, nutrient uptake and water retention (Blanco-Canqui, 2017).

2.2.1 Soil bulk density (BD)

Biochar application on soils had been found to decrease bulk density (Burrell *et al.*, 2016; Blanco-Canqui, 2017; Jeffery *et al.*, 2017). In a review by Blanco-Canqui (2017) on biochar and soil physical properties, application of biochar can reduce soil bulk density up to 31%. This is an indication that biochar applied to soil can generally decrease the bulk density. He further explained that the extent of the effect of biochar on soil bulk density may vary depending on soil type. The application of biochar to soils will significantly decrease the soil bulk density by increasing the soil pore volume as a result of higher porosity of the biochar (Glab *et al.*, 2016).

In a similar study, bulk density was found to decrease with increasing application of biochar (Glab *et al.*, 2016; Liu *et al.*, 2016a). Burrell *et al.* (2016) found that soil bulk density was decreased in soils amended with different biochar types (straw, woodchip and vineyard) and persisted in the soil for over 3 years relative to the control. They further explained that biochar with low density can dilute the soil to reduce the bulk density. The combined effect of biochar and compost application on soil bulk density has also been studied (Bass *et al.*, 2016).

According to Bass *et al.* (2016), application of biochar together with compost decreased bulk density as compared to the control treatment at the initial stage of the field trial however, at the trial end, difference in bulk density among the treatments were not significant. In another trial location, application of biochar together with compost did not significantly change bulk density after cultivation. Due to the above reasons, soil bulk density should be assessed site-specific basis.

2.2.2 Soil aggregate stability

Soil aggregate stability is an important indicator of soil structural stability and resilience as it affects many vital soil processes such as erosion, water infiltration and macropores development (Blanco-Canqui *et al.*, 2017). Previous studies have reported both positive (Curaqueo *et al.*, 2014; Burrell *et al.*, 2016; Gamage *et al.*, 2016; Ma *et al.* 2016; Obia *et al.*, 2016) and no effect (Jeffery *et al.*, 2015; Zhang *et al.*, 2015; Burrell *et al.*, 2016) of biochar application on soil aggregate stability. In a review, Blanco-Canqui (2017) found out that biochar applied alone increased aggregate stability of 24 soil types but had no effect on 10 soil types.

In a field trial conducted by Burrell *et al.* (2016) on 3 soil types (Planosol, Chernozem and Cambisol) and 3 biochar types (straw, woodchip and vineyard), biochar application was found to have significantly increased the soil aggregate stability in the Planosol and Chernozem but had no effect on the Cambisol. An increase in the soil aggregate stability of 28 to 92% was recorded in the Planosol and 26% in the Chernozem.

In a similar study, Gamage *et al.* (2016) found an increase in aggregate stability with increasing biochar application but differences were only significant in the 1% biochar amended soil at 180 days after application. They further explained that the interactions between biochar particles and soil mineral particles during aggregate formation often depend on the clay content of the soil. This means that the effect of biochar application on aggregate stability will be greater on clayey soil than sandy soils. Also, according to Aslam *et al.* (2014), biochar application to soils provides refuge for microorganisms

which in return secrete certain polysaccharides to increase the adherence of soil colloidal particles, resulting in improved soil aggregation.

2.2.3 Soil water holding capacity (WHC)

Water Holding Capacity (WHC) represent the nutrient retention capacity of the soil (Cao *et al.*, 2018). The WHC plays an important role in water management and serves as an indicator of soils suitability for agriculture especially in arid and semi-arid regions (Blanco-Canqui, 2017). Cao *et al.* (2018) reported an increase in WHC in both biochar and compost amended soils and attributed the increase to the carbon content of the biochar and compost used in their study. They explained that the increase in WHC resulted in an increase in CEC in the amended soils, which suggest combined efficiency of compost and biochar in enhancing soil water and nutrient retention capacities.

Agegnehu *et al.* (2016) recorded an increase of 24.5% water content in biochar + compost + fertilizer amended soil compared to the control soil. In a similar study on two soil types (Ferralsol and Chromosol), Bass *et al.* (2016) found an increase in soil WHC of all organic amended Ferralsol by 23.3% (combine) to 40.8% (biochar) but the difference in WHC of Chromosol soils were not significant.

Water retention capacity of a soil is very crucial when plant growth is of concern. Soils with higher water holding capacity will require less irrigation and can support plant growth better (Cao *et al.*, 2018). Agegnehu *et al.* (2016) stated that the soil available water content can be increased up to 24.5% in biochar-compost amended soils. According to Cao *et al.* (2018), biochar-compost amended soils can retain 87.6 to 173% more moisture

than soils without biochar. The study concluded that the increase in water retention capacity of soils by biochar application is only restricted to the coarser textured soils.

2.3 Effect of biochar, compost and their combined application on soil chemical properties

Various scholars (Agegnehu *et al.*, 2016; Bass *et al.*, 2016; Bonanomi *et al.*, 2017; Jeffery *et al.*, 2017; Trupiano *et al.*, 2017; Cao *et al.*, 2018; Mensah and Frimpong, 2018; Shareef *et al.*, 2018; Manolikaki and Diamadopoulos, 2019; Sigua *et al.*, 2019) have reported improvement in soil chemical properties following biochar and/or compost applications. The reported improvement in chemical properties varied with biochar type, pyrolysis temperature, combined rates and soil type.

2.3.1 Soil pH

An increase in pH following biochar and/or compost application had been observed by many studies (Chintala *et al.*, 2014; Bass *et al.*, 2016; Kiran *et al.*, 2017; Shareef *et al.*, 2018; Mensah and Frimpong, 2018) Biochars are mostly alkaline (pH > 7) with higher base cation concentrations, and when applied to soils can release base cations into the soil solution to reduce acidity through proton consumption reactions (Chintala *et al.*, 2014).

In a pot experiment conducted by Mensah and Frimpong (2018), the sole application of biochar was found to have increased soil pH from 4.8 to 6.1. The increase in pH in the biochar amended soils was attributed to the high pH of the biochar used in their experiment. It was concluded that biochar can be used as an alternative option to lime materials to ameliorate acidic soils. In a similar study conducted by Shareef *et al.* (2018), pH of biochar amended soil was found to increase with increasing pyrolysis temperature.

In their study, the highest pH was recorded in soils amended with biochar pyrolysed at 600°C (11.03) followed by 300°C (8.63).

In a field trial conducted by Bass *et al.* (2016), application of biochar was found to have significantly increased the soil pH only in the first half of the trial, however, at the trial completion, differences among treatments were not significant. Also, application of compost and the combined application of biochar and compost was found to have recorded higher pH values than the control, but the differences were not significant. They explained that the no significant differences observed at the trial completion could be due to the low application rates of biochar and compost used. Since soil pH can change under changing climatic conditions and changing land-use practices, it is important that biochar and compost effect on soil pH be assessed regularly in the long term to further understand the dynamics in pH of soils with differing acidity.

2.3.2 Electrical conductivity (EC)

In previous studies (Chintala *et al.*, 2014; Burrell *et al.*, 2016; Shareef *et al.*, 2018), EC was found to have increased with an increasing application rate of biochar. Chintala *et al.* (2014) attributed the increase in EC to alkalinity, CaCO₃ content, proton consumption capacity, and base cation concentration of the biochar used in their study. They explained that biochar contains higher soluble salts which are released into the soil solution which could increase the soil EC. The increase in EC was also attributed by Shareef *et al.* (2018) to the release of weakly bound ions of the biochar into the soil solution making it easy to be absorbed by the plant.

In a pot experiment conducted by Burrell *et al.* (2016) on 3 soil types (Planosol, Chernozem and Cambisol), EC was found to have increased significantly in the woodchip-biochar amended soils from $6.8 \mu\text{S cm}^{-1}$ immediately after application to $113 \mu\text{S cm}^{-1}$ 3 years after application. However, in the Chernozem and Cambisol, differences in EC after 3 years were not significant relative to the control. This supports the claim that biochar and compost effect on soil properties are specific to soil type and amendment properties.

2.3.3 Total nitrogen (TN)

Nitrogen, being one of the most important macronutrients for crop growth and development is limited in most tropical soils. The C/N ratio is widely used as a factor to assess availability of nitrogen in soils. When the C/N ratio of organic material is greater than 10, N becomes immobile (Manolikaki and Diamadopoulos, 2019), hence unavailable for plant use. This suggests that N losses in soil either by plant uptake or by leaching will be higher in un-amended soils than the biochar amended soils (Khan *et al.*, 2018).

Previous studies (Chintala *et al.*, 2014; Agegnehu *et al.*, 2016; Khan *et al.*, 2018; Manolikaki and Diamadopoulos, 2019) have shown significant improvement in soil TN following the application of biochar and compost. For example, Agegnehu *et al.* (2016) found that applying biochar together with compost can increase soil TN by 14% to 29%. Schulz *et al.* (2013) also reported that composted-biochar application can increase soil TN and correlates significantly with plant height and plant weight.

2.3.4 Total carbon and C/N ratio

In a field trial by Bass *et al.* (2016), the soil carbon content was increased significantly by all the organic amendments (biochar, compost and biochar-compost). At the end of their field trial, the average carbon stock had increased to 24.2, 8.4 and 17.6 t ha⁻¹ for biochar, compost and biochar-compost respectively. They explained that the increase in carbon stock was seen in the significant increase in the %C and C/N ratio of the soil at the trial end. Other studies (Bayu *et al.*, 2016; Trupiano *et al.*, 2017; Mensah and Frimpong, 2018; Manolikaki and Diamadopoulou, 2019) have also reported an increase in soil carbon content after biochar and/or compost was applied.

According to Bayu *et al.* (2016) applying different rates of biochar to acidic soils will significantly increase the mean soil carbon (OC) content, organic matter (OM) content and nitrogen (TN) content. Their findings indicated a percentage increase of 35.0% OC, 35.1% OM and 34% TN as a result of biochar application. Mensah and Frimpong (2018) found an increase in the carbon content of biochar and compost amended soils and attributed the increase to the biochar's ability to enhance carbon accumulation and sequestration.

In a similar study, Frimpong *et al.* (2016) found that organic carbon content of soils amended with cow dung and biochar were higher as compared to the control soil. Additionally, Trupiano *et al.* (2017) found that biochar and compost amended soils have high soil carbon content than the un-amended soils, which is an indication that compost and biochar applications to soils can enhance carbon accumulation and sequestration.

2.3.5 Available phosphorus (P)

Phosphorus and Nitrogen are important macronutrients which are widely and heavily applied on agricultural fields. Phosphorus and nitrogen losses either through leaching or runoff in agricultural field represent a major environmental risk in most countries leading to eutrophication and deterioration of both surface and groundwater (Cao *et al.*, 2018). It is apparent that sustainable farming practices are geared towards minimizing P losses in agricultural soils. Biochar application to soils had been reported to reduce P losses (Chintala *et al.*, 2014; Cao *et al.*, 2018). The ability of biochar to reduce P losses have been attributed to the high affinity of biochar for P which transforms P from readily available form to less available form (Cao *et al.*, 2018)

In a pot experiment, Mensah and Frimpong (2018) found out that the application of biochar and compost significantly increased the soil available P. The highest available P content was found in the sole biochar amended soils (722.1 to 760 mg kg⁻¹) as compared to the control soils (570.4 to 593.8 mg kg⁻¹). They attributed the increase in available P to reduced Fe and Al activities as influenced by the increase in soil pH. Also, in a long term field study on Ferralsol, Agegnehu *et al.* (2016) found that biochar applied solely or in combination with compost increased soil available P by 59% - 117%.

2.3.6 Exchangeable cations (Mg⁺², Ca⁺², Na⁺ and K⁺) and cation exchange capacity (CEC)

According to Bayu *et al.* (2016), increase in CEC of biochar-amended soils can be attributed to negative charges released from carboxyl groups of the organic matter. It was found that the untreated acidic soil had 24.95 me/100 g level of CEC before biochar

application. The CEC level increased from 24.95 to 34.9 me/100 g (28.7% increase) after biochar application. Nigussie *et al.* (2012) reported an increase in soil exchangeable bases in chromium polluted soils in Ethiopia after applying biochar to the soil. The increase in exchangeable bases was attributed to the existence of ash in the biochar which helps in continues release of minerals like Ca and K for crop use.

In a similar study, Mensah and Frimpong (2018) recorded higher significant exchangeable Ca and Mg value in soil types amended with 2% compost. They attributed the increase in Ca and Mg to the higher ECEC of the compost used in their experiment. In another study, Cao *et al.* (2018) found an increase in CEC in both low nutrient and high nutrient soils. They explained that the increase in CEC could be due to the higher carbon content of the biochar and compost applied to the soil. CEC represents the nutrient retention capacity of a soil and therefore soil with low CEC will be prone to nutrient leaching.

Biochar is porous in nature with the higher surface area which can retain more nutrients on its charged surfaces making nutrients less mobile (Rawat *et al.*, 2019). Bass *et al.* (2016) reported an increase in CEC by 27.5%, 24.7% and 4.1% in biochar, compost and biochar-compost amended soils respectively. Also, in an incubation experiment, Chintala *et al.* (2014) observed an increase in CEC continuously over the incubation period in all the biochar treatments. They attributed the increase in CEC to alkalinity, proton consumption capacity, and base cations concentration of the biochars used in their study.

2.4 Effect of biochar, compost and their combined application on crop growth and yield

Plant growth and development in biochar amended soil are directly related to nutrients released from biochar material and indirectly to the positive responses due to biochar application either by nutrient savings or improved fertilizer-use efficiency (Rawat *et al.*, 2019). The effects of biochar on crop growth and yield have been documented for many crops. The effects have been shown to depend on the quantity and the quality of the biochar applied.

Increased crop yield and performance in biochar-amended soils has been reported for crops including rice (Agusalim *et al.*, 2010), maize (Agegnehu *et al.*, 2016; Mensah and Frimpong 2018; Shareef *et al.*, 2018; Manolikaki and Diamadopoulos, 2019), cabbage (Kiran *et al.*, 2017), cucumber (Cao *et al.*, 2018), lettuce (Bonanomi *et al.*, 2017) and banana and papaya (Bass *et al.*, 2016).

2.4.1 Maize growth

Improvements in the physicochemical properties of biochar-amended soils will result in an improved crop performance (Shareef *et al.*, 2018). Significant increase in plant height and stem diameter has been reported in previous studies (Mensah and Frimpong, 2018; Shareef *et al.*, 2018; Manolikaki and Diamadopoulos, 2019). Mensah and Frimpong (2018) reported an increase in plant height and stem diameter of two maize varieties in Ghana following the application of biochar and compost. The researchers attributed the increased in the plant height and stem diameter to the increased soil pH and nutrient availability in the biochar and compost amended soils.

In a pot experiment conducted on two soil types (Loam and Sandy Loam soils) by Manolikaki and Diamadopoulos (2019), the application of biochar and biochar + compost was found to significantly increased the plant height and stem diameter of maize plant, 30 days after seed germination. In a similar study, Sharref *et al.* (2018) found that plant height was influenced by application rate and pyrolysis temperature. In the study, corn cob biochar pyrolysed at 300°C and applied at lower rates (7 and 14 g/2000g soil) recorded higher plant height and stem diameter than biochar pyrolysed at 600°C and applied at higher rate (21 and 28 g/2000g soil).

2.4.2 Nutrient concentration and grain yield

Plant nutrient uptake and distribution are directly linked to the physical and the chemical properties of the soil. Manolikaki and Diamadopoulos (2019), found out that the application of all organic amendment types increased the potassium (K) concentration in both the aboveground and belowground tissue of maize plant with highest increase observed in the biochar-compost amended soils. Although in the study, nitrogen, phosphorus and calcium concentration in both the aboveground and belowground plant tissue in the amended soils were higher than the control, differences among the treatments were not significant.

