EFFECT OF BIOCHAR ON SOIL PHYSICAL PROPERTIES, WATER USE EFFICIENCY, AND GROWTH OF MAIZE IN A SANDY LOAM SOIL

BY

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AT

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DECLARATION

I hereby declare that except for references to works of other researchers, which have been duly cited, this work is the result of my original research and that this thesis has neither in whole nor in part been presented to any other University for the award of a degree.

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DEDICATION

I solemnly dedicate this work to Dr. Eric Oppong Danso, who through his relentless support and coaching has seen to the successful outcome of this work. May the Lord God bless every contribution you have made to this work.
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LIST OF ABBREVIATIONS

BA  Biochar amount
BD  Bulk density
CBP Coarse biochar particles
CCI Chlorophyll content index
DI  Deficit irrigation
DMY Dry matter yield
FBP Fine biochar particles
FI  Full irrigation
IR  Irrigation regime
LA  Leaf area
MAD Management allowable depletion
PH  Plant height
PS  Particle size
SG  Stem girth
TE  Transpiration efficiency
W   Weight
WR  Water retention
WUE Water use efficiency

LIST OF SYMBOLS

Θs  Saturated water content
Θr  Residual water content
Θg  Gravimetric water content
Θv  Volumetric water content
α   Empirical constant
ρ   Bulk density
ABSTRACT

There has been claims that biochar improves water retention in soil and aid in improved crop productivity. Hence, recent conservation practices in the area of agricultural lands have focused research attention on the performance mechanism of biochar. In this study, the effect of corn cob biochar particle sizes (<2 mm & ~2-4 mm) and amounts (0, 20, 40, 80 tons/ha) on soil physical properties (soil bulk density and soil water retention) and biomass yield were investigated. It further investigated the effect of deficit (DI) and full (FI) irrigation in combination with biochar on plant physiology and water use efficiency.

Corn cob biochar was mixed with the top 20 cm sandy loam soil at a rate of (0, 20, 40 & 80 tons/ha) in pots made of PVC columns (20 cm diameter x 75 cm height). Three maize seeds were planted and thinned out two weeks after planting leaving one maize plant per pot. NPK fertilizer (3.1 g) was applied to all pots. Soil moisture content reading was taken every third day for the first three weeks and every second day afterwards. From the beginning, each pot was supplied with the amount of water lost to restore to field capacity. After three weeks, deficit irrigation (DI) strategy was implement. All full irrigation (FI) treatments were irrigated immediately water loss exceeded a management allowable depletion (MAD) of 30 % of the pot field capacity, and for the DI treatments at MAD of 80 %. Three drying cycles were achieved between day 26 and day 70 (last day of terminating the work). The results showed that bulk density (BD) decreased significantly between the control (1.46 g/cm³) and the 80 tons/ha (1.30 g/cm³) biochar treatment. Also, BD decreased insignificantly with decreasing biochar particle sizes relative to the control. BD was found to decrease with increasing biochar fine i.e. (CBP (2-
Bulk densities of 1.39 g/cm³ and 1.35 g/cm³ were found for the coarse biochar particle (CBP) and fine biochar particle (FBP) respectively relative to the control 1.46 g/cm³. Soil water retention characteristics were affected by addition of biochar. The result shows that addition of 20 tons/ha biochar surprisingly did not alter the curve that much though at higher matric potential tends to hold substantial amount of water relative to the no biochar treatment. However, biochar application rate of 80 tons/ha had significant effect relative to the control. It was discovered in general that, applying corn stover biochar at a rate beyond 20 tons/ha will improve the water retention characteristic of sandy loam soil. Furthermore, biochar particle size also affected the water retention characteristics as it was discovered that, the FBP retained more water at low matric potential but as matric potential increased beyond -300 kPa, the CBP retained more water.

Furthermore, the biomass yield (BY) results showed a yield loss of 21.2% for DI treatments relative to the FI treatments. However, 59.2% water was conserved in this case for the DI treatments. This implies biochar addition to soil with deficit irrigation practices may be a promising water conservation strategy. It was also observed that, the yield values for the DI biochar treatments were close to the FI control values. Transpiration efficiency was significant between the DI treatments (32 g/mm) and the FI treatments (20 g/mm). Plant physiology was also enhanced by the addition of biochar even though the differences were not consistently significant.

Therefore, it is concluded in this study that addition of corn cob biochar does improve soil physical properties and enhance water retention within the soil, and that biochar amendment in combination with deficit irrigation does have the potential to improve water use efficiency by enhancing plant physiology and yield.
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CHAPTER ONE

1.0 INTRODUCTION

Biochar is a carbon-rich solid by-product from biomass subjected to anaerobic thermochemical pyrolysis. It has been identified by research as a soil amendment tool with the potential of enhancing soil water holding capacity (Streubel et al., 2011; Mukherjee and Lal, 2013; Yu et al., 2013). It is also known to enhance soil nutrient retention and availability (Glaser et al., 2002; Liang et al., 2006; Karhu et al., 2011). It seems therefore that soils amended with biochar have the tendency to retain more water and nutrients for crop production. Thus biochar application could be a worthy strategy to enable sustainable crop production.

Drought stress negatively affects crop growth especially at the early reproductive stage (Liu et al., 2003), and to curb this, farmers rely on irrigation to avert potential damages to crops. Irrigation practice such as deficit irrigation (DI) is an optimization strategy used to sustain crop production by limiting irrigation to drought-sensitive growth stages of crops especially in cases of reduced water supply (Saqib et al., 2014; Geert and Raes, 2009). This practice aims to maximize water use efficiency (WUE) and to stabilize yields. WUE has been defined as the amount of vegetative dry matter produced per unit volume of water taken up by crop from the soil (Viets, 1962), and has been identified as a key term in evaluating DI strategies (Molden, 1997).

Biochar can be produced from a wide range of biomass feedstock. In Ghana, straw and stalk residues from cereals are generated in large quantities with corn stover being the commonest residue available (Duku et al., 2011). Corn stover biochar application increased
water retention of a sandy loam soil at low matric potential, which means that even though the soil may be dry, the biochar will still retain some water (Devereux et al., 2012). Corn stover biochar application in some studies has shown positive effect by decreasing the soil bulk density (Brewer et al., 2011; Cornelissen et al., 2013) which therefore makes it a very good biomass material for biochar production.

Further research has shown that, biochar obtained from crop residues such as rice husk and corn cob has high mineral ash content which contains important macro and micro nutrients such as Phosphorus (P), Potassium (K), Silicon (Si), Iron (Fe), Sulphur (S), Magnesium (Mg), and Calcium (Ca) (Sombroek et al., 2003; Shoemaker, 2008). These nutrients are readily utilized by plants for improved growth. Meanwhile, the acid soils in tropical regions are deficient in several of these nutrients especially the micro nutrients which are lost as a result of high temperature and heavy rainfalls (Richmond and Sussman, 2003). Thus application of biochar to these soils may replenish some of the lost nutrients in the soil.