In a similar study, Bass *et al.* (2016), reported a decrease in the yield of banana and papaya following the application of biochar. They explained that though the application of biochar improved the soil quality, it did not increased the yield of banana and papaya.

2.5 Conceptual framework

This study adopts and modifies the conceptual framework used by Agegnehu *et al.* (2017) to study the role of biochar and compost in improving soil quality and crop performance. In the study, they reviewed available field and laboratory studies on biochar and compost; their properties and their effect on soil quality and crop performance. However, the current study entail comprehensive field and laboratory study involving biochar and compost application, plant data collection and soil analyses.

The conceptual framework (Figure 2.1) explains how the application of organic resources such as biochar, compost and their combinations can increase crop yield by improving the physicochemical properties acidic Ferralsol. Plant growth and yield are directly dependent on nutrient availability, water and soil type. It is therefore important to understand the quantitative linkages and magnitudes at which biochar and compost application to soils can affect these selected soil physicochemical properties in Kamiti sub-catchment to help farmers take appropriate measures in addressing issues of crop yield. The findings of this study will also provide information which can improve the understanding of farmers and other stakeholders in the study area on biochar and compost use, and serve as a basis for adoption.

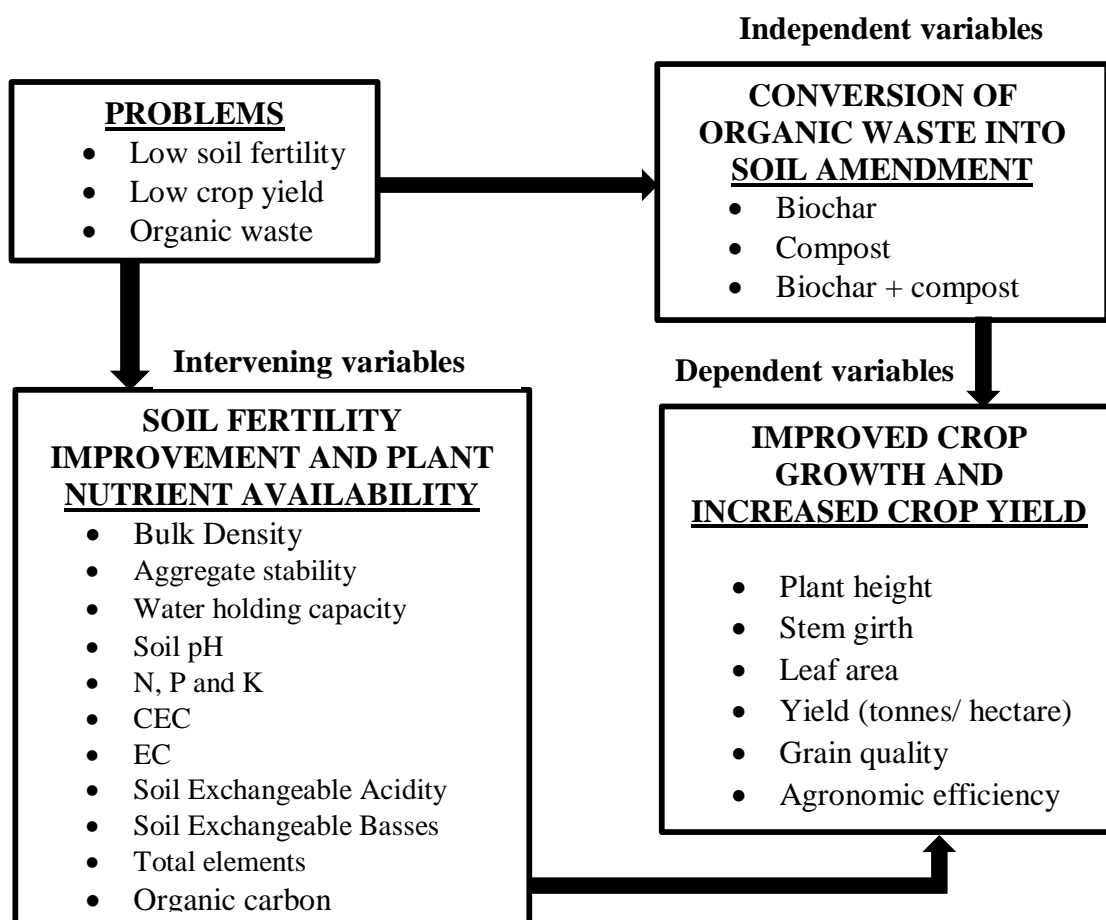


Figure 2.1: Conceptual framework showing the effects of biochar and compost application on soil physicochemical properties and maize yield.

Source: Adapted and modified from Agegnehu, *et al.* (2017).

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Study area

The study was conducted at Kenyatta University Research farm (1.1966°S and 36.9638°E) in Kamiti sub-catchment located in Ruiru District in Kiambu County, Kenya (Figure 3.1). The district has a population size of 252,901 and a population density of about 1,256 persons per km² (County Government of Kiambu, 2018). The sub-catchment has a bimodal rainfall pattern with an average rainfall of 989mm. The months of April and May have the highest rainfall, followed by cool seasons during July and August, ending in short rains in October and November (Makokha *et al.*, 2001).

Temperature in the sub-catchment varies from humid to semi-humid characteristics. In the humid zone, temperature ranges from 7°C and 18°C, while in the sub-humid to semi-humid zones temperatures of 15.4°C and 34°C are recorded. January to March is the hottest period with a maximum temperature of 34.4°C. The average temperatures of the catchment is 26°C (County Government of Kiambu, 2018).

The soil of the study area is classified as Orthic *Ferralsol* (FAO, 2006). These soils are highly weathered and contain a higher concentration of clay-sized minerals consisting of sesquioxides (Fe and Al oxides) that are mixed with varying amount of silicate clays (kaolinite). Weatherable minerals such as feldspar, mica and ferromagnesian are nearly absent (FAO, 2006). The study area lies in the tertiary volcanic rocks zone of the eastern part of Kenya which forms part of the semi-arid areas characterized by low soil fertility. The soil is described as red to dark brown friable clays with laterite horizon (Figure 3.2).

Table 3.1 shows the physicochemical properties of soil used for study. The soil have low pH (4.9), high bulk density (approximately 1.0 g cm^{-3}), high Al and Fe content (27.14 and 30.28 g kg^{-1} respectively), low concentration of available phosphorus and exchangeable cations (Table 3.1).

Table 3.1: Physicochemical properties of soil (Ferralsol) used in the study.

Property	Unit	Soil
Clay	%	19.1
Silt	%	63.6
Sand	%	17.3
Textual class		Silty loam
Bulk density	g cm^{-3}	0.998
pH (CaCl_2)		4.97
EC (H_2O)	$\mu\text{s cm}^{-1}$	144.05
N	%	0.36
C	%	3.80
S	%	0.17
C/N ratio		10.66
Available P	g kg^{-1}	0.088
Total Na	g kg^{-1}	0.37
Total P	g kg^{-1}	0.54
Total K	g kg^{-1}	1.12
Total Mg	g kg^{-1}	1.39
Total Ca	g kg^{-1}	4.85
Total Fe	g kg^{-1}	30.28
Total Al	g kg^{-1}	27.14
Ca^{+2}	Cmol. kg^{-1}	19.53
Mg^{+2}	Cmol. kg^{-1}	5.02
Na^+	Cmol. kg^{-1}	0.40
K^+	Cmol. kg^{-1}	2.49
CEC	Cmol. kg^{-1}	27.44

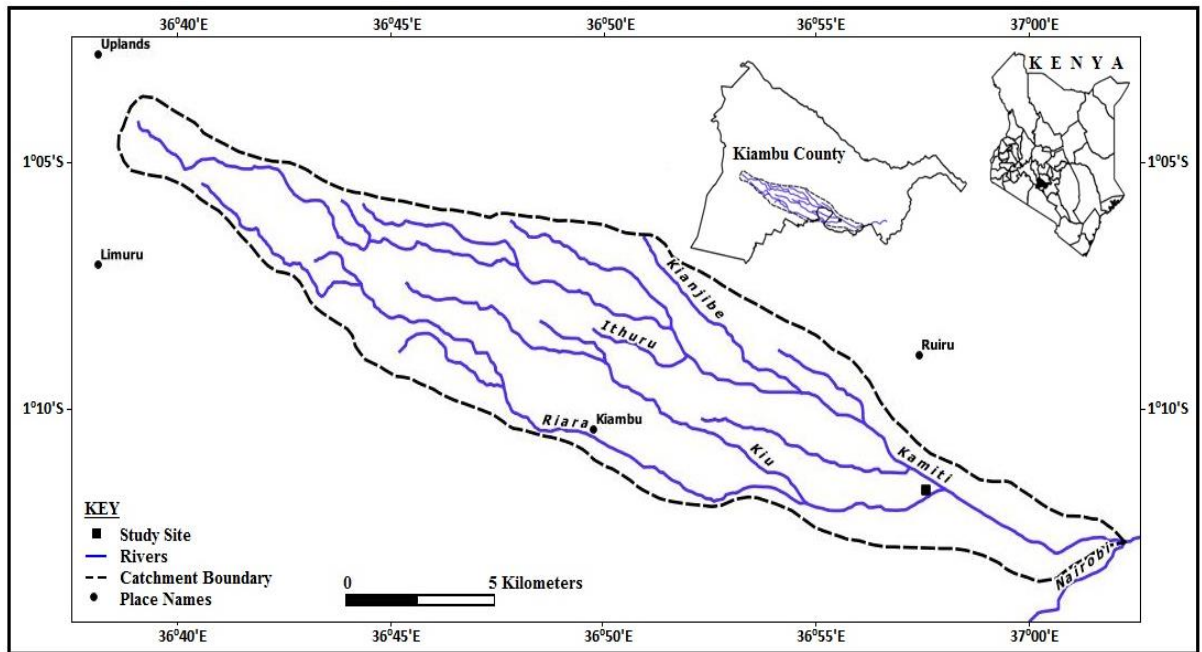


Figure 3.1: Map of Kamiti sub-catchment showing the study site.

Source: Drawn from Survey of Kenya Topographic Sheet for Nairobi (SA-37-5) as source map.

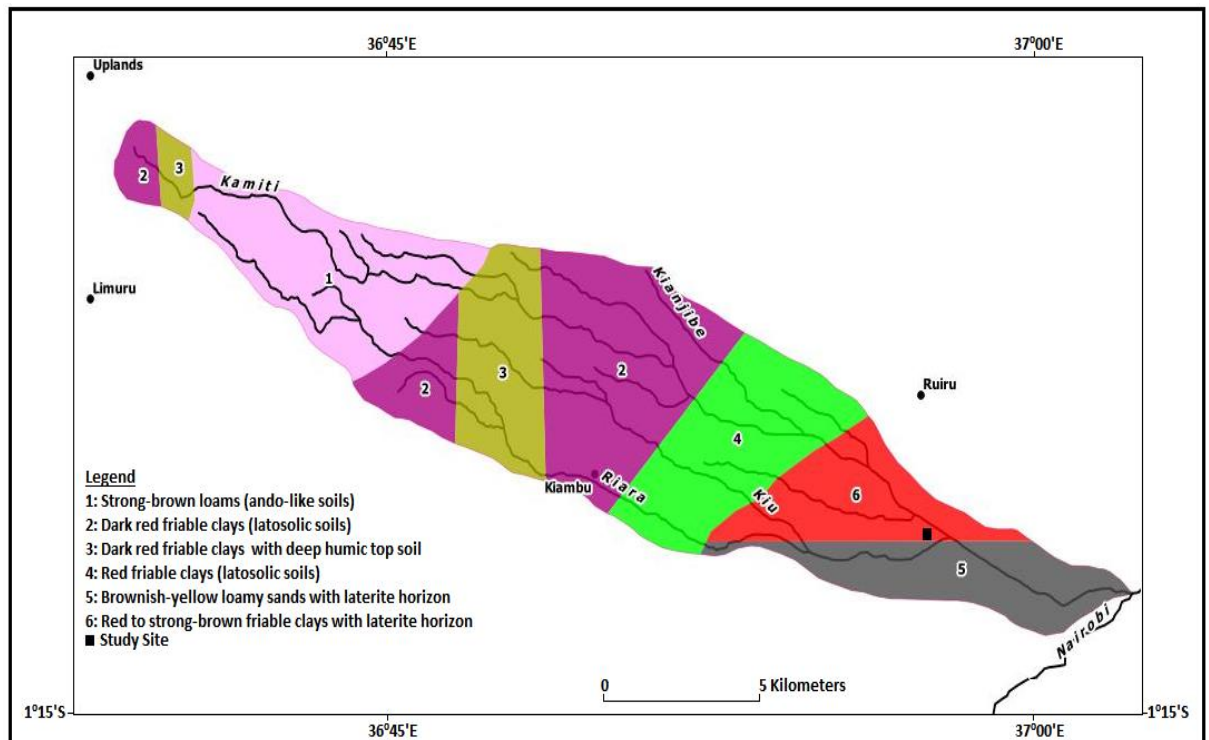


Figure 3.2: Soil map of the study area.

Source: National Atlas of Kenya; 3rd Edition, 1970.

3.2 Research design

The study adopted the Randomized Complete Block Design (RCBD) consisting six treatments which included biochar and compost applied at different levels singly or together as shown in the field layout (Appendix 1). The treatment also included a no biochar, no compost control. This research design is appropriate for this study because it isolates any known or suspected variations in soil characteristics, therefore making field conditions as homogenous as possible. Three different application rates of biochar, compost and their combination were applied. Each treatment was replicated four times in the field including the control. There were 24 sub-plots each measuring 2m × 2m (Appendix 1). The treatment details are shown in Table 3.2.

Table 3.2: Treatments and application rates of biochar and compost used in the study (t ha⁻¹).

Level:	Description	Particle size
0	Control (C)	
1	20 t ha ⁻¹ Biochar (20B)	< 2 mm
2	20 t ha ⁻¹ Compost (20C)	
3	40 t ha ⁻¹ Biochar (40B)	< 2 mm
4	40 t ha ⁻¹ Compost (40C)	
5	20 t ha ⁻¹ Biochar + 20 t ha ⁻¹ Compost (BC)	

Each treatment, including the control, were randomly distributed (appendix 1).

3.3 Biochar and compost production

3.3.1 Biochar production

Biochar was produced from corn cobs collected from nearby town (Githuria market) within the study area using the locally designed oven (Plate 1). The oven was made from two barrels of different sizes (200 liters barrel and 110 liters barrel) at the Kenyatta University School of Engineering workshop. The bigger barrel (200 liters) has a chimney on the lid and perforations at both ends of the barrel. The smaller barrel has perforations only at the bottom. The perforations on the bigger barrel allowed little oxygen to enter the oven whereas the perforations at the bottom of the smaller barrel allowed the release of toxic gasses (by-products) produced during pyrolysis.



Plate 1: Locally designed oven for biochar production. School of Engineering, Kenyatta University (Author, 19th November 2018).

Corn cobs were gathered from Githuria market and sun-dried for 7 days to remove moisture (Plate 2) before pyrolysis. Well-dried firewood was cut into smaller pieces of approximately 85 cm heights. The smaller barrel was put in the bigger barrel and filled

with the dried corn cobs and covered. Firewood was tightly packed in the gap between the bigger barrel and the smaller barrel, lighted with fire and covered (Plate 3). The pyrolysis lasted for about 3 - 4 hours. The pyrolysis temperature was approximately 460°C (Plate 4). The percent output of biochar ranged from 46 - 52% on weight basis (Plate 5).



Plate 2: Drying of corn cobs at the Kenyatta University Research Farm (Author, 24th November 2018).



Plate 3: Pyrolysis of corn cobs (Author, 3rd December 2018).



Plate 4: Checking temperature during pyrolysis (Author, 3rd December 2018).



Plate 5: Biochar produced after pyrolysis (Author, 4th December 2018).

The corn cob biochar was milled into powder with particle size less than 2mm using a hammer mill (Plate 6) at the Department of Biochemistry and Biotechnology, Kenyatta University, Nairobi, Kenya.



Plate 6: Milling of corn cob biochar (Author, 28th January 2019).

3.3.2 Compost preparation

The compost used in the study was prepared from partially decomposed small animal (rabbits, rats and guinea pigs) manure, poultry manure and farm wastes. The manure was obtained from Zoology Department, Kenyatta University whereas the farm wastes were gathered from the Kenyatta University Research Farm. A pit of 1 m depth, 1.5 m wide and 3 m long was dug at the research farm. The animal manure and the farm waste was spread in alternating layers in the pit, adding to each layer a little amount of soil and water to introduce microbes and initiate the decomposition process. The pit was then covered

with polythene sheet (Plate 7) to prevent rainfall from wetting the heap. The compost was turned every two weeks (Plate 8) and matured in 9 weeks.

Physicochemical properties of the biochar and the compost used for the study are presented in Table 3.3.



Plate 7: Compost preparation (Author, 23rd November 2018).



Plate 8: Turning of compost (Author, 21st December 2018).

Table 3.3: Properties of biochar and compost used in the study.

Property	Unit	Biochar	Compost
Yield (Output)	%	48.9	nd
Ash content	%	16.59	nd
pH (CaCl ₂)		8.99	7.54
EC (H ₂ O)	µs cm ⁻¹	5620	10020
N	%	1.15	1.85
C	%	79.13	20.46
S	%	1.15	0.82
C/N ratio		68.60	11.06
Available P	g kg ⁻¹	1.07	10.92
Total Na	g kg ⁻¹	0.87	2.91
Total P	g kg ⁻¹	2.45	26.99
Total K	g kg ⁻¹	13.58	14.59
Total Mg	g kg ⁻¹	1.56	11.48
Total Ca	g kg ⁻¹	0.81	40.10
Total Fe	g kg ⁻¹	0.77	18.59
Total Al	g kg ⁻¹	0.40	14.61
Exc. Ca	Cmol. kg ⁻¹	0.76	8.27
Exc. Mg	Cmol. kg ⁻¹	2.261	10.82
Exc. Na	Cmol. kg ⁻¹	0.15	7.14
Exc. K	Cmol. kg ⁻¹	27.00	35.97
CEC	Cmol. kg ⁻¹	30.17	62.19

‘nd’ = not determined

Both biochar and compost used for the study have high pH, EC, CEC and nitrogen content (Table 3.3). Total element concentration, exchangeable cations and available phosphorus in the compost are much higher as compared to the biochar. Carbon content and C/N ratio of the biochar were higher than the compost.

3.4 Land preparation, treatment application and sowing

A land of size 14 m × 10 m was used in the study in a Randomized Complete Block Design (RCBD). The weeds on the field were first cleared with a cutlass and then ploughed with a hoe. The field was divided into 4 sections and soil samples were taken

from each section for the determination of the selected physicochemical properties and to characterize the entire field. In each section, 6 sub-plots of 2 m × 2 m each were prepared using pegs and line, making a total of 24 plots (Plate 9).

The treatments (biochar and compost) were applied at different rates and combination as described in Table 3.2. The amendments were first spread uniformly on their assigned plots and ploughed to the required depth of 20 cm using a hoe (Plate 10). The field was irrigated once a week for 2 weeks to allow mineralization of the amendments to begin before planting. The maize variety used in this study is “SC Duma 43”. The variety is drought-resilient with a maturity period of 90 days. The seeds (3 per hole) were sown on 15th February 2019 at a planting distance of 50 cm between rows and 40 cm within rows. A 100% germination was recorded 6 days after sowing (Plate 11).



Plate 9: Field layout (Completely Randomized Design) (Author, 3rd February 2019).



Plate 10: Biochar and compost application (Author, 1st February 2019).



Plate 11: Sprouted maize seeds (Author, 21st February 2019).

3.5 Soil sampling

Soil sampling was done prior to land preparation and at the physical maturity stage of the maize plant. Systematic soil sampling method (Keith, 1991) was used in this study. Each

plot was divided into 4 sub plots and soil samples were taken diagonally at 3 points within each sub plot using a screw auger or a core sampler (Plate 12). Samples taken from the different sub plots were bulked and mixed thoroughly. Composite samples were taken for the laboratory analysis. Soil samples taken with the core samplers were oven-dried at 105°C for 48 hours to determine their bulk densities. The composite soil samples taken from each plot were air-dried for 7 days in a well-ventilated space free from contamination (Plate 13) and made to pass through a 2mm sieve and kept in plastic sealable bags.



Plate 12: Soil sampling (Author, 15th February 2019 and 15th April 2019, respectively).



Plate 13: Air drying of soil and compost samples (Author, 19th February 2019).

3.6 Plant measurements and agronomic practices

Five maize plants were randomly selected in each plot and tagged 3 weeks after germination for data collection. Data on plant height, stem diameter, leaf length (LL) and leaf width (LW) were collected. The plant height was measured from the soil surface level to the tallest drooping leaf of the plant using a long meter rule. The stem diameter/girth was measured using a Vernier caliper (Plate 14). Mean leaf area of each plant was determined by measuring the length and width of three different leaves with visible leaf collars using a ruler. The length of the leaf was measured from the leaf collar to the tip of the leaf, whereas the leaf width was measured at the broadest part of the leaf using a meter rule (Plate 14).

Leaf Area (LA) was computed using the formula presented in equation 3.1 below. The methods for measuring plant height, stem diameter, leaf length and leaf width were adopted from the methods described by Musa and Hassan, (2016) and Masarirambi *et al.* (2012).

Leaf Area (LA) = lamina length (LL) x maximum width (LW) x k

Where k (0.75) is the coefficient (Musa and Hassan, 2016)

$$LA \text{ (cm}^2\text{)} = LL \times LW \times 0.75 \dots\dots\dots \text{Equation 3.1}$$



Plate 14: Measuring of stem diameter, leaf length and leaf width (Author, 28th March 2019).

The maize plants were sprayed against fall armyworms which were first seen 2 weeks after germination (Plate 15). A systemic pesticide called “Ampligo” was used to control the fall armyworms at an application rate of 10 ml of pesticide in 20 L of water (Plate

16). The fall armyworms infestation was extensive at the seedling stage which interrupted the apical dominance and resulted in death of some seedlings (Plate 15).

Irrigation was done twice a week for 6 weeks after which it was done only once a week until the plants attained physical maturity (12 weeks after germination). Weeding was done as and when weeds growth increases. No chemical fertilizers were applied on the soil or on the plants throughout the growth period.



Plate 15: Fall armyworm-infested seedlings (Author, 28th February 2019).



Plate 16: Spraying on seedlings against fall armyworms. (Author, 28th February 2019).

Three (3) maize plants at tasselling stage were randomly selected on each plot and processed for laboratory analysis. The shoot of each plant was separated from the root, washed, cut into pieces and kept in paper bags. Both the shoot and the root samples were oven dried at 60°C for 48 hours using the *WTC Binder* oven. The oven-dried samples were then milled to particle size of less than 2 mm and kept in plastic sellable bags for laboratory analysis.

At maturity, maize plants were harvested on each plot separately and sundried to further remove moisture. Maximum of 2 cobs per plant was assumed for all the plants in the field. Maize yield per plot was calculated by multiplying the weight of grains (2 cobs) per plant by the total number of maize plants on each plot (20 plants per plot). The grain

yield per plot was then extrapolated into yield per hectare. Hundred grains from each plot were selected and weighed to determine grain filling.

3.7 Laboratory analysis

Laboratory experiments on plant and soil samples were conducted at Soil Science/ Soil Ecology research laboratory of the Ruhr University Bochum, Germany.

3.7.1 Soil texture (Particle Size Distribution)

Soil particle size was determined by means of laser particle diffraction analysis (Ryżak and Bieganowski, 2011). In this method, carbon was first destroyed in the sample by weighing 30 g of the soil into 1000 ml beaker and water added to the 100 ml mark. Approximately 30 ml H₂O₂ was added to the solution to destroy carbon in the sample and then dried at 60°C for 24 hours. The dried sample was crushed, weighed (about 20 g) and sieved with 0.2 mm sieve.

The weight of sample materials < 0.2 mm was recorded and sample materials > 0.2 mm was transferred into a 100 ml beaker. Approximately 50 ml of water was added to the sample in the beaker and placed in the ultrasonic bath for about 3 minutes. The supernatant suspension was decanted off and the process repeated again until the supernatant solution was clear. The sample was then dried in a drying cabinet at 60°C for 24 hours. The particle size distribution was determined using the laser particle diffraction analyser.

3.7.2 Soil bulk density (BD)

Soil bulk density was determined at the Kenyatta University, Department of Geography technical laboratory using the intact core method as described by Hardie *et al.* (2013). A core sampler with a height and diameter of 5 cm was driven into the soil to sample from 5 to 10 cm depth. Both ends of the core samplers were trimmed and flushed with a straight edge knife and covered with a lid. The weight of each soil core samples was recorded and then oven-dried to a constant weight using the *WTC Binder* oven at 105°C for 24 hours. The soil bulk density was calculated using the formula in equation 3.2 below:

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{\text{Wt. of soil core (g)} - \text{Wt. of oven dry soil (g)}}{\text{Vol. of soil core (cm}^3\text{)}} \dots \text{Equation 3.2}$$

3.7.3 Soil aggregate stability (SAS)

Soil aggregate stability was determined using the wet sieving method (Burrel *et al.*, 2016). Soil samples were air-dried and sieved to obtain a particle size (aggregates) range of 1 mm to 2 mm. Five grams of the 1 – 2 mm soil aggregates were weighed and placed on a 250 µm sieve and mechanically raised and lowered (42 cycles/min) for 5 min in deionized water. The weakly aggregated materials disintegrated under the mechanical pressure of the deionized water and passed through the sieve, leaving the stable aggregates, sand, organic particles and biochar on top of the sieve.

The materials were then oven-dried at 105°C for 24 hours and weighed. The oven-dried sample was then immersed in 0.1 M Na₄P₂O₇.H₂O for 5 minutes to breakdown the stable aggregates leaving the sand, organic particles and the biochar. The samples were then

oven-dried at 105°C for 24 hours and weighed again. The Soil Aggregate Stability (SAS) was then calculated using equation 3.3 below.

$$SAS(\%) = \frac{A-B}{W-B} \times 100 \quad \dots\dots\dots \text{Equation 3.3}$$

Where A = weight of stable aggregate, sand, organic particles and biochar

B = weight of sand, organic particles and biochar

W = the air-dried weight of the sample.

3.7.4 Soil water holding capacity (WHC)

The soil water holding capacity was measured as a percentage of soil moisture content at 100% WHC (at field capacity). Two pieces of filter paper were folded inside a plastic funnel and saturated with deionized water and allowed to stand till dripping stopped (5-10 minutes). The weight of the saturated filter paper and the funnel was recorded. Five grams of air-dried soil was added to the filter paper inside the funnel and fully oversaturated it with deionized water. The funnel with soil was allowed to stand till dripping stopped (3 – 4 hours) and the weight (funnel + wet filter paper + wet soil) was recorded. The dry weight equivalent of the soil added to the funnel, and the weight of the wet soil was also calculated.

The soil water holding capacity was calculated using equation 3.4 below.

$$WHC(\%) = \frac{\text{wet wt. of soil (g)} - \text{dry wt. of soil(g)}}{\text{dry wt.of soil (g)}} \times 100 \quad \dots\dots\dots \text{Equation 3.4}$$

3.7.5 Soil pH and electrical conductivity (EC)

The pH of the soil samples was determined using a pH meter (pH 730, WTW series). All pH measurements were performed using a 1:5 (w/v) soil: CaCl₂ ratio by weighing 5 g of ≤ 2 mm air-dried soil into a 50-ml glass beaker and adding 25 ml of 0.1M CaCl₂ solution. The suspension was mixed with a glass rod and allowed to stand for 1 hour before pH was measured. Electrical conductivity meter (Cond 730, WTW Series) was used to measure the soil EC in a 1:5 (w/v) soil: water ratio suspension, by weighing 20 g of air-dried soil into a 250 ml PE bottle and adding 100 ml of deionized water. The solution was shaken for 30 minutes on a horizontal shaker and filtered (using filter paper and funnel). EC was measured in the supernatant with the electrode of the EC meter.

3.7.6 Total carbon (C), total nitrogen (N) and total sulphur (S)

The total C, total N and total S were determined by dry combustion (Vario EL the Elemetar Analysensysteme GmbH, Hanau, Germany) (Shareef *et al.*, 2018). The sieved soil samples (< 2 mm) were ball milled to reduce the particle size. The plant samples were also finely ground before weighing. Sample weighing was done in milligrams (25 mg for soil and 10 mg for the plant) using the Sartorius weighing balance (BP 211D). The samples were weighed into aluminium foil cups and folded into smaller cylindrical shapes before determining by dry combustion using the Vario EL (the Elemetar Analysensysteme).

3.7.7 Total elements (Na, Mg, Ca, K, P, Al and Fe)

The total element (Na, Mg, Ca, K, P, Al and Fe) concentrations were determined by nitric acid (HNO₃) digestion (Sigua *et al.*, 2019) at 120°C using the Microwave Mars Express

(by CEM). Finely ground samples were weighed (0.25 g for soil and 0.125 g for plant samples) into a digestion vessel (TFM Hostafion container) and 10 ml of concentrated HNO₃ was added. The digestion vessels were sealed and microwaved with the appropriate program depending on the number of samples for 15 minutes. The samples were allowed to cool and 10 ml of deionized water was added and filtered through 0.45 ml membrane filter. The filtrate was kept in 50 ml PE bottles and the concentrations of the total elements were measured with the Inductively Coupled Plasma Spectroscopy (ICP-OES).

The total element concentrations in mg kg⁻¹ were calculated using equation 3.5 below.

$$\text{Total element (mg kg}^{-1}\text{)} = \frac{\text{sample conc. (mg)} \times \text{extraction vol. (ml)}}{\text{wt. of sample (g)}} \dots\dots\dots \text{Equation 3.5}$$

3.7.8 Soil available phosphorus (P)

The soil available P was determined using the P-Bray method. Five grams of air-dried soil samples (< 2mm) were weighed into 100 ml PE bottles and 50 ml of Bray solution was added. The solution was shaken on a horizontal shaker for 1.5 minutes and then filtered over a dry blue ribbon filter into a 50 ml PE bottle. The first 5 ml of the filtrate was discarded and 5 ml of the remaining filtrate was taken into a 50 ml beaker and 7.5 ml of 0.5M HCl, 0.5 ml of Ammonium molybdate solution and 0.5 ml of Ascorbic acid solution were added. The solution was allowed to react for 30 minutes before the concentration was measured with the UV/VIS Spectrometer (Lambda 2). The soil available P was calculated using equation 3.6 below.

$$\text{Available P (mg kg}^{-1}\text{)} = \frac{(\text{sample conc.} - \text{blank conc.}) \times \text{vol.} \times \text{extr. vol.}}{\text{wt. of soil} \times \text{wt. of filtrate}} \dots\dots\dots \text{Equation 3.6}$$

3.7.9 Exchangeable cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and cation exchange capacity (CEC)

The exchangeable cations and CEC were determined using the ammonium chloride (at pH 7) extraction method. Approximately, 2.5 g of the sample was weighed into a 50 ml beaker and 10 ml of the exchange solution was added. The beaker was covered with watch glass and allowed to stand for 24 hours. Percolation was done after 24 hours by rinsing the sample with the solution into the filter paper and collected in 100 ml measuring flask. The percolation lasted about 4 hours with approximately 90 ml of the percolate in the flask. The concentration of the exchangeable cation was measured with the Inductively Coupled Plasma Spectroscopy (ICP-OES). The CEC was calculated as the sum of the exchangeable cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+).