Biochar has the ability to improve soil physical properties (i.e., surface area, SA, porosity, bulk density, BD) (Laird et al., 2010; Lehmann et al., 2011; Mukherjee and Lal, 2013) and soil hydrological properties (i.e., water holding capacity, WHC, moisture content, MC, water retention, WR, infiltration rate, IR, hydraulic conductivity, HC), (Downie et al., 2009; Major et al., 2009; Atkinson et al., 2010; Sohi et al., 2010; Verheijen et al., 2009). Mankasingh et al. (2011) reported of a decrease in BD from 1.66 to 1.53 gcm⁻³ in a biochar-amended soil while Brodowski et al. (2006) showed that biochar-soil interaction through aggregation affects the soil moisture retention pattern as well as soil drainage. Yu et al. (2013) observed a doubling in water holding capacity of loamy sand after addition of biochar. Thus, the ability of biochar to increase
water holding capacity is likely to have a profound effect on areas prone to drought or water shortage (Karhu et al., 2011).

Primarily, biochar is composed of single and condensed carbon aromatic rings (Lehmann, 2007), and is noted to have high surface area per unit mass with high charge density. This makes biochar have high capacity to absorb cations as compared to soil organic matter (Liang et al., 2006; Van Zwieten et al., 2009). Biochar is also reported to have high porosity with pore size ranging from < 2nm to > 50 nm (Liang et al., 2006; Downie et al., 2009; Hina et al., 2010). This high porous nature of biochar influences hydraulic conductivity and aeration (Brodowski et al., 2006). Also, the particle size (PS) of the biochar influences its effect on the soil. Boadu (2000) observed that addition of fine biochar particles may increase soil porosity. Brodowski et al. (2007) further discussed that biochar over time degrades into silt sized particles changing the porosity and saturated hydraulic conductivity (K) of the amended soil.

International Biochar Initiative IBI (2010) stated that “Long-term studies in different soils are required to draw strong conclusions regarding the effect of the size of biochar particles on soil improvement”, and that, “Ideal particle sizes to improve soil moisture retention have not been determined”. According to Lehman et al. (2009), 2 mm biochar grain size is the most suitable for application to agricultural lands. However, Tryon (1948) discovered that finer biochar particles (<1 mm) showed a higher impact on soil water retention curve than the larger particle size biochar (2-5 mm). This therefore calls for further examination of the effect of biochar particle size on soil physical properties, since there is limited information available.

Therefore, this research seeks to study how two different particle sizes (<2 mm, and 2-4 mm) of a corn cob biochar in combination with two irrigation regimes (deficit and full irrigation)
will contribute to water use efficiency, effect on soil physical properties (bulk density, water retention), and examine the overall influence on the growth of maize. The knowledge from this work will help to determine the particle size suitability for biochar-soil amendment and also help in proper irrigation planning and scheduling.

1.1 OBJECTIVES

The aim of the study is:

➢ To evaluate the effect biochar application on plant-soil interactions and how this translates to improved yields

The objectives of the study are:

1. To determine the effect of two biochar corn cob particles sizes on bulk density and water retention of a sandy loam soil.
2. To determine the effect of different biochar quantities on bulk density and water retention of a sandy loam soil.
3. To determine the transpiration and biomass yield of maize grown in biochar treated soil under full and deficit irrigation

Research Hypothesis

I. \( H_0 \): Different particle size of corn cob biochar will affect soil physical properties

\[ H_A: \text{Different particle size of corn cob biochar will not affect soil physical properties.} \]

II. \( H_0 \): Different corn cob biochar quantity will affect soil physical properties

\[ H_A: \text{Different corn cob biochar quantity will not affect soil physical properties} \]
III.  \( H_0 \): Full irrigation will positively influence biomass yield of maize over deficit irrigation

\( H_A \): Full irrigation will not positively influence biomass yield of maize over deficit irrigation
CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Biochar History and impact on Agriculture

The term biochar was first used to refer to the pyrolysis residue of solid biomass produced for sequestrating carbon from the atmosphere in the soil (Bapat and Manahan, 1998; Lehmann, 2007). This carbon (C)-rich biochar substance is made by heating organic matter under a low-oxygen condition. Intensive biochar application in agriculture dates back to the early 1600s in Japan and possibly earlier in China (Ogawa and Okimori, 2010). When it is applied to soils, it does not only sequester carbon from the atmosphere into the soil but also perform additional functions such as improve soil fertility and enhance soil physical and chemical properties.

Studies have shown that adding biochar to the soil decreases soil bulk density, increases cation exchange capacity and enhances nutrient and soil water availability (Laird et al., 2010). It also improves plant nutrient uptake, water use and plant productivity which leads to reduction in the use of fertilizers (Glaser et al., 2002; Lehmann, 2007). These findings have sparked great interest in biochar research especially in the area of its impact on agricultural soils.

2.2 Biochar Physicochemical Composition

The impact of biochar on soil properties depends on its physical and chemical properties. Key functional properties of a biochar include surface area, porosity and structural arrangement, surface charge and alkalinity, and organic carbon content (Brewer et al., 2009; Spokas et al., 2011). These properties are mostly influenced by the nature of feedstock (soft wood, hardwood,
straw or stalk), process conditions (pyrolysis temperature, reactor type, charring duration), and the post-production treatments (Gaskin et al., 2008; Sohi et al., 2010; Zimmerman, 2010). The influence of these factors, according to Downie et al. (2009), affects the final macro-and micro-structure of the biochar particle, which in turn enhances the physical and chemical nature of the biochar.