3.8 Data analyses and processing

The data obtained were first subjected to a normality test to determine the normal distribution of the data using the Shapiro Wilk test at $P < 0.05$ (SPSS version 25). Values greater than 0.05 were found to be normally distributed and values less than 0.05 were found not to be normally distributed. Data comparison was done using the univariate Analysis of Variance under the General Linear Model (SPSS version 25) with Duncan's multiple range post-hoc test to deduce treatment differences at $P < 0.05$. Values less than 0.05 were deemed significant and values greater than 0.05 were considered not significant. Correlation analysis was performed to compare the strengths of relationships among some of the measured parameters.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Effect of biochar, compost and their combination on soil physical properties

The results from the study showed that soil bulk density, water holding capacity and aggregate stability improved after biochar and / or compost application to the soil as described in Figure 4.1, 4.2 and 4.3.

4.1.1 Soil bulk density (BD)

Bulk density of all amended soils was significantly reduced ($P < 0.05$) relative to the control. Application of amendments decreased soil bulk density by 4.1 – 8.7%. Combined application of biochar and compost (BC) decreased soil bulk density by 8.7% while the sole application of compost (20C) decreased soil bulk density by 4.1% compared to the control treatment. In general, the biochar amended soils showed lower bulk density values than the compost amended soils but combined application of biochar and compost resulted in a much higher decrease in soil bulk density.

The decrease in soil bulk density of the biochar amended soil is as a result of the lower bulk density of the biochar which reduces the overall bulk density of the soil (Verheijen *et al.*, 2010). Figure 4.1 shows the effects of biochar and/ or compost application on soil bulk density.

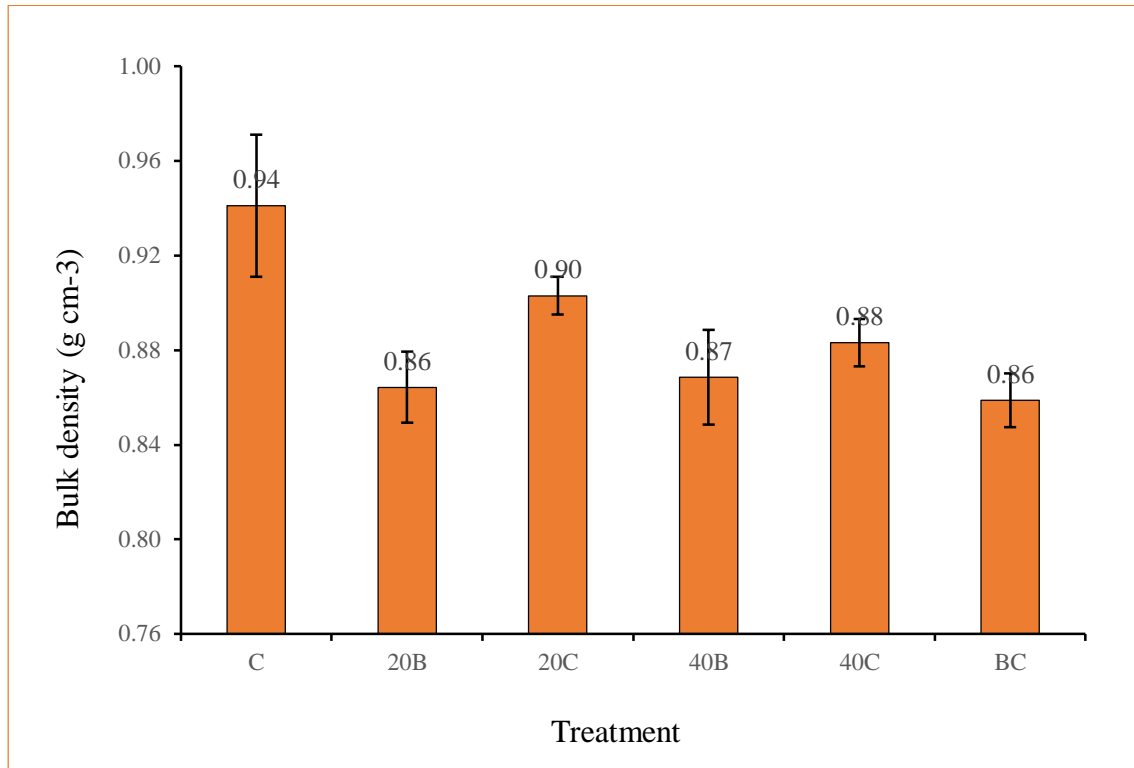


Figure 4.1: Effects of biochar and/or compost application on soil bulk density. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P = 0.02$, $LSD = 0.05$).

The effects of biochar application on soil bulk density has been widely studied (Agegnehu *et al.*, 2016; Bass *et al.*, 2016; Burrell *et al.*, 2016; Liu *et al.*, 2016b; Ma *et al.*, 2016; Obia *et al.*, 2016; Zheng *et al.*, 2016; Jeffery *et al.*, 2017). Following a review on the impact of biochar on soil physical properties, Blanco-Canqui (2017) reported that biochar application reduced soil bulk density by 3 to 31% in 19 out of 22 soils, which is indicative that biochar addition to soils can decrease soil bulk density. He further explained that the magnitude of the effect of biochar application on soil bulk density may vary depending on soil type.

In the current study, increasing biochar application rates did not result in a reducing soil bulk density, therefore differences between 20B and 40B were not statistically significant at $P = 0.05$. The bulk density of 20B (0.86 g cm^{-3}) was lower than 40B (0.87 g cm^{-3}) which is in contrast to the findings of Lui *et al.* (2016a) and Glab *et al.* (2016) who found that soil bulk density decreases with increasing application of biochar.

Burrell *et al.* (2016) found that soil bulk density was decreased in soils amended with different biochar types (straw, woodchip and vineyard) and persisted in the soil for over 3 years relative to the control which increased over time. This indicates that biochar has a long term effect on soil bulk density. A plausible reason for the persistence in bulk density decreases observed in biochar amended soil is the large amount of recalcitrant carbon contained in the biochar which can persist in soils for decades (Rawat *et al.*, 2019).

4.1.2 Soil aggregates stability

Greater aggregate stability was found in all amended soils compared to the control (Figure 4.2). The 20B, 20C, 40B, 40C and BC recorded percentage increase in aggregates stability by 63.90%, 132.93%, 75.19%, 139.18% and 164.74% respectively compared to the control treatment. Aggregate stability increased with increasing application of biochar and compost. The percent stable aggregate in the compost amended soils (24.97 to 25.64%) were much higher than in the biochar amended soils (17.56 to 18.78%), but the combined application of biochar and compost (BC) resulted in a greater percent stable aggregates (28.38%). Application of biochar and compost provide refuge for soil microorganism which in return secrete certain polysaccharides to increase adherence of soil colloidal particles, resulting in improved soil aggregation (Aslam *et al.*, 2014).

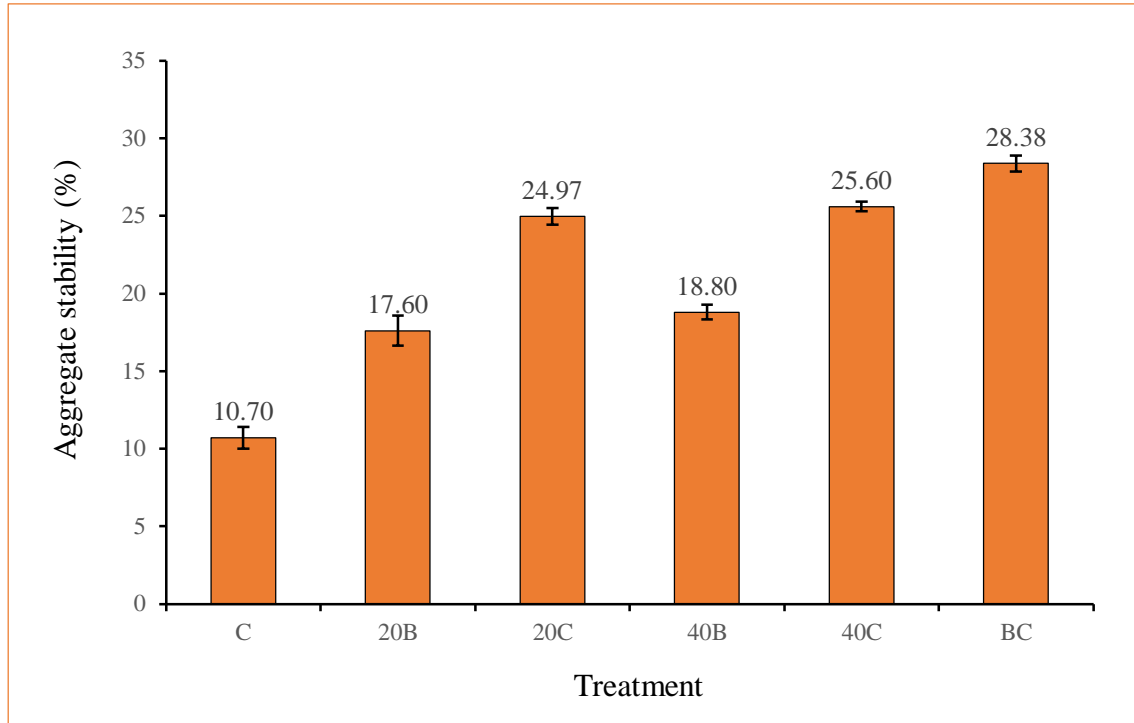


Figure 4.2: Effects of biochar and/or compost application on soil aggregate stability. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.001$, $LSD = 0.92$).

In a study conducted by Burrell *et al.* (2016) involving 3 soil types (Planosol, Chernozem and Cambisol) and 3 biochar types (straw, woodchip and vineyard), biochar application was found to have significantly increased the soil aggregate stability in the Planosol and Chernozem but had no effect on the Cambisol. An increase in the soil aggregate stability of 28 to 92% was recorded in the Planosol and 26% in the Chernozem. This is indicated that the effect of biochar on soil properties varies with soil type, biochar type and application rate (Banco-Canqui, 2017).

The results of the present study are in agreement with the findings of Gamage *et al.* (2016), who found an increase in aggregate stability with increasing biochar application

rate. They explained that the interaction between soil mineral particles and biochar during aggregate formation often depend on the clay content of the soil. They concluded that biochar application improved aggregate stability in clayey soils than sandy soils. The high aggregate stability found in the biochar and compost amended soils in the present study confirms this observation.

In a 1-year field experiment conducted by Zhang *et al.* (2015), biochar did not significantly increase aggregate stability in a Fluvisol Cambisol. Zhang *et al.* (2015) attributed the insignificant effect of biochar on aggregate stability to the coarse biochar particle size ($> 1\text{mm}$) used in their study which limited the soil microbe-biochar interactions. They concluded that soil aggregate formation is a function of biological activity and time, therefore, biochar application cannot increase significantly aggregate stability in a 1 year period, but findings from the present study is contrary to this report.

4.1.3 Soil water holding capacity (WHC)

Biochar applied alone significantly ($P < 0.05$) increased WHC by 36.64 - 46.15% whilst compost applied alone increased WHC by 34.98 - 35.08% (Figure 4.3). When biochar was applied together with compost, WHC was increased more than when compost was applied alone. In the present study, WHC was increased when biochar application rates were increased. However, increasing compost application rates did not proportionally resulted in an increased soil WHC. The increase in WHC of the biochar amended soils could be due to the porous nature of biochar which absorbs and retains moisture when applied to soils. The increase in WHC following biochar and compost application in the present study agrees with the findings of many previous studies (Agegnehu *et al.*, 2016;

Bass *et al.*, 2016; Burrell *et al.*, 2016; Liu *et al.*, 2016a; Obia *et al.*, 2016; Cao *et al.*, 2018).

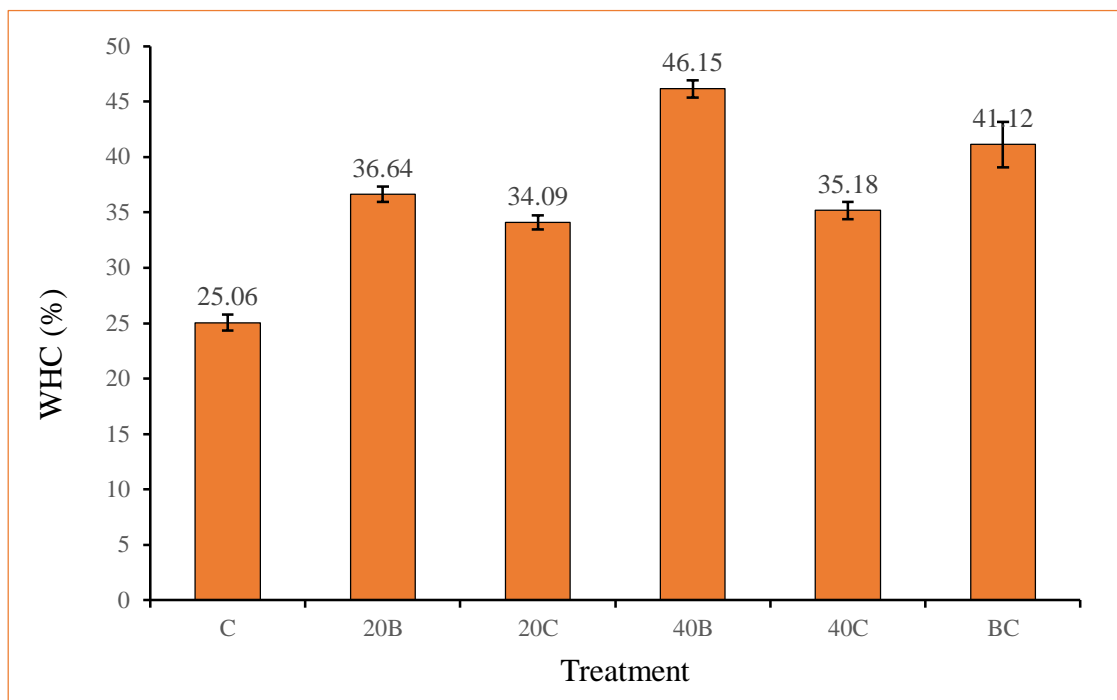


Figure 4.3: Effects of biochar and/or compost application on soil water holding capacity (WHC). Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.001$, $LSD = 1.58$).

Cao *et al.* (2018) reported an increase in WHC in both biochar and compost amended soils and attributed the increase to the carbon content of the biochar and compost used in their study. They further explained that the increase in WHC resulted in an increase in CEC in the amended soils, which suggest that combined application of compost and biochar is an effective strategy for enhancing soil water retention capacities. Agegnehu

et al. (2016) recorded an increase of 24.5% water content in biochar + compost + fertilizer amended soil compared to the control soil.

In a similar study on two soil types (Ferralsol and Chromosol), Bass *et al.* (2016) found an increase in soil WHC in all organic amended Ferralsol soils by 23.3% (combined biochar and compost) to 40.8% (biochar only) but the difference in WHC of Chromosol soils were not significant. This is an indication that biochar applied alone or in combination with compost has potential on WHC than compost applied alone.

4.2 Effects of biochar and compost application on soil chemical properties

The effects of biochar and/ or compost application on soil pH, EC, TN, TC, TS C: N ratio, Available P, Exchangeable cations (Na^+ , K^+ , Mg^{+2} and Ca^{+2}), CEC and total elements (Na, P, K, Mg, Ca, Fe and Al) are reported and discussed in the following paragraphs.