2.2.1 Physical Composition

The most important physical properties of biochar are the specific surface area (SSA), bulk density (BD), porosity (pore size and volume), and the particle size distribution (PSD). The porosity and particle size distribution affect the impact of biochar on soil physical properties. Porosity, according to Downie et al. (2010), depends on the parent feedstock and pyrolysis conditions. Atkinson et al. (2010) explained that biochar retains the cell wall structure of the parent feedstock and as a result has very high porosity. The pore size of biochar classified by Verheijen et al. (2009) according to their internal diameters (ID) ranges from <2 to >50 nm (i.e. macropores (ID >50 nm), mesopores (2 nm< ID <50 nm) and micropores (ID <2 nm). Downie et al. (2009) observed that woody feedstocks produce biochar with higher proportion of meso- and macropores and having larger surface areas than herbaceous feedstocks. Kwon and Pignatello (2005) found that biochar produced above 450°C mostly have high porosity, but those produced below such temperatures normally have their pores being blocked by volatile organic compounds which affect their adsorption capacity (Kwon and Pignatello, 2005; Pignatello et al., 2006). This is because as production temperatures increase, more volatile contents, H, O, N, ratios are lost in the biochar matrix, while porosity, surface area and ash content increase (Downie et al., 2009; Keiluweit et al., 2010; Wang et al., 2013).
Also, a wide range of pore sizes contribute to a large surface area and low bulk density in biochar. The surface area of biochar from different feedstocks produced at temperatures ranging from ~250 to 600 °C may vary from 1 m\(^2\)g\(^{-1}\) to 750 m\(^2\)g\(^{-1}\) according to Downie et al. (2009). This is influenced by the presence of the micropores according to Brown (2009). However, large portions of the surface area is above 300 m\(^2\)g\(^{-1}\) and according to Mohan et al. (2007) some biochars can have very large specific surface areas of ~1000 m\(^2\)g\(^{-1}\). The bulk density (BD) of biochar according to Brady and Weil (2004) is far lower than that of a mineral soil (i.e. 0.3 Mgm\(^{-3}\) for biochar as compared to a typical soil bulk density of 1.3 Mgm\(^{-3}\)).

Biochar particle size distribution depends on the pyrolysis conditions and the characteristics of the initial feedstock. During pyrolysis, there is attrition and mass loss in the organic materials which cause cracks and shrinkage in the feedstock leading to a breakdown into different particle sizes (Downie et al., 2009). The texture of the biochar depends on the type of feedstock, production chamber and the duration of pyrolysis. Brewer et al. (2009) observed that biochar produced via gasification generates chars with smaller or finer particles which have higher SSA. Woody biomass mostly produces coarser particles unlike herbaceous biomass which produces finer particles (Verheijen et al., 2009). The finer particles according to Yargicoglu et al. (2015) have lower hydraulic conductivity and high water holding capacity because of their smaller pore spaces. Biochar particle size normally used in experiments ranges from 2 to 20 mm (Lehman et al., 2009; Novak et al., 2009). However, Lehman et al. (2009) has suggested the 2 mm size fraction to be more appropriate for agricultural lands.

2.2.2 Chemical composition

Chemically, Lehman (2007) describes biochar as composed primarily of single and condensed carbon aromatic rings and McElligott (2011) adds that these rings have contents of
plant micro and macro nutrients retained from the starting feedstock. And according to Amonette and Joseph (2009), biochar contains a recalcitrant organic carbon (C), which is held in aromatic form giving biochar a strong sequestration and stability potential, and also making it highly resistant to decomposition in the soil. Chan et al. (2007) found that the C composition in biochar range between 172 g/kg and 905 g/kg and this was explained by Downie (2009) to be dependent on the feedstock type and pyrolysis condition. In the case of nutrient analysis, literature has estimated the nitrogen content in biochar to range from 1.8 g/kg to 56.4 g/kg, total Phosphorus (P) from 2.7 g/kg to 480 g/kg and total potassium (K) from 1.0 g/kg to 58 g/kg (Lehmann et al., 2003; Lima and Marshall, 2005; Chan et al., 2007). Biochar also contains varying concentrations of other elements such as Oxygen (O), Hydrogen (H), Sulfur, (Goldberg, 1985; Preston and Schmidt, 2006). The pH of biochar typically ranges from 4 to 12, and this according to Lehmann (2007), is dependent on the starting feedstock and the operating conditions. Generally, low pyrolysis temperatures (< 400 °C) yield acidic biochar, while increasing pyrolysis temperatures produce alkaline biochar. The cation exchange capacity (CEC) of biochar can increase up to about 40 cmol g⁻¹ (Lehmann, 2007). However, it is very low in freshly produced biochar, but increases with time as the biochar interact and ages in the presence of O₂ and water (Glaser et al., 2001; Cheng et al., 2008; Cheng et al., 2006; Liang et al., 2006).

2.3 Impact of Biochar on soil

2.3.1 Influence on Soil Surface Area and Porosity

According to Downie et al. (2009), when biochar is incorporated into the soil, it may alter soil physical properties such as structure, pore size distribution, bulk density, total porosity and surface area, which further influence soil aeration, water holding capacity, and plant growth. Van Zwieten et al. (2009) explained that most essential functions of the soil like water and nutrient
holding capacity, microbial activities and aeration are influenced by the soil surface area (SA) and porosity. Similarly, Downie et al. (2009) also explained that the high porous structure of biochar contributes to water retention and nutrient availability in the soil. These claims which can be inferred from Glaser et al. (2002) are further supported by the findings of Karhu et al. (2011).

2.3.2 Influence on Soil Bulk Density

Biochar has the potential to decrease soil bulk density (BD) as a result of its low bulk density (~0.3 Mgm⁻³) and high porous structure (Brady and Weil, 2004; Verheijen et al., 2009; Atkinson et al., 2010). This improvement in total soil BD enhances soil structure, infiltration, and aeration (Brady and Weil, 2004; Atkinson et al., 2010; Laird et al., 2010; Jones et al., 2010; Chen et al., 2011). For example, Mankasingh et al. (2011) observed a change in BD from 1.66 to 1.53 g/cm³ in a biochar amended soil and Chen et al. (2011) also reported 4.5-6% decrease in BD in a three-year field experiment with biochar amendment. Also, Abebe et al. (2012) reported 13% decrease in BD with biochar at a kiln site, and Oguntunde et al. (2008) and Ayodele et al. (2009) all reported decreased BD at biochar sites compared to adjacent soils. The foregoing suggests BD decrease with increasing biochar concentration. According to Mukherjee and Lal (2013) about 2% of biochar amendment is enough to cause a change in BD. Lowering the BD enhances plant growth as more root development and air availability increases (Downie et al., 2009). Though biochar has the potential to reduce bulk density, its level of impact is determined by factors such as the feedstock, particle size, application rate, and soil type. Thus, it is important not only to look at the application rate and soil type but also to compare the effect of different particle sizes of the same biochar at different application rate in a study. The result gives farmers the option to select the right biochar particle size and rate to apply.
2.3.3 Influence on Water Retention and Water Holding Capacity

Impact of biochar on surface area, total porosity, and BD of amended soils leads to improvement in soil structure and aggregation, enhanced water retention and water holding capacity (WHC). It also improves hydraulic conductivity, and infiltration (Piccolo and Mbagwu, 1990; Piccolo et al., 1996; Mbagwu and Piccolo, 1997) in amended soils. Brady and Weil (2004) observed that pore connectivity and distribution largely affect water retention within the soil matrix, and this pore connectivity and distribution can be enhanced by improved structure, aggregation and organic content in soil through biochar addition.

In a research, Brockhoff et al. (2010) observed that biochar applied at rates of 25-45% by volume improved water retention in sandy soils whereas Verheijen et al. (2009) reported biochar decreased moisture content in clay soils. Tryon (1948) observed an 18% increase in moisture content in sandy soil after addition of a wood-based biochar at 45% by volume, while there was a decrease in a clay soil. The possible mechanism behind the decreased water retention in clay soil after addition of biochar could be that the biochar replaces the clay with higher water retention capacity (Verheijen et al., 2009). On the other hand, Major et al. (2010) attributed this phenomenon to the hydrophobic nature of biochar which causes preferential flow or decreased infiltration of water thereby decreasing the water holding capacity of clay soils. Several authors have reported improvement in water retention after amending soil with biochar. For example, Novak et al. (2009) reported increased water holding capacity ranging from 7 to 16% in a sandy loam soil with 2% biochar amendment. Yu et al. (2013) observed 1.7 % increase in water holding capacity of a loamy soil for 1% added biochar.

Similarly, Glaser et al. (2002) reported 18% increase in field water holding capacity of biochar enriched Anthrosol. Gaskin et al. (2007) also reported significant increase in water
holding capacity (WHC) after measuring a water retention curve (WRC) of a biochar amended soil at pressures of 20-100 kPa, whereas Pereira et al. (2012) also observed an increase in soil WRC at matric potential lower than -6 kPa in a biochar amended soil. Barnes et al. (2014) observed 92% and 67% decrease in hydraulic conductivity (K) in sand and organic soil respectively, but 328% increase in clay-rich soil. Devereux et al. (2012) observed decreasing saturated hydraulic conductivity ($K_{\text{sat}}$) from $4.8 \times 10^{-3} \text{ cms}^{-1}$ to $2.3 \times 10^{-3} \text{ cms}^{-1}$ for control soil down to 5% biochar signifying increased water retention at higher biochar concentration in a sandy loam soil. Additionally, Atkinson et al. (2009) also observed a $K_{\text{sat}}$ of $1.86 \times 10^{-3} \text{ cms}^{-1}$ in a sandy loam soil though from Hillel (1998) $K_{\text{sat}}$ for sandy loam is usually around $10^{-6}$ to $10^{-7}$ cms$^{-1}$. However, the reviews above did not take into consideration the effect of different particle sizes of the biochar used in their study. Soil texture and aggregation are affected by the surface area and porosity of biochar. Biochar properties are also affected by the particle sizes. Thus, it is appropriate to compare the effect of different particle sizes of the same biochar in a study to ascertain their level of impact.

2.3.4 Addition of minerals and organic matter

Biochar as carbon aromatic material is very recalcitrant and is itself a soil organic matter (SOM) (Glaser et al., 2002) though different from other organic carbon pool due to its slow decomposition in soil. The physicochemical nature of biochar allows it to contribute to soil stabilization by aggregation, and water and nutrient retention. However, depending on the characteristics of the initial feedstock, the mineral ash content or mineralization of biochar may supply some important macro- and micronutrients that are beneficial for the plant and soil microbial community (Preston and Schmidt, 2006; Chan et al., 2007; Bruun, 2011). Biochar obtained from crop residues such as corn cob have high mineral ash content rich in important
macro and micro nutrients such as phosphorus (P), potassium (K), silicon (Si), iron (Fe), sulphur (S), magnesium (Mg), and calcium (Ca). These nutrients are readily utilized by plants for improved growth. For example, Si uptake in plants has been linked to disease and pest resistance in plants (Bockhaven et al., 2013).

2.3.5 Influence on nutrient retention

Several field and laboratory studies have reported the ability of biochar to reduce nutrient leaching from soil (e.g. Glaser et al., 2002; Novak et al., 2009; Laird et al., 2010). Leaching of nutrients from soil causes loss of soil fertility thereby increases need for fertilizer input. However, the large surface area of biochar gives it a high absorption capability to retain nutrients through ionic and covalent bonding. According to Bruun (2011), the ability of biochar to increase water holding capacity of soils also improves nutrient retention time in the topsoil.

2.3.6 Influence of Biochar on soil fertility and crop production

Several studies have revealed high beneficial effect of biochar on crop yield (Chan et al., 2007; Asai et al., 2009; Van Zwieten et al., 2010), although others have also shown only small or even negative crop yield responses with biochar (Gaskin et al., 2010; Van Zwieten et al., 2010). The beneficial yield responses have been associated with increased fertilizer effect (Major et al., 2010), and the liming effect (Verheijen et al., 2009). For example, after a four year field study, Major et al. (2010) observed maize grain yield increase by 28, 30 and 140% from year two through to four respectively. They observed between 77-320% availability of Ca and Mg in the biochar amended soil and thus attributed the result to this nutrient availability. Thus increased nutrient retention may be the most important factor for the increased crop yield as supported by other authors like Chan et al. (2007) and Asai et al. (2009). Results from other studies (Yamato et al., 2006; Asai et al., 2009) have all shown positive effects of biochar in combination with
fertilizer (organic or inorganic fertilizer) on plant growth and nutrient availability than fertilizer or biochar alone treatments. Yamato et al. (2006) reported 200% increase in yield of biochar-fertilizer treatment relative to no biochar, and unfertilized treatments. High yields have also been reported with biochar-fertilizer amendment (Glaser et al., 2002; Lehmann et al., 2002; Steiner et al., 2007; Van Zwieten et al., 2007). These positive effects have also been attributed to the low bulk density, high water holding and nutrient retention capacity of biochar (Chan and Xu, 2009).

2.3.7 Impact of Biochar on crop water use efficiency or crop-water Productivity

Water plays a major role in crop production and so water scarcity will be a serious threat to food production. Water scarcity for agricultural purpose may result from inadequate rainfall and the increasing diversion of limited fresh-water resources to competing urban and industrial uses. Plant-stress induced by drought causes rapid inhibition of shoot and root growth, and depending on the intensity of the stress may result in plant death. Drought-stress causes stomatal closure in plant and thus causes reductions in transpiration and CO$_2$ uptake for photosynthesis, which further may cause interrupted reproductive development, pre-mature leaf senescence, wilting, desiccation and death (Schulze, 1986).