4.2.1 Soil pH

The pH of all treatments were higher as compared to the control. The pH of biochar applied at 40 t ha⁻¹ (40B) was higher than biochar applied at 20 t ha⁻¹ (20B). Compost applied alone at 20 t ha⁻¹ and 40 t ha⁻¹ (20C and 40C) increased pH by 0.2 units whilst biochar applied at 20 t ha⁻¹ and 40 t ha⁻¹ increased pH by 0.2 and 0.4 units respectively. Increasing compost application rate did not result in an increased pH, but when compost was combined with biochar pH was increased by 0.4 units. (Figure 4.4).

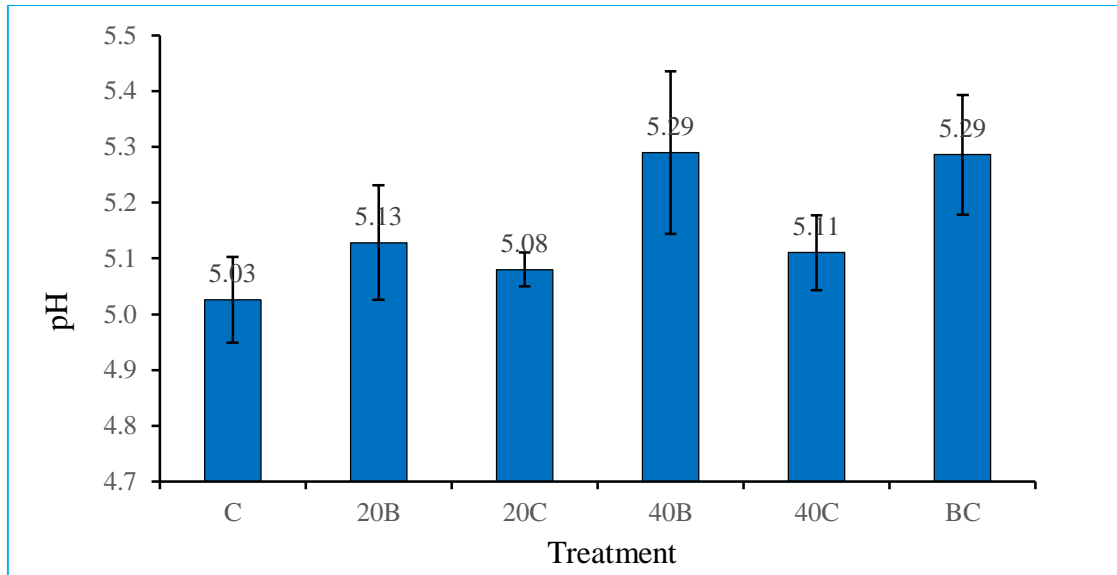


Figure 4.4: Effects of biochar and/or compost application on soil pH. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.001$, $LSD = 0.14$).

Biochars are mostly alkaline ($pH > 7$) with higher base cation concentrations. Consequently, biochar applied to soils can release base cations into the soil solution to reduce acidity through proton consumption reactions as indicated by Chintala *et al.* (2014). In this study, pH increased with increasing application rate of biochar and compost (Figure 4.4). The pH of the biochar and compost used in this study were 9.0 and 7.5 respectively (Table 3.1). The increase in soil pH after amendment application could be attributed directly to the higher pH of the biochar and the compost used in the study. The result agrees with the findings of previous studies (Bass *et al.*, 2016; Mensah and Frimpong, 2018; Manolikaki and Diamadopoulos, 2019; Sigua *et al.*, 2019).

In a pot experiment conducted by Mensah and Frimpong (2018), sole application of biochar increased soil pH from 4.8 to 6.1. They attributed the increase in pH in the biochar

amended soils to the high pH of the biochar used for their experiment. It was concluded that biochar can be used as an alternative to lime materials to ameliorate soil acidity. Since soil pH can change under changing climatic conditions and land-use practices, it is recommended that biochar effect on soil pH should be assessed in the long term to further understand the dynamics in pH of soils with differing acidity.

4.2.2 Electrical conductivity (EC)

EC was significantly ($P < 0.05$) higher in the sole compost treatment (20C and 40C) than in the sole biochar treatment (20B and 40B). EC consequently increased with increasing compost application rates. Biochar applied alone did not significantly increase EC but when biochar was applied together with compost, EC was increased significantly ($P < 0.05$) by 30.5 %. EC recorded in the different treatments are presented in figure 4.5.

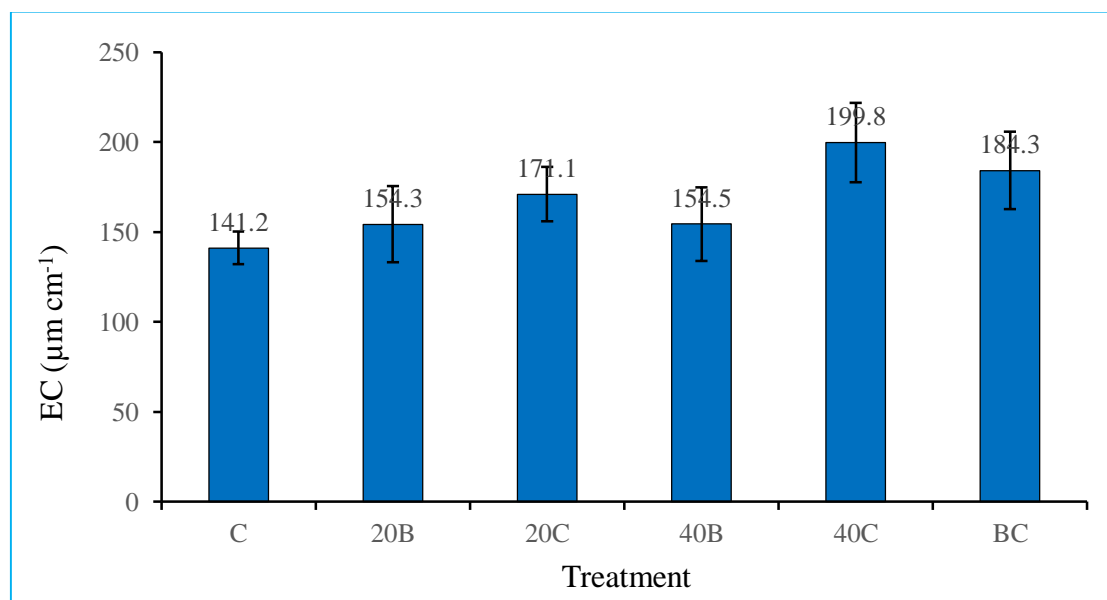


Figure 4.5: Effects of biochar and/or compost application on soil EC. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.03$, $LSD = 36.6$).

In previous studies Shareef *et al.* (2018) and Chintala *et al.* (2014) found that EC increased with increasing application rate of biochar. Chintala *et al.* (2014) attributed the increase in EC to alkalinity, CaCO₃ content, proton consumption capacity, and base cation concentration of the biochar used in their study. They further explained that biochar contains higher soluble salts which are released into the soil solution which increases the soil EC. The increase in EC was also attributed by Shareef *et al.* (2018) to the release of weakly bound ions of the biochar into the soil solution making it easy to be absorbed by the plant.

In this study, the highest EC was recorded in the 40C followed by BC (Figure 4.5). Contrary to the above findings, EC was not influenced by the application rate of biochar. However, the significant increase in EC in the sole compost amended soils (20C and 40C) and the combined application of biochar and compost (BC) could be attributed to the quick release of nutrients (anions and cations) in the compost into the soil solution.

4.2.3 Total nitrogen (TN)

Total nitrogen (TN) in all the treatments was significantly ($P < 0.05$) higher than the control except for compost applied at 20 t ha⁻¹ (20C). All treatments significantly increased TN by 2.9% except for 20C. The result of the study showed that increasing application of biochar and compost did not result in significantly increased TN (Figure 4.6). The increase in TN could be directly linked to the TN contents of the biochar and compost used in the study.

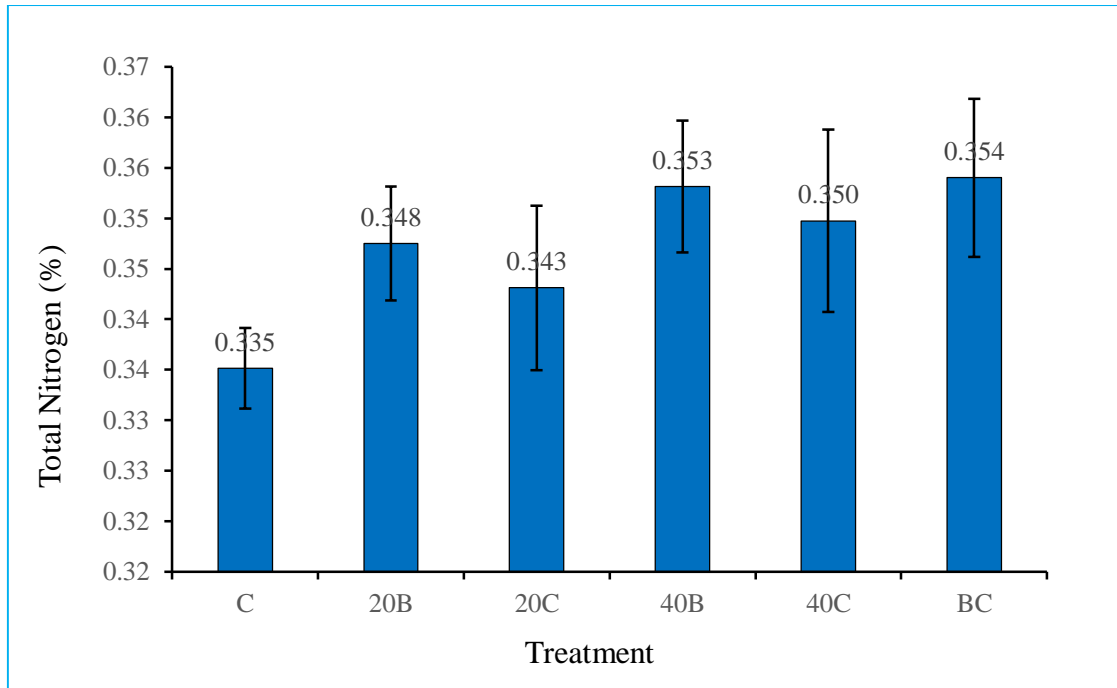


Figure 4.6: Effects of biochar and/or compost application on soil total nitrogen (TN). Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.03$, $LSD = 0.01$).

Many scholars (Agegnehu *et al.*, 2016; Khan *et al.*, 2018; Manolikaki and Diamadopoulos, 2019) have found significant increase in soil TN content following the application of biochar and / or compost. For example, Agegnehu *et al.* (2016) found that the application of biochar and compost increased soil TN by 14% to 29%. Schulz *et al.* (2013) also reported that the application of composted biochar increased soil TN and correlated significantly with plant height and dry mater yield. Similarly, in a pot experiment, Khan *et al.* (2018) found that the application of all biochar types increased soil TN relative to the control.

In this study, the C/N ratio of the biochar and the compost used were 68.60 and 11.06 respectively. The C/N ratio is widely used as a factor to assess nitrogen availability in

soils. When the C/N ratio of organic material is greater than 10, N becomes immobile (Manolikaki and Diamadopoulos, 2019). Thus, our result suggests that N release for plant uptake and possibly N losses by leaching is likely to be higher in the compost amended soils than the biochar amended soils (Khan *et al.*, 2018). However, given that TN in the biochar and compost used in the study were high (1.15% and 1.85% respectively) (Table 3.3), supplementary N fertilization may not be necessary.

4.2.4 Total carbon (TC) and C/N ratio

Total carbon (TC) and C/N ratio in the sole compost treatments were similar to the control. Biochar applied alone and in combination with compost significantly ($P < 0.001$) increased both TC and C/N ratio as compared to the control treatment. Treatment 40B, 20B and BC increased the soil TC by 46.9%, 33.0% and 32.5% respectively. From the study, increasing application of biochar, compost and applying biochar and compost together did not significantly ($P < 0.05$) resulted in increased TC and C/N ratio (Figure 4.7). The increase in TC of biochar amended soils can be attributed directly to the high carbon content of the corn cob biochar used in the study, which is indicative that application of biochar can enhance carbon accumulation and sequestration as indicated by Mensah and Frimpong (2018).

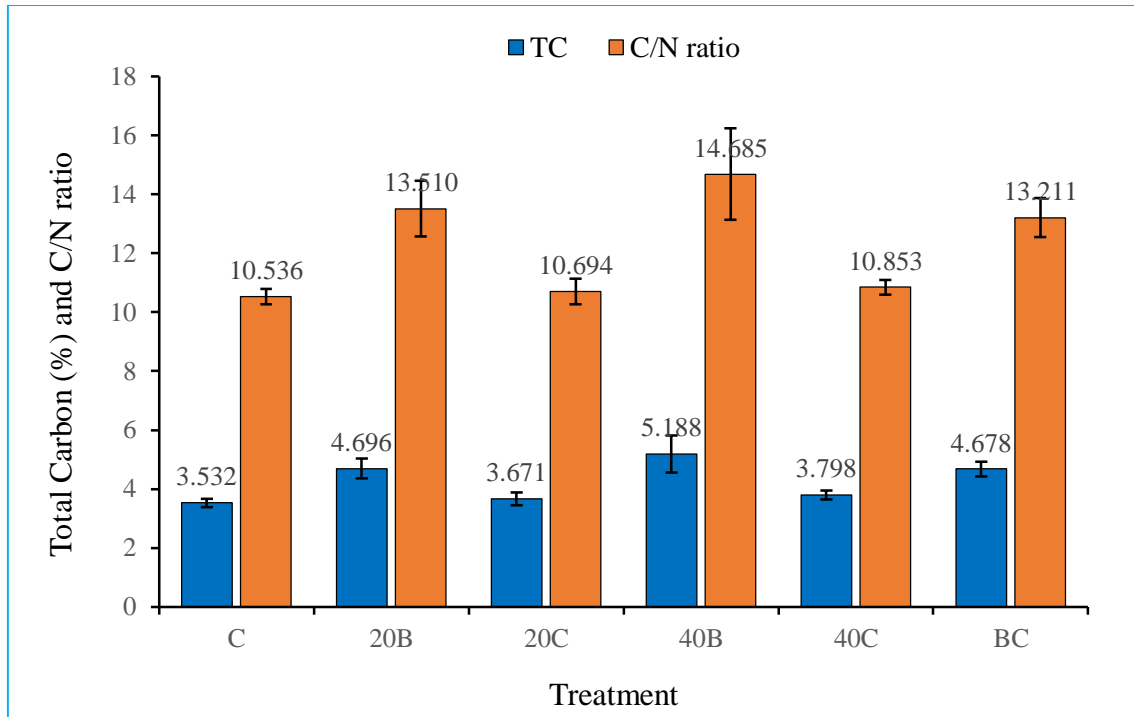


Figure 4.7: Effects of biochar and/or compost application on soil total carbon and C/N ratio. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments (TC: $n = 24$, $P < 0.001$, $LSD = 0.5$, C/N ratio: $n = 24$, $P < 0.001$, $LSD = 1.22$).

In a field experiment, Bass *et al.* (2016) found that soil carbon content was increased significantly ($P < 0.05$) by all the organic amendments (biochar, compost and biochar-compost) applied. At the end of their field trial, the average carbon stock had increased to 24.2, 8.4 and 17.6 t ha⁻¹ for biochar, compost and biochar-compost respectively, which is similar to the findings of this study. They explained that the increases in carbon reflected in the significant increases in %C and C/N ratio of the soil at the trial end. Other studies (Mensah and Frimpong, 2018; Manolikaki and Diamadopoulos, 2019) have also reported increases in soil carbon content following application of biochar, compost and their combinations.

4.2.5 Available phosphorus (P)

Soil available phosphorus in the sole compost and the combined compost and biochar treatments were significantly ($P < 0.001$) higher relative to the control treatment. Compost applied alone increased available P by 600 – 650%. Available P in the sole biochar treatments (20B and 40B) and the control treatment were similar however, when biochar was combined with compost, available P was increased by 550% (Figure 4.8).

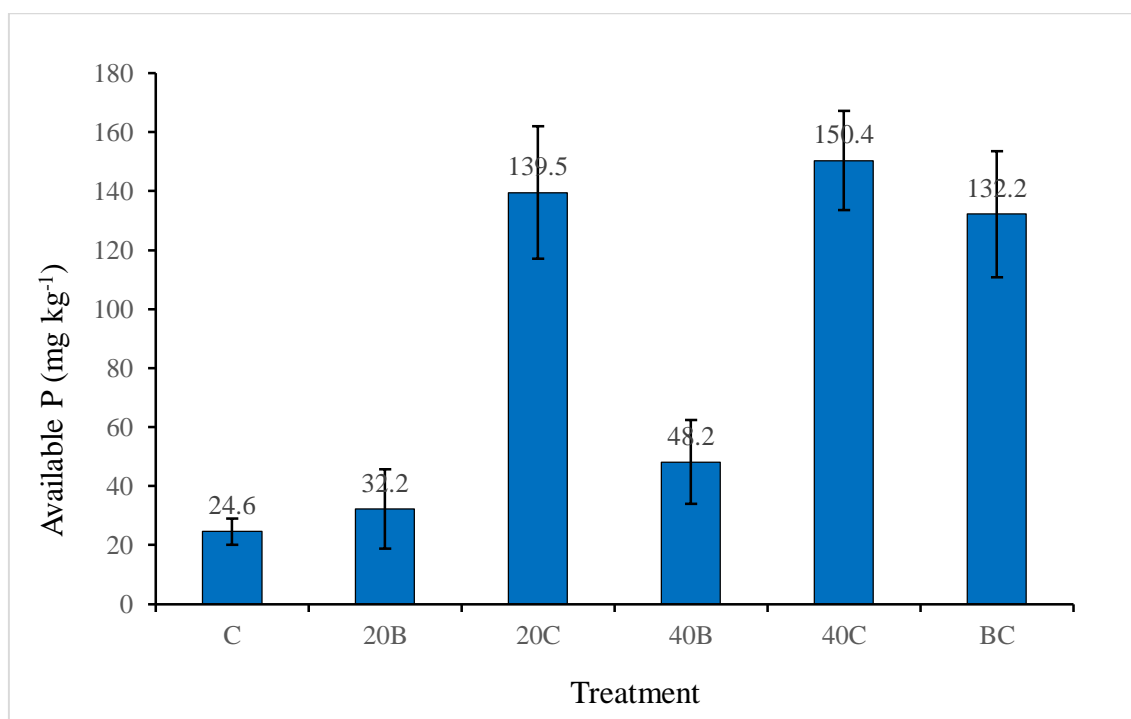


Figure 4.8: Effects of biochar and/or compost application on soil available phosphorus. Numbers on top of each bar represent mean values for each treatment. Error bars represent the standard deviations of the means for 4 samples in each treatments ($n = 24$, $P < 0.001$, $LSD = 0.02$).

The result also showed that soil available P increased with increasing compost and biochar application. Compared to the biochar, the compost used in the study contain higher available P content (Table 3.3), which reflected in the relatively higher available

P content of the compost amended soils. Previous studies (Agegnehu *et al.*, 2016; Cao *et al.*, 2018; Mensah and Frimpong, 2018) have reported similar results.

In a pot experiment, Mensah and Frimpong (2018) found out that application of biochar and compost significantly increased soil available P. In contrast to this study, the highest available P content was found in the sole biochar amended soils. They attributed the increase in soil available P to reduced Fe and Al activities as influenced by the increased in soil pH. Also, in a long term field study on Ferralsol, Agegnehu *et al.* (2016) found that biochar applied solely or in combination with compost increased soil available P between 59 to 117%.

Phosphorus (P) and Nitrogen (N) are important macronutrients which are widely and heavily applied. P and N Loses either by runoff, erosion or leaching in agricultural soils represent a major environmental risk in most countries leading to eutrophication and deterioration of both groundwater and surface water (Cao *et al.*, 2018). Biochar application to soils has been reported to reduce P losses (Chintala *et al.*, 2014; Cao *et al.*, 2018). The ability of biochar to reduce P losses have been attributed to the high affinity of biochar for P which transforms P from readily available form to less available form (Cao *et al.*, 2018).

4.2.6 Exchangeable bases (Mg^{+2} , Ca^{+2} , Na^{+} and K^{+}) and Cation exchange capacity (CEC)

Changes in soil exchangeable base (Mg^{+2} , Ca^{+2} , Na^{+} and K^{+}) contents and CEC as influenced by the application of biochar, compost and their combination are presented in Table 4.1.

Table 4.1: Changes in soil exchangeable cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺) and CEC following the application of biochar, compost and the combination of the two.

Treatment	Ca (cmol. kg ⁻¹)	K (cmol. kg ⁻¹)	Mg (cmol. kg ⁻¹)	Na (cmol. kg ⁻¹)	CEC (cmol. kg ⁻¹)
C	19.94 ± 0.23	2.95 ± 0.09a	5.10 ± 0.09a	1.42 ± 0.14	29.41 ± 0.41a
20B	20.47 ± 1.99	3.47 ± 0.48b	5.59 ± 0.29b	1.59 ± 0.33	31.12 ± 1.64b
20C	21.29 ± 1.02	3.62 ± 0.45b	6.40 ± 0.43c	1.61 ± 0.26	32.92 ± 1.71c
40B	21.10 ± 0.27	4.45 ± 0.04c	5.93 ± 0.22b	1.86 ± 0.06	33.37 ± 0.47c
40C	21.54 ± 0.75	3.50 ± 0.26b	6.52 ± 0.07c	1.70 ± 0.19	33.26 ± 0.78c
BC	22.03 ± 0.21	4.04 ± 0.19c	6.30 ± 0.54c	1.72 ± 0.26	34.09 ± 1.08c
<i>p</i> value	0.08	< 0.00	< 0.00	0.14	< 0.00
LSD (0.05)	2.37	10.00	11.39	1.94	9.52

Numbers are means values ± standard deviations. Different letters within each column indicate significant differences at $P < 0.05$.

Significant ($P < 0.001$) differences were observed for exchangeable Mg, K and CEC, however among the treatments, no significant differences were observed for exchangeable Ca and Na. The biochar amended soils recorded higher exchangeable K while the compost amended soils recorded higher exchangeable Mg. Treatment BC recorded the highest CEC value. The result of the current study agrees with the findings of previous studies (Chintala *et al.*, 2014; Agegnehu *et al.*, 2016; Bass *et al.*, 2016; Cao *et al.*, 2017).

Mensah and Frimpong recorded significantly higher exchangeable Ca and Mg value in soils amended with 2% compost. They attributed the increase in Ca and Mg to the higher ECEC of the compost used in their experiment. In this current study, the CEC of biochar and compost used in the study were 30.17 and 62.19 cmol. kg⁻¹ respectively. In a pot experiment, Cao *et al.* (2018) found an increase in CEC in low nutrient and high nutrient

soils. They explained that the increase in CEC could be due to the higher carbon content of the biochar and compost applied to the soil. CEC represents the nutrient retention capacity of a soil and therefore soil with low CEC will be prone to nutrient leaching. Biochar is porous in nature with the higher surface area which can retain more nutrients on its charge surfaces making nutrients less mobile (Rawat *et al.*, 2019). In contrast to this study, Bass *et al.* (2016) reported an increase in CEC by 27.5%, 24.7% and 4.1% in biochar, compost and biochar-compost amended soils respectively. In an incubation experiment, Chintala *et al.* (2014) observed an increase in CEC continuously over the incubation period (165 days) in all the biochar treatments. They attributed the increase in CEC to alkalinity, proton consumption capacity, and base cations concentration of the biochars used in their study.

4.3 Effects of biochar and compost application on maize growth

Results of the effects of biochar and / or compost application on some plant growth parameters are summarized in the following paragraphs.

4.3.1 Plant height

Sole compost treatments and the combined compost and biochar treatment significantly ($P < 0.05$) increased plant heights of maize from 3WAG to 9WAG (WAG = weeks after germination) relative to the sole biochar treatments and the control treatment. Plant heights of treatment 20B and 40B were significantly ($P < 0.05$) lower than the control treatment at 3WAG, 5WAG and 7WAG. At maturity (9WAG), the plant heights followed the decreasing order BC > 40B > 40C > 20C. No significant differences were observed between plant height of treatment 20B and the control treatment at 9WAG (Figure 4.9).

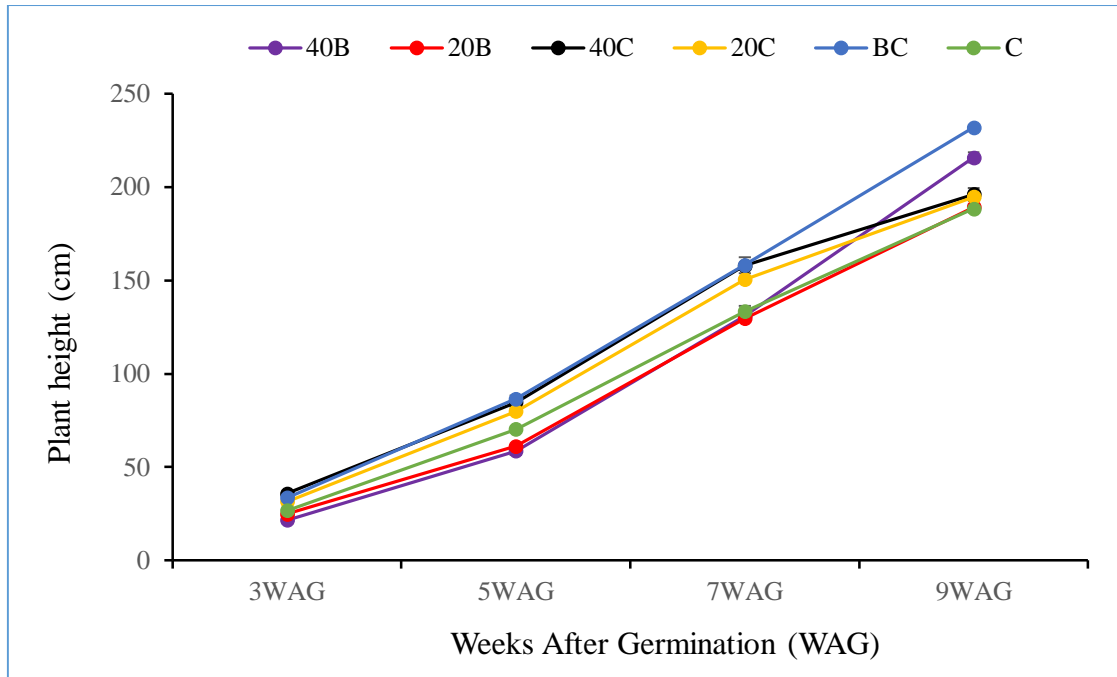


Figure 4.9: Effects of biochar and/or compost application on maize plant height. Error bars represent ± 1 standard deviations of the means.

Significant increases in the heights of plants grown in biochar and compost amended soil have been demonstrated in previous studies (Mensah and Frimpong, 2018; Shareef *et al.*, 2018; Manolikaki and Diamadopoulos, 2019). Mensah and Frimpong (2018) reported an increase in the heights of two maize varieties in Ghana following the application of biochar and compost. They attributed the increase in plant height to the increased soil pH, which potentially promoted increase nutrient availability, especially in the combined biochar and compost amended soils.

In a pot experiment conducted on two soil types (loam and sandy loam) by Manolikaki and Diamadopoulos (2019), the application of biochar and biochar + compost significantly increased the height and stem diameter of maize plant 30 days after seed

germination. Additionally, Sharref *et al.* (2018) found that plant height was influenced by biochar application rate and pyrolysis temperature. In this study, plant height increased with increasing application of biochar and compost. At maturity (9WAG), BC gave the highest significant value followed by 40B but no significant differences were observed among 20B and C (Figure 4.9).

4.3.2 Stem diameter

Sole compost treatments and the combined compost and biochar treatment significantly ($P < 0.05$) increased stem diameter from 3WAG to 9WAG relative to the control treatment. No significant differences were observed in the stem diameter of the sole biochar (20B, 40B) and the control treatment (C). At maturity, the stem diameters followed the decreasing order of BC > 40C > 20C (Figure 4.10).

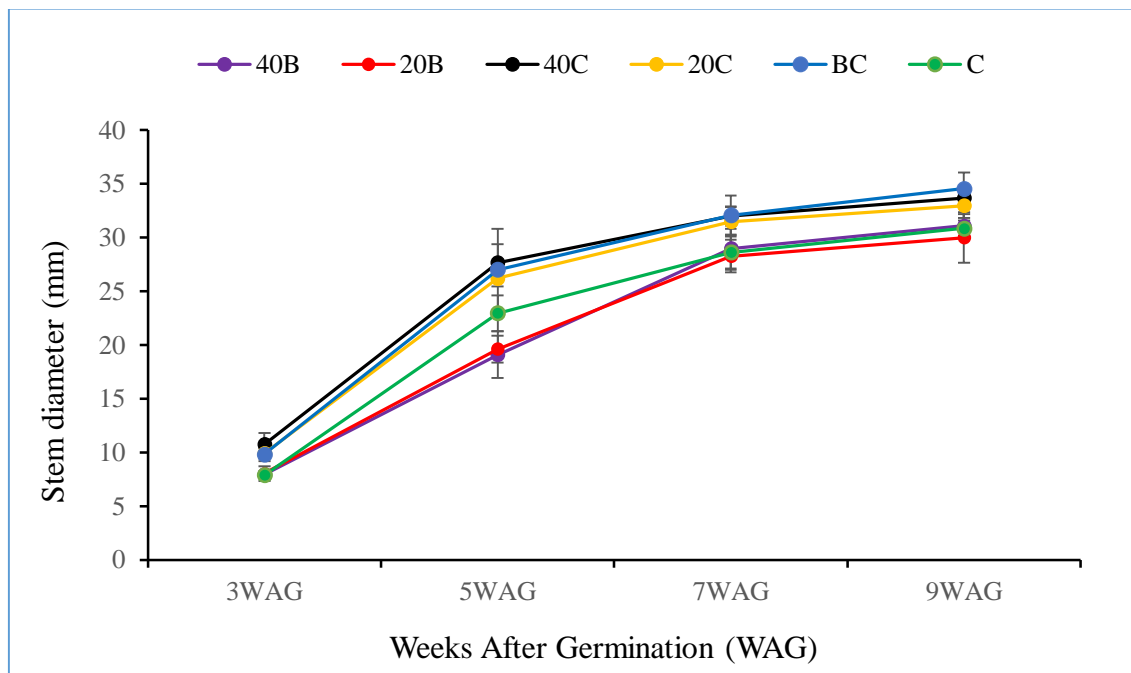


Figure 4.10: Effects of biochar and/or compost application on maize stem diameter. Error bars represent ± 1 standard deviations of the means.

In this study, the application of biochar (20B and 40B) did not influence the stem diameter of the maize plant. The result of this study is similar to the findings of Mensah and Frimpong (2018) where the application of biochar on coastal savannah soil in Ghana decreases the stem diameter (12.8mm and 12.0mm for improved variety and local variety respectively) as compared to the control (21.0mm and 17.17mm for improved variety and local variety respectively). Contrary to the findings of this study, Shareef *et al.* (2018) found an increase in stem diameter with an increasing application rate of biochar. Manolikaki and Diamadopoulos (2019) also found an increase in stem diameter (1.7cm to 2.03cm) in all amended soils compared to the control (1.46cm).