Irrigation management aims to supply adequate water to meet crop water requirement at the time needed while ensuring maximum crop-water productivity. Water supplied to crop replaces depleted water lost to the atmosphere through evapotranspiration (ET). Water supplied is expected to be efficiently used by plants in food and biomass production. Thus the crop-water production function or water use efficiency defined as the relationship between crop production and water received (Molden, 1997) helps to estimate the yield per unit land area to the level of water inputs, and help maximize the efficiency of irrigation water use. It seems however that, very soon irrigated agriculture might take place under limited water availability condition
looking at the pace of population growth and demand for water for human survival. This is likely to force irrigation management to shift from the current emphasis on production per unit area towards maximizing production per unit of water consumed.

Full irrigation (FI) supplies exactly the amount of depleted water to restore the water lost back to field capacity or previously accumulated ETc. However, deficit irrigation (DI) is the application of water below the full crop-water requirement (Fereres and Soriano, 2006). DI is considered an important tool for achieving the goal of reducing irrigation water use while sustaining and maximizing crop production. Research has shown that there is low risk involved in the application of DI with reference to the yield response curve to water supply, implying the possibility to save a considerable amount of water with DI without imposing significant yield reduction compared with FI. A study by Zhang and Oweis (1999) observed that DI strategy can allow application of about 40-70% less irrigation water and achieve a grain yield loss of only 13%. Also, according to English and Raja (1996), a DI of 64% of FI was economically equivalent to FI when water was the limiting factor.

Biochar helps soil retain nutrient and water, thereby reducing the cost of irrigation and fertilization. There is the need for adequate moisture to be available within the root zone of crops to help achieve maximum yield and production stability. Hence combining DI with biochar in a way should be able to sustain and maximize crop production since biochar has the capacity to retain water even at very low matric potential. However, to ensure effective application of DI, it is required to have control over the amount and timing of water application to avoid endangering the crop to stress that can limit productivity. The aim is to maximize crop-water productivity using DI in combination with biochar for sustainable growth and yield.
CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experimental Site Description

The pot experiment took place in a greenhouse at the University of Ghana Forest and Horticultural Crops Research Centre (FOHCREC); Okumaning, in the Denkyembour District of the Eastern Region of Ghana, a distance of 123 km north-west of Accra. The site lies within the deciduous forest zone and located on latitude 6°.0854’N and longitude 0°.5400’W at an altitude of 114 m above sea level. The study area has Haplic Acrisol as the dominant soil (FAO/UNESCO, 1990). It has a bimodal rainfall pattern with annual rainfall ranging between 1300-1800 mm (Ofosu-Budu, 2003). Rainfall is heaviest between May and July, followed by another heavy rainfall period between September and October. This rainfall or weather pattern makes the area have two possible growing seasons. The dry season in the area normally lasts between 120 and 130 days with mean annual minimum and maximum temperatures ranging between 25 and 38 °C (Nkansah et al., 2011).

3.2 Biochar and Soil Processing

The stover biochar used for the study was supplied by Soil Research Institute (SRI), Kumasi. Details of the stover properties are presented in Table 4.2. Two biochar particle sizes were selected for the experiment. The biochar was screened with 4.0 mm and 2 mm sieves. During the sieving process, the 4.0 mm sieve was first used to sieve the stover to separate large grain particles from those that passed through the sieve. Further, biochar particles less than 4 mm
were sieved with 2 mm sieve to separate the particle sizes less than 2 mm from those between 2 mm – 4 mm particles. Thus these two biochar particle sizes (< 2 mm, 2- 4 mm) were used for the experiment.

Representative samples of the top and subsoil were collected from an area close to the experimental field at 0-20 cm and 20-40 cm depth respectively. The soil samples were characterized for their initial physical and chemical properties. Both topsoil and subsoil sampled for the experiment were dug from the same spot and separately passed through a 2 cm diameter mesh screen to minimize disturbance of soil aggregates.

3.3 Experimental Setup

3.3.1 Pot filling with Soil and Biochar

Polyvinyl (PVC) pipe of 20 cm diameter was cut to a height of 75 cm and used as a pot in this experiment; in total sixty-four pots were prepared. The bottom of the pots was lined with 2 mm nylon mesh screen to support the packed soil. Each pot was filled to a dry bulk density of 1.52 g/cm$^3$ as found on the field. The amount of soil required as the sub-soil was weighed out using the dry bulk density of the soil and compacted to fill 50 cm depth using a wooden stick and a carpenter’s rule. The amount of top soil was similarly determined as above and mixed with the appropriate biochar amounts and particle sizes. It was then placed on the subsoil but without or only slightly compacting it. Since the field bulk density was known, the weights for both sub and top soils were calculated using the equation below.
\[ V = \pi r^2 h ; \quad \text{Eqn. 1} \]

\[ BD = \frac{M}{V} \quad \text{Eqn. 2} \]

where \( V \) is volume of cylindrical PVC pot, \( r \), is radius of PVC pot, \( h \), is height of pot, \( M \), is mass of soil sample and \( BD \) is soil bulk density.

Using the field bulk density of 1.52 g/cm\(^3\) and the equations above, a subsoil mass of 24 kg was weighed to fill up to 50 cm pot depth. Similarly, topsoil mass of 9.5 kg was weighed and mixed thoroughly with the various biochar rate and quality. The mixture was then poured on top of the subsoil to fill to a depth of 20 cm leaving a head space of 5 cm in the pots. For each biochar particle size i.e., fine biochar particle (FBP (< 2 mm)) and coarse biochar particle (CBP (2-4 mm)) used in this study, different rates (0, 20, 40 and 80 tons/ha) equivalent to (0, 68.2, 125.6, 251.2 g) were measured and mixed with the top soil. The pots were finally randomized completely and arranged in a controlled environment.

### 3.3.2. Determination of Moisture Content at Field Capacity

The packed columns were watered with enough water to allow drainage occur and covered with black plastic bowls to prevent evaporation from the surface. The pots were then left to stand on a flat moist soil surface for 72 hours to drain to field capacity. The wetting of the ground surface was to ensure hydraulic contact between the ground surface and the bottom of the pots. Two probes with a length of 65 cm and diameter 0.5 cm were inserted in the centre of each pot. The water content of the soils in the pots was then measured with the Time Domain Reflectometer (TDR100) instrument to determine the field capacity (FC).
3.3.3 Fertilization and Planting

NPK was applied to all pots at a rate of (1.0, 0.7, 0.4 g) for (N, P, K) respectively. The amount per pot applied was estimated from the amount per hectare taking the surface area of the pot into consideration. The fertilizer was ground to fine particles and mixed thoroughly with the topsoil. 5 mm of water was then added to enable the fertilizer dissolve and mix completely with the soil before planting. However, two weeks after emergence, 1 g of Nitrogen (N) was further applied to each pot and then 5 mm of water added for the fertilizer to dissolve. Nutrient rate supplied to the pots is shown in Table 3.1

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Nutrient</th>
<th>Rate</th>
<th>Amount per pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>Nitrogen</td>
<td>150 kg/ha</td>
<td>1.0 g N/pot</td>
</tr>
<tr>
<td>Triple super phosphate</td>
<td>Phosphorus</td>
<td>30 kg/ha</td>
<td>0.7 g P/pot</td>
</tr>
<tr>
<td>Muriate of Potash</td>
<td>Potassium</td>
<td>90 kg/ha</td>
<td>0.4 g K/pot</td>
</tr>
</tbody>
</table>

Three seeds of ‘Obatanpa’ maize variety were planted per pot at an approximate depth of 3 cm on April 11, 2015. After the seeds had germinated, black plastic sheets were used to cover the soil surface around the plants to prevent evaporation from the soil. Two weeks after planting, the seedlings were thinned out to one plant per pot.