4.3.3 Leaf area

The leaf area of treatment BC, 20C and 40C were significantly ($p < 0.05$) higher than the control at 3WAG, 5WAG and 7WAG (Figure 4.11). The application of biochar reduced the leaf area at 3WAG, 5WAG, 7WAG and 9WAG. The BC, 40C and 20C gave higher values of leaf area at all times depicting a similar trend as was observed with plant height and the stem diameter. The leaf area of all treatments at maturity (9WAG) were similar. This implies that the application of biochar and compost in this study did not significantly influence the leaf area of maize. However, the increase in plant height, stem diameter and leaf area of compost amended soils could be attributed to high mineralization of organic matter and the quick release of nutrient to the plant (Rawat *et al.*, 2019).

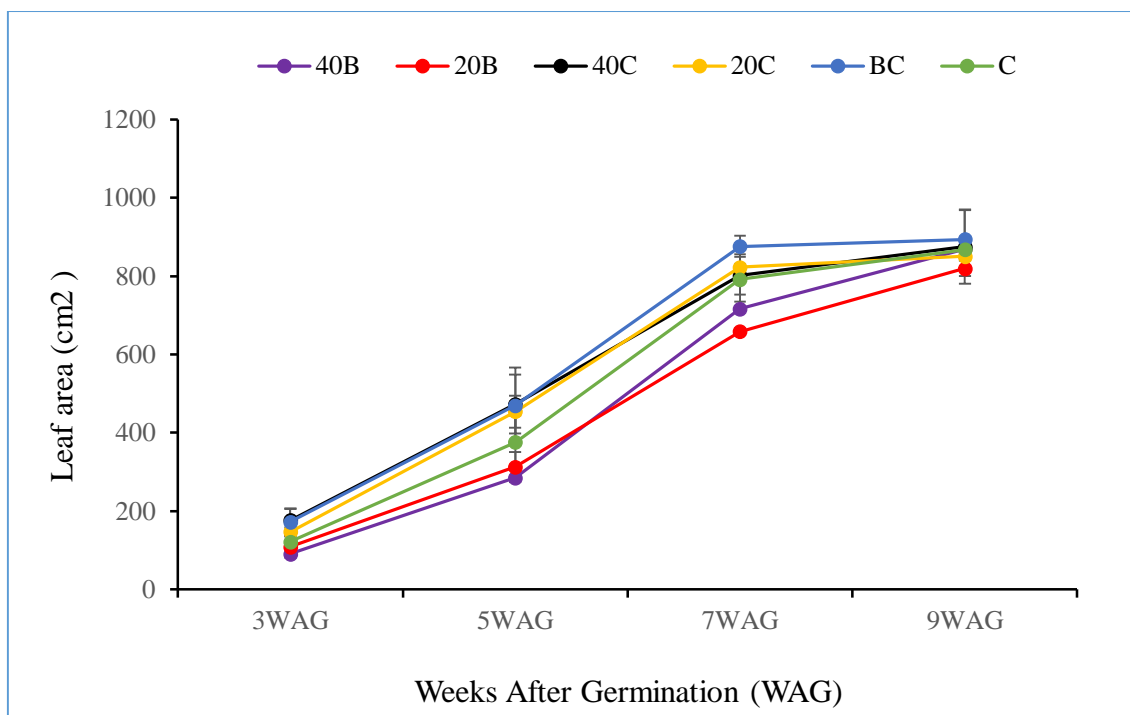


Figure 4.11: Effects of biochar and/or compost application on maize leaf area. Error bars represent ± 1 standard deviations of the means.

4.4 Effects of biochar, compost and their combinations on plant nutrient concentration and maize yield

4.4.1 Plant nutrient concentrations

The nutrient concentrations in the aboveground tissues (shoot) and the belowground tissues (root) are presented in Tables 4.2 and 4.3 respectively. The concentrations of nutrients in the aboveground tissue were not significantly ($P = 0.05$) different among the treatments except for Ca. The concentration of Ca was significantly higher in the sole compost amended soils (20C and 40C) compared to the control treatment (C).

Table 4.2: Effects of biochar, compost and the combination of the two on nutrient concentration in the aboveground tissues (shoot) of maize (within each row, means with different letters are statistically significant at $p < 0.05$).

Parameters	Unit	C	20B	20C	40B	40C	BC	<i>P level</i>
C/N ratio	-	16.86 ± 0.75	16.01 ± 0.24	16.05 ± 0.90	16.83 ± 2.27	16.01 ± 0.75	17.45 ± 0.67	NS
N	%	2.53 ± 0.12	2.62 ± 0.06	2.60 ± 0.16	2.54 ± 0.35	2.61 ± 0.15	2.45 ± 0.12	NS
C	%	42.55 ± 0.32	41.98 ± 0.47	41.63 ± 0.70	42.18 ± 0.34	41.76 ± 0.85	42.64 ± 0.65	NS
S	%	0.48 ± 0.04	0.50 ± 0.03	0.50 ± 0.04	0.49 ± 0.04	0.47 ± 0.02	0.50 ± 0.03	NS
Total Na	g/kg	0.39 ± 0.03	0.42 ± 0.072	0.47 ± 0.08	0.44 ± 0.01	0.48 ± 0.06	0.43 ± 0.01	NS
Total K	g/kg	14.56 ± 1.29	14.78 ± 2.69	15.81 ± 2.28	15.57 ± 1.04	16.39 ± 1.44	14.83 ± 1.29	NS
Total Mg	g/kg	1.56 ± 0.03	1.46 ± 0.31	1.68 ± 0.18	1.56 ± 0.09	1.83 ± 0.17	1.60 ± 0.11	NS
Total Ca	g/kg	2.71 ± 0.25ab	2.71 ± 0.31ab	3.08 ± 0.31bc	2.68 ± 0.39ab	3.35 ± 0.57c	2.49 ± 0.33a	0.045
Total Fe	g/kg	0.52 ± 0.31	0.33 ± 0.07	0.36 ± 0.05	0.41 ± 0.12	0.32 ± 0.04	0.44 ± 0.03	NS
Total P	g/kg	1.97 ± 0.13	2.07 ± 0.34	2.40 ± 0.16*	2.13 ± 0.33	2.27 ± 0.28	2.43 ± 0.17	NS
Total Al	g/kg	0.28 ± 0.07	0.22 ± 0.06	0.23 ± 0.08	0.20 ± 0.01	0.19 ± 0.02	0.23 ± 0.04	NS

Numbers are mean values ± standard deviations

Table 4.3: Effects of biochar, compost and the combination of the two on nutrient concentration in the belowground tissues (root) of maize (within each row, means with different letters are statistically significant at $p < 0.05$).

Parameters	Unit	C	20B	20C	40B	40C	BC	<i>p level</i>
C/N ratio		32.94 ± 1.66	34.92 ± 6.69	31.51 ± 4.56	32.63 ± 1.51	30.71 ± 3.12	38.40 ± 5.27	NS
N	%	1.28 ± 0.07	1.26 ± 0.22	1.34 ± 0.20	1.31 ± 0.06	1.35 ± 0.12	1.12 ± 0.14	NS
C	%	42.08 ± 0.50bc	42.72 ± 0.45c	41.59 ± 0.49ab	42.51 ± 0.70c	41.32 ± 0.37a	42.57 ± 0.25c	0.003
S	%	0.45 ± 0.04	0.47 ± 0.05	0.46 ± 0.01	0.44 ± 0.02	0.50 ± 0.02	0.44 ± 0.03	NS
Total Na	g/kg	1.80 ± 0.22	1.75 ± 0.05	1.99 ± 0.25	1.85 ± 0.29	2.16 ± 0.07	2.07 ± 0.46	NS
Total K	g/kg	13.59 ± 0.67a	14.22 ± 2.36a	15.04 ± 1.81ab	14.98 ± 1.37ab	16.92 ± 0.82b	12.84 ± 1.45a	0.024
Total Mg	g/kg	0.68 ± 0.12	0.75 ± 0.12	0.85 ± 0.12	0.69 ± 0.06	0.83 ± 0.13	0.75 ± 0.07	NS
Total Ca	g/kg	0.84 ± 0.13	0.84 ± 0.17	0.96 ± 0.09	0.80 ± 0.09	1.02 ± 0.17	0.85 ± 0.12	NS
Total Fe	g/kg	1.48 ± 0.75	0.88 ± 0.23	1.22 ± 0.30	0.98 ± 0.31	1.30 ± 0.39	0.83 ± 0.20	NS
Total P	g/kg	0.77 ± 0.07	0.91 ± 0.21	0.94 ± 0.12	0.92 ± 0.22	1.08 ± 0.19	0.81 ± 0.13	NS
Total Al	g/kg	1.35 ± 0.59	0.71 ± 0.19	1.13 ± 0.36	0.83 ± 0.27	1.16 ± 0.32	0.69 ± 0.21	NS

Treatments 20C and 40C had a Ca concentration of 3.08 and 3.35 g kg⁻¹ respectively. The findings agree with those of Manolikaki and Diamadopoulos (2019) who found a significant increase in the concentration of Ca in the aboveground tissue in the sole compost amended soils. However, contrary to their findings, no significant differences were observed in the Ca concentration of the belowground tissue. They explain that the translocation of Ca from soil to the plant root could be suppressed by the biochar application. In the present study, the lower concentrations of Ca in the biochar amended soils could be attributed to the biochar's capacity to retain plant nutrient on its charged surfaces making it unavailable for plant use and preventing nutrient losses through leaching (Rawat *et al.*, 2019). The higher concentration of Ca in the aboveground tissues in the compost amended soils could be attributed to the higher concentration of Ca in the compost used in the study (Table 3.3).

The belowground nutrient concentrations were only significant for total C and total K. The C concentration of belowground tissue was decreased in 20C and 40C whereas the higher concentrations were recorded in the order of 20B > 40B > BC (Table 4.2). The higher concentrations of C in the biochar amended soils could be due to the higher carbon content of the biochar used in the study (Table 3.3). The concentration of K in belowground tissue was only significant in 40C (16.92 ± 0.8).

In this study, the concentration of most nutrients both in the aboveground tissue (C, N, S, P, Mg, K, Na, Fe and Al) and the belowground tissue (N, S, P, Mg, Ca, Na, Fe and Al) were not significantly different among the treatments. However, significant differences may have existed among the treatment if nutrient uptake in different treatments were

determined. Besides, nutrient concentrations in the grains may have varied as nutrients are likely to be retranslocated from the aboveground biomass into the seeds during grain filling. Therefore, I recommend that future research should consider nutrient uptake in both the belowground tissue and the aboveground tissue.

4.4.2 Maize yield

Hundred grain weight (HGW) and grain yield (GY) are presented in Tables 4.6.

Table 4.4: Effects of biochar, compost and their combination on maize yield.

TREATMENTS	GY (t ha ⁻¹)	HGW (g)
C	5.35 ± 0.06a	36.62 ± 0.82a
20B	5.43 ± 0.04a	37.57 ± 0.52b
20C	5.73 ± 0.07ab	39.12 ± 0.63c
40B	6.00 ± 0.21b	40.00 ± 0.32cd
40C	6.00 ± 0.59b	39.22 ± 0.67c
BC	6.57 ± 1.59c	40.35 ± 0.55d
<i>p</i> value	< 0.00	< 0.00
LSD (0.05)	6.5	22.8

Numbers are means values ± standard deviations. Different letters within each column indicate significant differences at $p < 0.05$. GY: grain yield; HGW: hundred grain weight; LSD: least significant difference.

Grain yield (GY) of 20B and 20C were similar to the control treatment. Biochar and compost applied at 40 t ha⁻¹ (40B and 40C) significantly ($P < 0.05$) increased GY by 12.2%. Combined application of biochar and compost (BC) significantly increase GY by 22.8% as compared to the control. Grain yield (GY) increased with increasing application of biochar and compost. Hundred grain weight (HGW) of all amended soils were significantly ($P < 0.001$) higher relative to the control. The increased in HGY of the biochar amended soil resulted in a corresponding increase in GY.

The increase in GY and HGW of the amended soils could be the reason for the no significant differences observed in the plant nutrient concentrations in the aboveground tissues, since the nutrient could be translocated into the seeds during grain filling. These improvement in GY and HGW are consistent with other studies (Agegnehu *et al.*, 2016; Zhang *et al.*, 2016) and could be attributed to the improved nutrient availability and soil moisture. The results of this study is similar to the findings of Agegnehu *et al.* (2016). According to Agegnehu *et al.* (2016), application of biochar and compost to red Ferrersols soil increased GY by 8.1 to 9.2 t ha⁻¹ and HGW by 33.5 to 39.5 g. They attributed the increased in GY and HGW to the improvement in soil nutrient availability in the amended soils.

4.5 Correlation coefficients among soil physicochemical properties and maize yield

Correlation analysis between soil physicochemical properties and maize yield showed strongly positive relationships except for soil bulk density, Total C and Exch. Na (Table 4.5). Maize yield correlated positively with Soil aggregate stability ($r = 0.636, p < 0.01$), Total N ($r = 0.620, p < 0.01$), Available P ($r = 0.552, p < 0.01$), Exch. K ($r = 0.535, p < 0.01$), Exch. Mg ($r = 0.579, p < 0.01$), CEC ($r = 0.645, p < 0.01$), pH ($r = 0.499, p < 0.05$), WHC ($r = 0.487, p < 0.05$), and Exch. Ca ($r = 0.464, p < 0.05$) and correlated negatively with bulk density ($r = -0.436, p < 0.05$). This means that improvement in soil physicochemical properties will result in corresponding increase in maize yield. The results confirms the findings of other scholars (Cerri and Magalhaes, 2012; Agegnehu *et al.*, 2016).

Table 4.5: Pearson correlation matrix between soil physicochemical properties and maize yield in Kamiti sub-catchment, Kenya.

Parameter	BD	WHC	AS	pH (CaCl ₂)	Total N	Total C	Av. P	Exch. Ca	Exch. K	Exch. Mg	Exch. Na	CEC
GY	-0.436*	0.487*	0.636**	0.499*	0.620**	0.261 ^{ns}	0.552**	0.464*	0.535**	0.579**	0.324 ^{ns}	0.645**
CEC	-0.445*	0.643**	0.778**	0.564**	0.563**	0.267 ^{ns}	0.650**	0.827**	0.685**	0.795**	0.596**	
Exch. Na	-0.238 ^{ns}	0.534**	0.32 ^{ns}	0.227 ^{ns}	0.208 ^{ns}	0.352 ^{ns}	0.161 ^{ns}	0.192 ^{ns}	0.764**	0.434*		
Exch. Mg	-0.260 ^{ns}	0.378 ^{ns}	0.827**	0.269 ^{ns}	0.398 ^{ns}	0.003 ^{ns}	0.845**	0.494*	0.501*			
Exch. K	-0.440*	0.822**	0.416*	0.599**	0.539**	0.665**	0.185 ^{ns}	0.243 ^{ns}				
Exch. Ca	-0.354 ^{ns}	0.375 ^{ns}	0.625**	0.477*	0.442*	0.044 ^{ns}	0.548**					
Av. P	-0.173 ^{ns}	0.128 ^{ns}	0.878**	0.162 ^{ns}	0.266 ^{ns}	-0.266 ^{ns}						
Total C	-0.623**	0.800**	0.104 ^{ns}	0.613**	0.646**							
Total N	-0.635**	0.629**	0.466*	0.580**								
pH	-0.509*	0.835**	0.463*									
As	-0.438*	0.497*										
WHC	-0.625**											

GY: grain yield; BD: bulk density; WHC: water holding capacity; AS: aggregate stability; Av. P: available phosphorus; CEC: cation exchange capacity; ns: not significant.