3.3.4 Irrigation Management

Twenty six days after planting, the plants were subjected to two irrigation regimes, i.e. full irrigation (FI) and deficit Irrigation (DI). For the FI pots, irrigation was applied after the plants had used 30% of the moisture at FC in the pot. But for the DI pots, the plants were irrigated after using 80% of moisture at FC in the pot. Thus, moisture depletion level before irrigation was set to management allowable depletion (MAD) of 30% and 80% of FC for FI and
DI respectively. Irrigation was applied using a measuring cylinder and the soil surface covered with black plastic sheet to avoid evaporation. There was no leaching loss as the pots were only recharged to their individual field capacities. To take moisture readings, the TDR instrument was connected to two probes installed to a depth of 65 cm in the middle of each pot and the reading recorded (Fig 3.1a). The result was used to compute the depleted moisture in the pot. Thus, the required moisture is then added to bring the pots back to FC. Readings were done every second day. Overall, three drying cycles were achieved for the DI treatments at the time of terminating the experiment in the seventh week.

Figure 3.1  Moisture content reading with TDR100 (a), and irrigation using measuring cylinder (b)
3.4 Experimental Treatments and Design

The experiment had 16 treatments that consisted of a combination of three factors: two biochar particle sizes (<2 mm, 2-4 mm), four biochar quantities (0, 20, 40, and 80 tons/ha) and two irrigation levels (Full (FI) and Deficit (DI) irrigation). The treatments were replicated four times and arranged in completely randomized design. The experiment was carried out under a shed of dimension, 9 m length x 7 m breadth and a height of 5 m and covered with transparent plastic sheet, see Fig. 3.2.

Figure 3.2: Experimental shed with randomized pots arrangement
3.5 Experimental Data Collected

3.5.1 Growth Data

Plant height, leaf area, stem girth, and number of leaves were recorded weekly for 7 weeks as growth data. Plant height was measured with a ruler from the soil surface to the arch of the uppermost leaf that is more than 50% emerged. Stem girth was measured with a vernier caliper. The number of leaves were recorded by visually counting the total number of leaves that were more than 50% emerged on the plant. Leaf area measurement was done by the calculation method based on linear measurement (Daughtry, 1990). In this method, the maize leaf is modeled as a simple geometric shape and the area $A_L$ is determined by its linear dimensions, i.e., length (L) and maximum width (W) using the formula:

$$A_L = (b_1 LW) \times N$$

Eqn.3

where $b_1$ is the maize regression coefficient = 0.75, (Kvet and Marshall, 1971); $N$ is the number of leaves on the maize plant.

3.5.2 Chlorophyll Content

Weekly chlorophyll content of each plant was taken with a chlorophyll content meter (Apogee instruments, model CCM-200 plus). The data was collected for 7 weeks starting one week after emergence to the 7th week. The CCM-200 plus is a rapid, non-destructive battery-operated hand-held instrument that uses transmittance to estimate the chlorophyll content in leaf tissue. The meter measures the transmittance of two wavelengths and calculates a chlorophyll content index CCI value that is proportional to the amount of chlorophyll in the leaf.
3.5.3 Biomass yield

Biomass was measured by harvesting the above ground biomass of corn from each pot at the end of the 70 days of experimenting. The stalks, leaves and fruits were chopped, put in separate known weight brown envelops and their fresh weight measured. The sub-samples were taken to the laboratory and dried at 80 °C to constant weight, and their dry weight measured. The total biomass yield was calculated by summing the dry weight of the stalks, leaves and fruit.

3.5.4 Transpiration Efficiency/ Water productivity

Water productivity is the ratio of the yield to the amount of water supplied. In this work, water productivity is also considered as transpiration efficiency in that, the soil surface was fully covered with plastic sheet to avoid evaporation. Water loss from the pot was only by transpiration. Thus the transpiration efficiency was estimated as follow:

\[
T = (\theta_i - \theta_{i-1}) + I + R - D
\]

Eqn. 4

Where T is transpiration (mm), \( \theta \) is the volumetric water content in 0-65cm depth (mm), i is day of TDR measurement, (i-1) is previous time of TDR measurement, I is irrigation amount (mm), R is precipitation (mm) which was zero because the crop was grown in a green house, D is downward drainage out of the root zone which was zero because no water drained out of the pots as irrigation was controlled.

Finally transpiration efficiency (TE) was calculated as

\[
TE = \frac{DMY(g)}{T(mm)}
\]

Eqn. 5

where \( DMY \) is dry matter yield and \( T \) crop transpiration.
3.5.4 **Soil Water Retention & Soil Bulk Density**

After harvest, three (3) undisturbed topsoil samples for each treatment were randomly taken to the Ecological Laboratory, University of Ghana for Water retention analysis.

The samples were pre-saturated overnight and the saturated weight taken as \( W_1 \). They were then subjected to the different pressure levels (-33, -50, -100, -200, -300 kPa) using the pressure plate method described by Dane and Hopmans (2002). The weights (\( W_2, W_3, W_4, W_5, W_6 \)) after each suction were measured for the different pressure levels. However, suction data could not be obtained after 300 kPa due to a breakdown of the pressure plate apparatus. The samples were then oven dried at 105 °C for 48 hours in an oven and the dry weight \( W_7 \) taken. From the measured weight the gravimetric water content at each pressure was calculated using the formulae:

\[
\theta_g (g g^{-1}) = \frac{w_1 - w_7}{w_7 - w_t} 
\]

Eqn. 6

where \( \theta_g \) is gravimetric water content.

Bulk density (\( \rho_b \)) was calculated from the results using the formula

\[
\rho_b (g cm^{-3}) = \frac{w_1 - w_7}{V_c} 
\]

Eqn. 7

where \( V_c \) is the core volume.

Thence, the volumetric water content (\( \theta_v \)) was calculated using the equation

\[
\theta_v (cm^3 cm^{-3}) = \frac{\theta_g}{\rho_b} 
\]

Eqn. 8

The six volumetric water content data points from 0 to 300 kPa were fitted into Van Genuchten (1980) water retention model using the RETC software from Pc-progress (www.pc-
progress.com). The model was then used to predict the volumetric water content at pressure (500, 1000, 1500 kPa).

The result was used to plot the water retention curve for both the measured and predicted values.

3.6 Data analysis

Data was analyzed with GenStat 9th edition for a completely randomized design and the means separated with the Least Significant Difference (LSD) at $\alpha=0.05$ level for all treatments.
CHAPTER FOUR

4.0 RESULTS

4.1 Soil and biochar properties

The soil used for the study was a sandy loam soil with about 66.3% sand content from the textural analysis shown in Table 4.1. The chemical analysis shows the sandy loam soil is acidic with a pH of 5.5 and an electrical conductivity EC of 0.36 mS/cm. The physical properties of the soil sampled from different parts of the field are described in Table 4.1. The soil has mean field bulk density of 1.52 g cm$^{-3}$ and porosity 0.43 cm$^3$/cm$^3$. The elemental analysis of the corn stover biochar used for this study reveals the stover is alkaline with a pH of 10.2, total carbon of 38.8% and organic matter content of 38.5% as shown in (Table 4.2).
Table 4.1  Chemical and physical properties of the soil material.

<table>
<thead>
<tr>
<th>SITE</th>
<th>pH_\text{H}_2\text{O}</th>
<th>Electrical Conductivity (mS/cm)</th>
<th>Phosphorus (mg/100g)</th>
<th>Potassium (mg/100g)</th>
<th>Tot. Nitrogen (%)</th>
<th>Organic Matter (%)</th>
<th>Clay (&lt;0.002 mm) (%)</th>
<th>Silt (0.002-0.02 mm) (%)</th>
<th>Fine Sand (0.02-0.2 mm) (%)</th>
<th>Coarse Sand (0.02-0.2 mm) (%)</th>
<th>bulk density (g/cm$^3$)</th>
<th>Total Porosity (cm$^3$/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UG A</td>
<td>5.21</td>
<td>0.28</td>
<td>&lt;0.40</td>
<td>9.30</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.47</td>
<td>0.44</td>
</tr>
<tr>
<td>UG B</td>
<td>5.61</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.46</td>
<td>0.45</td>
</tr>
<tr>
<td>UG C</td>
<td>5.68</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.52</td>
<td>0.43</td>
</tr>
<tr>
<td>UG D</td>
<td>5.63</td>
<td>0.35</td>
<td>&lt;0.40</td>
<td>14.00</td>
<td>0.16</td>
<td>2.80</td>
<td>20.00</td>
<td>12.00</td>
<td>48.00</td>
<td>18.00</td>
<td>1.51</td>
<td>0.43</td>
</tr>
<tr>
<td>UG E</td>
<td>5.76</td>
<td>0.30</td>
<td></td>
<td>0.12</td>
<td>1.90</td>
<td>21.00</td>
<td>10.00</td>
<td>47.00</td>
<td>19.00</td>
<td>1.52</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>UG F</td>
<td>5.36</td>
<td>0.39</td>
<td>&lt;0.40</td>
<td>21.00</td>
<td>0.10</td>
<td>2.20</td>
<td>20.00</td>
<td>11.00</td>
<td>50.00</td>
<td>17.00</td>
<td>1.64</td>
<td>0.38</td>
</tr>
<tr>
<td>Mean</td>
<td>5.54</td>
<td>0.36</td>
<td>&lt;0.40</td>
<td>14.77</td>
<td>0.12</td>
<td>2.30</td>
<td>20.33</td>
<td>11.00</td>
<td>48.33</td>
<td>18.00</td>
<td>1.52</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 4.2  Properties of corn stover biochar used for this study

<table>
<thead>
<tr>
<th>Component</th>
<th>pH</th>
<th>Phosphorus (mg/kg)</th>
<th>Potassium (mg/kg)</th>
<th>Magnesium (mg/kg)</th>
<th>Tot. Nitrogen (%)</th>
<th>Organic Matter (%)</th>
<th>Tot. Carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td>10.2</td>
<td>3150</td>
<td>31800</td>
<td>4510</td>
<td>0.9</td>
<td>38.5</td>
<td>38.8</td>
</tr>
</tbody>
</table>
4.2 Biochar effect on soil physical properties

4.2.1 Soil bulk density

Addition of biochar decreased soil bulk density (BD) with increasing biochar amount (Fig. 4.1). The 80 ton/ha had the minimum BD (1.30 g/cm$^3$) and this was significantly lower (P<0.05) than the 0 tons/ha (control) (1.46 g/cm$^3$) and 20 tons/ha (1.42 g/cm$^3$) but insignificant compared with the 40 tons/ha (1.40 g/cm$^3$). Biochar size of <2 mm (FBP) had the lowest BD (1.35 g/cm$^3$) and this was statistically insignificant compared to biochar size of between 2 and 4 mm (CBP) (1.39 g/cm$^3$) and control (1.46 g/cm$^3$).

![Fig. 4.1 Effect of biochar amount on soil bulk density.](image-url)
4.2.2 Water Retention Curve

Table 4.3 shows the analytical results of the volumetric water content at different pressure levels for different biochar amounts and particle sizes. At all pressure levels, amended soil contained high water content compared to the unamended soil. Figure 4.3 shows the water release curve for the different treatments of soil with biochar. The results show water retention increased with increasing biochar amount. There was no significant difference in volumetric water content between the 0 tons/ha (control), 20 tons/ha and 40 tons/ha treatments. However, significant difference was observed for the 80 tons/ha treatment compared to lower concentrations and the unamended treatment. With respect to biochar particle size effect on water retention, it is observed in Fig 4.4 that fine biochar particles (FBP) hold more water at low matric potential but as matric potential increased, the coarse biochar particles (CBP) retained more water. This result for the particle size shows that although the presence of biochar may
cause an increase in water holding capacity within the soil matrix, the biochar particle size may also affect the amount of water held within the matrix at each matric potential.

Table 4.3 Volumetric water content at different pressure levels for different biochar amounts and particle sizes

<table>
<thead>
<tr>
<th>Measured volumetric water content (cm$^3$/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$(kPa)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>33</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>300</td>
</tr>
</tbody>
</table>

Table 4.4 Estimated volumetric water content at different pressure levels for different biochar amounts and particle sizes.