** . Correlation is significant at the 0.01 level.

* . Correlation is significant at the 0.05 level.

CHAPTER FIVE

5 SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of key findings

Based on the soil and plant analyses, the growth parameters measured on the field and the yield obtained from the maize crop, the following findings were observed:

The soil characterization showed that the study site is very low in nutrient (Table 3.1). The soil recorded very low content of available P (0.09 g kg^{-1}). There was also a high concentration of Fe (30.28 g kg^{-1}) and Al (27.14 g kg^{-1}) in the soil. The textural class of the soil in the study area was found to be silty-loam with clay, silt and sand content of 19.1, 63.6 and 17.3% respectively. The chemical properties of the amendments (biochar and compost) used in the study varied considerably. For instance, the pH of the biochar and the compost were 8.99 and 7.54 respectively. This is an indication that biochar and compost can increase the pH of acidic soils to different extents when applied in the same quantities. The carbon content was higher in the biochar (79.13%) than in the compost (20.46%). Other nutrients elements such as Total N, P, Na, Ca, Mg and available P were all higher in the compost than in the biochar. This is also a good indication that compost will provide more nutrient to the soil than the biochar.

In general, the application of biochar, compost and their combinations improved the soil physical properties. Soil bulk density was significantly decreased by all organic amendments relative to the control. Soil aggregate stability was significantly increased by all amendment types compared to the control. Aggregates stability was found to have increased with increasing application of both biochar and compost. Water holding

capacity (WHC) of the soil was also significantly increased by all amendment type with the biochar amendments having a greater impact. Soil WHC was also found to have increased with increasing application of biochar and compost.

Soil chemical properties as affected by biochar and compost application was assessed. Soil pH increased significantly ($P < 0.01$) in the sole biochar treatment. However, the sole compost treatments did not significantly influence soil pH. Sole application of biochar and combined application of biochar and compost significantly ($P < 0.05$) increased soil TN, TC and the C/N ratio more than compost applied alone. The application of compost alone and in combination with biochar significantly ($P < 0.001$) increased the soil available P. It was also found that the soil available P increased with increasing compost application. The effect of the organic amendments on soil exchangeable cations was only significant ($P < 0.001$) for K and Mg. The biochar amended soils recorded higher exchangeable K whereas the compost amended soils recorded higher exchangeable Mg. The soil total elements (Mg, Na, Ca, K, Fe and Al) concentrations in all amended soils were not statistically significant ($P = 0.05$) compared to the control except for total P. The total P was only significant in the sole compost treated soils.

In general, the application of the organic amendments improved the maize growth (Plant height and stem diameter). The plant height and the stem diameter were statistically significant ($p < 0.05$) in all the compost amended soils (20C, 40C and BC) relative to the control. The plant height of 40B was only significant at maturity (9WAG). The biochar amended soils did not significantly influence the stem diameter. Only the compost

amended soil significantly improved the plant height and the stem diameter. The result of the study showed no significant difference in the leaf area among all treatments.

The nutrient concentration (Na, P, Mg, Ca, K, Fe and Al) in the aboveground tissue (shoot) were not statistically significant except for Ca. In the belowground tissue (roots), differences were only observed for total carbon (TC) and total K. The biochar amended soils increased the root TC but differences observed were not significant. In contrast, compost amended soil significantly decreased the root TC by 1.8% in 40C.

Grain yield (GY) and hundred grain weight (HGW) were significantly ($P < 0.05$) higher in all amended soils relative to the control (Table 4.4). The highest GY and HGW was recorded in BC (6.6 t ha⁻¹ and 40.4 g respectively). GY and HGW increased with increasing application of biochar, but increasing application of compost did not resulted in increased HGW.

5.2 Conclusions

The results of the study showed that biochar, compost and their combined application can improve soil properties and, growth and yield of maize grown on an acidic Ferralsol. The soil physical properties (bulk density, water holding capacity and aggregate stability) were significantly improved by all amendment type. Soil bulk density decreased with increasing application of biochar and compost. Conversely, the soil aggregate stability and the water holding capacity increased with increasing application of the amendment. The improvement in soil physical properties resulted in an improvement in the soil chemical properties (pH, EC, CEC, TC, TN and available P). For example, the WHC

represent the nutrient retention capacity of the soil, and therefore soils with high WHC can retain nutrients more than soils with low WHC.

In general, the maize growth was improved by the amendment application. Although no significant differences were observed among treatments for leaf area at maturity, the difference in plant height and stem diameter were significant. Combined application of biochar and compost recorded highest significant values for both plant height and stem diameter. This is an indication that biochar applied with compost can improve plant growth more than biochar or compost applied alone. The application of biochar and compost increased grain yield (GY) by 1.5 to 22.8% and hundred grain weight (HGW) by 2.6 to 10.3% with the combined application of biochar and compost (BC) having greater impact on both GY and HGW.

The combined application of biochar and compost (BC) recorded the highest significant values for bulk density, aggregate stability, total nitrogen, CEC, plant height and stem diameter, GY and HGW. Whenever the sole application of biochar or compost (20B, 20C, 40B and 40C) were higher than the BC (WHC, pH, EC, TC, available P), differences observed were not statistically significant. Base on the above observations, it could be concluded that the combined application of biochar and compost can be used to solve soil fertility problems on Ferralsol which is dominant in the Kamiti sub-catchment.

5.3 Recommendations

Based on the result of the study, the following recommendations are made:

- i. Farmers in the study area should use corn cob biochar and compost to improve soil fertility and to increase maize yield. Corn cob biochar and compost

application do not only add nutrient to the soil but also improves the physical conditions making the soil more efficient in supporting microbial activities and, retaining water and nutrient.

- ii. Biochar and compost should be seen as alternative used for organic waste. Organic waste management is a major problem in Kenya. Apart from environmental pollution, improper management of organic waste have public health implications which can affect the quality of life of the people living in such an environment.
- iii. Agricultural policies on soil fertility improvement and environmental relative policies on organic waste management should be geared towards large scale adoption of biochar and compost technologies. In order to achieve that, large scale research on biochar and compost should be conducted by the Kenya Ministry of Agriculture in collaboration with interested stakeholders on all the agro-ecological zones and all soil types in Kenya. The results of such research will enable the recommendation of biochar type, application rate and the ratio of combination of biochar with compost for each soil type in the agro-ecological zones in Kenya.

5.4 Areas for further research

Potential areas for further research on biochar and compost application on soil properties and crop yield in the sub-catchment include the following:

- i. Long-term effects of biochar and compost application on soil physicochemical properties and crop yield.

- ii. Effects of biochar type, pyrolysis temperature and application rate on soil properties.
- iii. Effects of biochar and compost application on soil microbial activities.
- iv. Potential of biochar for remediation of contaminated soils.
- v. Factors influencing the adoption of biochar and compost technologies by farmers.

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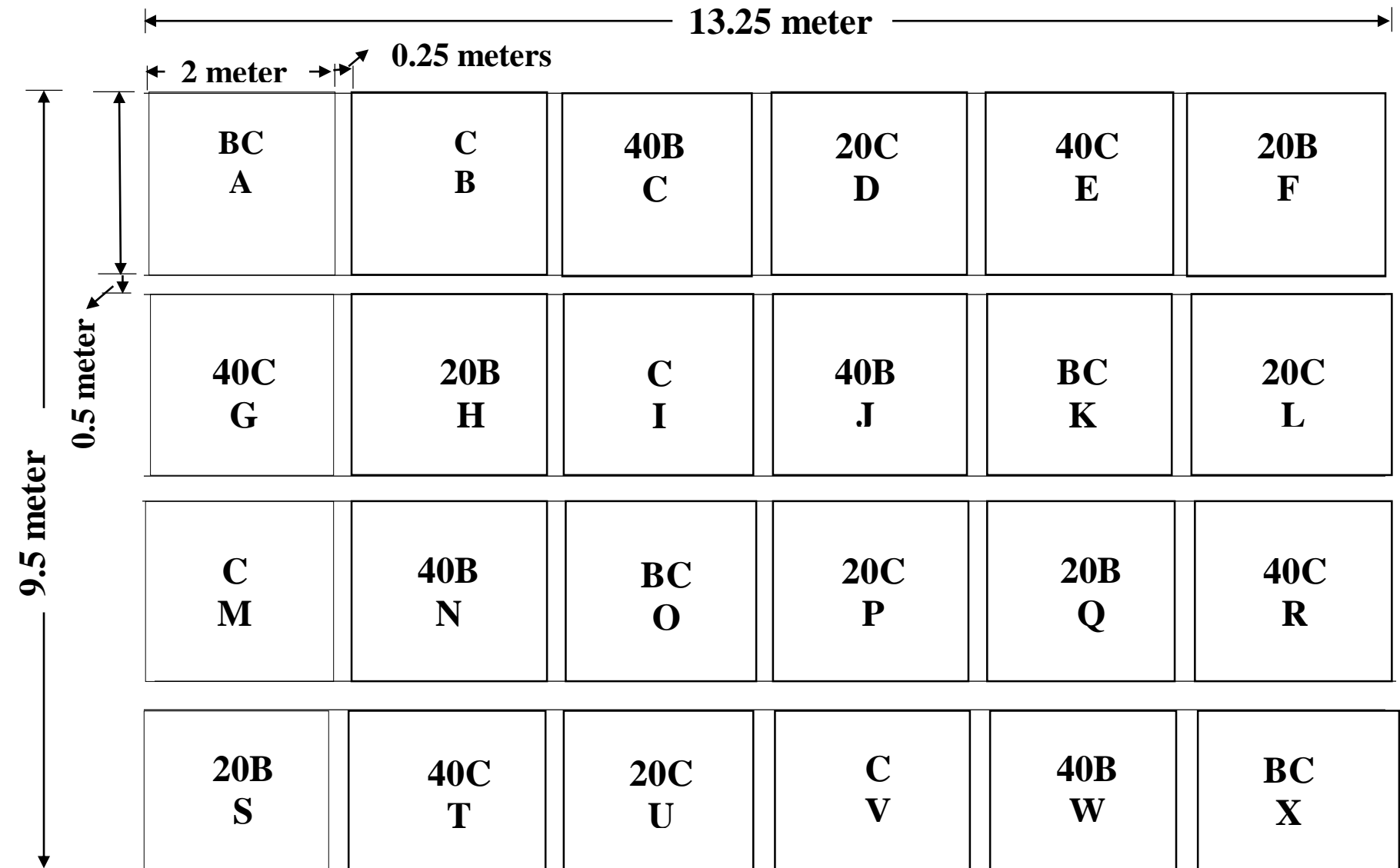
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APPENDICES

Appendix 1: Experimental Field Layout (Completely Randomized Design)



Appendix 2: Physiological observations of maize plants at maturity.

The maize plants at two months old (Plate 17) had already started tasseling (Plate 18) and producing multiple cobs (Plate 19).



Plate 17: Maize plant at two months old (Author, 18th April 2019).



Plate 18: Tasseling and silking (Author, 18th April 2019).



Plate 19: Multiple cob development (Author, 30th April 2019).

Appendix 3: Normality test for soil physicochemical data (Shapiro-Wilk)

Significant values > 0.05 are normally distributed, and values < 0.05 are not normally distributed.

		Tests of Normality					
TREATMENTS		Kolmogorov-Smirnov ^a			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
BD	20B	.298	4	.	.904	4	.453
	20C	.194	4	.	.989	4	.951
	40B	.251	4	.	.961	4	.785
	40C	.204	4	.	.971	4	.847
	BC	.207	4	.	.968	4	.828
	C	.318	4	.	.786	4	.079
WHC	20B	.197	4	.	.985	4	.931
	20C	.305	4	.	.900	4	.432
	40B	.266	4	.	.904	4	.453
	40C	.226	4	.	.942	4	.669
	BC	.233	4	.	.911	4	.489
	C	.243	4	.	.916	4	.515
AS	20B	.294	4	.	.851	4	.230
	20C	.267	4	.	.898	4	.420
	40B	.191	4	.	.979	4	.894
	40C	.192	4	.	.971	4	.850
	BC	.268	4	.	.926	4	.571
	C	.197	4	.	.965	4	.810
pH	20B	.264	4	.	.945	4	.682
	20C	.224	4	.	.945	4	.685
	40B	.274	4	.	.864	4	.273
	40C	.236	4	.	.941	4	.659
	BC	.254	4	.	.911	4	.488
	C	.259	4	.	.863	4	.272
CN	20B	.285	4	.	.876	4	.321
	20C	.262	4	.	.911	4	.485
	40B	.230	4	.	.934	4	.616
	40C	.256	4	.	.854	4	.241
	BC	.233	4	.	.904	4	.452
	C	.229	4	.	.937	4	.633
N	20B	.262	4	.	.886	4	.366

	20C	.172	4	.	.983	4	.917
	40B	.249	4	.	.925	4	.567
	40C	.299	4	.	.926	4	.570
	BC	.351	4	.	.791	4	.087
	C	.297	4	.	.779	4	.069
	20B	.194	4	.	.962	4	.790
	20C	.277	4	.	.857	4	.248
C	40B	.229	4	.	.919	4	.531
	40C	.304	4	.	.896	4	.412
	BC	.292	4	.	.816	4	.134
	C	.172	4	.	.982	4	.911
	20B	.183	4	.	.983	4	.920
	20C	.178	4	.	.994	4	.978
S	40B	.276	4	.	.887	4	.368
	40C	.340	4	.	.871	4	.303
	BC	.185	4	.	.981	4	.906
	C	.274	4	.	.864	4	.275
	20B	.203	4	.	.987	4	.940
	20C	.285	4	.	.840	4	.196
Na	40B	.290	4	.	.930	4	.592
	40C	.329	4	.	.882	4	.346
	BC	.298	4	.	.848	4	.219
	C	.381	4	.	.768	4	.056
	20B	.342	4	.	.821	4	.146
	20C	.252	4	.	.854	4	.241
K	40B	.251	4	.	.900	4	.429
	40C	.221	4	.	.971	4	.850
	BC	.356	4	.	.786	4	.079
	C	.211	4	.	.964	4	.802
	20B	.201	4	.	.972	4	.852
	20C	.165	4	.	.986	4	.939
Mg	40B	.258	4	.	.953	4	.735
	40C	.189	4	.	.990	4	.959
	BC	.236	4	.	.939	4	.647
	C	.189	4	.	.975	4	.870
	20B	.196	4	.	.989	4	.953
	20C	.274	4	.	.946	4	.693
Ca	40B	.279	4	.	.884	4	.358
	40C	.215	4	.	.957	4	.760

Fe	BC	.257	4	.	.838	4	.191
	C	.175	4	.	.981	4	.909
	20B	.223	4	.	.931	4	.599
	20C	.304	4	.	.910	4	.482
	40B	.188	4	.	.975	4	.870
	40C	.224	4	.	.955	4	.747
P	BC	.393	4	.	.699	4	.011
	C	.224	4	.	.956	4	.751
	20B	.217	4	.	.937	4	.636
	20C	.303	4	.	.852	4	.234
	40B	.247	4	.	.892	4	.392
	40C	.335	4	.	.863	4	.271
Al	BC	.259	4	.	.845	4	.209
	C	.217	4	.	.925	4	.565
	20B	.270	4	.	.842	4	.202
	20C	.283	4	.	.915	4	.511
	40B	.277	4	.	.944	4	.676
	40C	.271	4	.	.873	4	.308
AP	BC	.299	4	.	.838	4	.191
	C	.234	4	.	.944	4	.679
	20B	.241	4	.	.919	4	.532
	20C	.246	4	.	.961	4	.785
	40B	.207	4	.	.958	4	.768
	40C	.367	4	.	.743	4	.033
	BC	.270	4	.	.887	4	.367
	C	.240	4	.	.935	4	.625

a. Lilliefors Significance Correction