<table>
<thead>
<tr>
<th>Predicted Volumetric water content (cm$^3$/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$(kPa)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>33</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>1500</td>
</tr>
</tbody>
</table>
Table 4.5: The parameters of Van Genuchten (1980) model equations of biochar amount and particle size

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>Biochar Amount</th>
<th>ϴr (cm$^3$/cm$^3$)</th>
<th>ϴs (cm$^3$/cm$^3$)</th>
<th>α (k/Pa)</th>
<th>n</th>
<th>m</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctr</td>
<td>0</td>
<td>0.047</td>
<td>0.228</td>
<td>1.136</td>
<td>1.184</td>
<td>0.155</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.053</td>
<td>0.252</td>
<td>1.682</td>
<td>1.199</td>
<td>0.166</td>
<td>0.99</td>
</tr>
<tr>
<td>FBP: &lt;2</td>
<td>40</td>
<td>0.074</td>
<td>0.238</td>
<td>0.655</td>
<td>1.284</td>
<td>0.221</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0.056</td>
<td>0.296</td>
<td>0.996</td>
<td>1.198</td>
<td>0.165</td>
<td>0.99</td>
</tr>
<tr>
<td>CBP: 2-4</td>
<td>40</td>
<td>0.062</td>
<td>0.241</td>
<td>1.337</td>
<td>1.201</td>
<td>0.167</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0.070</td>
<td>0.280</td>
<td>1.419</td>
<td>1.193</td>
<td>0.161</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Where $ϴ_r$ (cm$^3$/cm$^3$) is residual water content, $ϴ_s$ (cm$^3$/cm$^3$) is saturated water content and $α$ (k/Pa), n, and m are empirical parameters.

Figure 4.3: Water release curve for the different treatments of soil with biochar. Smooth lines show predicted curves.
Figure 4.4: Water release curve for the different treatments of soil with biochar particle sizes. Smooth lines show predicted curves.

4.3 Dry matter yield

The results show that DMY increased with increasing biochar amount (Fig 4.5). There was no significant difference between the control and the 20 tons/ha treatment. However, there was significant difference observed for the 40 and 80 tons/ha treatment relative to the 20 and 0 tons/ha (control) treatments. The 80 tons/ha recorded the highest DMY of 117.4 g and the 0 tons/ha recorded the least DMY of 99.7 g. This is an indication that corn stover biochar can improve dry matter yield in a sandy loam soil.

With regards to biochar particle size, the size less than 2 mm (FBD) recorded the highest DMY (111.6 g) as compared to (107.5 g) for the 2-4 mm (CBP) particle size (Fig 4.6). The
difference was not statistically significant. However, FBP demonstrates more effective response as compared to CBP.

Figure 4.5: Dry matter yield (DMY) for the different biochar amounts.

Figure 4.6: Dry matter yield (DMY) for the different biochar particle sizes.
With regards to irrigation, dry matter yield (DMY) decreased by 21.2% in DI treatments as compared to FI (Fig 4.7). The difference was statistically significant. However, 59.2% of water was conserved for DI treatment compared to FI.

![Figure 4.7: Dry matter yield (DMY) for the different irrigation levels.](image)

**4.4 Transpiration Efficiency**

Biochar addition improved transpiration efficiency over the no biochar treatment (Fig 4.8). Transpiration efficiency increased with increasing biochar concentration. There was no difference between the control and 20 tons/ha biochar treatment. The result was only significant at the 80 tons/ha concentration level. Transpiration efficiency was the same for the two biochar particle sizes and thus did not show any significant difference (Fig 4.9). The result was not significant relative to the control (no biochar amendment).

Transpiration efficiency was higher in the DI treatment as compared to FI (Fig 4.10). The deficit irrigation treatment reached a higher productivity of total applied water (PAW) value of
(0.32 g/mm) than full irrigation (0.20 g/mm). The difference was statistically significant.

Transpiration was higher in FI (18113.09 mm) as compared to DI (8857.88 mm).

Figure 4.8 Transpiration efficiency (TE) for the different biochar amounts.

Figure 4.9: Transpiration efficiency (TE) for the different biochar particle sizes
4.5 Plant Growth Responses

4.5.1 Effect of biochar amount on plant height

Plant height generally increased with increasing biochar amount (Table 4.6). Biochar amount of 40 tons/ha did not differ significantly from the control. Also, further increasing biochar application beyond 40 tons/ha did not lead to any significant increase in plant height among biochar treatments.

Table 4.6 Plant height for the different biochar amount.

<table>
<thead>
<tr>
<th>Biochar (tons/ha)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA_0</td>
<td>12.9</td>
<td>19.0</td>
<td>58.7</td>
<td>83.5</td>
<td>139.4</td>
<td>223.0</td>
<td>234.1</td>
</tr>
<tr>
<td>BA_20</td>
<td>12.3</td>
<td>19.1</td>
<td>57.7</td>
<td>83.3</td>
<td>133.7</td>
<td>228.2</td>
<td>232.9</td>
</tr>
<tr>
<td>BA_40</td>
<td>12.9</td>
<td>19.2</td>
<td>59.3</td>
<td>84.4</td>
<td>141.8</td>
<td>226.4</td>
<td>237.3</td>
</tr>
<tr>
<td>BA_80</td>
<td>12.4</td>
<td>19.1</td>
<td>59.7</td>
<td>85.4</td>
<td>151.0</td>
<td>221.3</td>
<td>232.3</td>
</tr>
<tr>
<td>LSD(0.05)</td>
<td>1.0</td>
<td>2.2</td>
<td>9.4</td>
<td>10.3</td>
<td>17.1</td>
<td>12.9</td>
<td>14.9</td>
</tr>
</tbody>
</table>
4.5.2 Effect of biochar particle size on plant height

The results of (Table 4.7) showed general increase in plant height (PH) with increasing biochar particle size. It was observed that the FBP soils had the highest PH in weeks two to five relative to CBP, whereas, the CBP increased PH in week six and seven. However, this increment was not significant in any of the weeks.

Table 4.7 Plant height for the different biochar particle size.

<table>
<thead>
<tr>
<th>Maize Plant Height (cm)</th>
<th>Particle size</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBP</td>
<td>12.8</td>
<td>18.9</td>
<td>56.6</td>
<td>82.1</td>
<td>140.9</td>
<td>225.7</td>
<td>236.2</td>
<td></td>
</tr>
<tr>
<td>FBP</td>
<td>12.3</td>
<td>19.4</td>
<td>61.1</td>
<td>86.4</td>
<td>142.6</td>
<td>224.1</td>
<td>232.2</td>
<td></td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.9</td>
<td>2.1</td>
<td>8.9</td>
<td>9.7</td>
<td>16.1</td>
<td>12.1</td>
<td>14.0</td>
<td></td>
</tr>
</tbody>
</table>

4.5.3 Effect of irrigation on plant height

The result in Table 4.8 showed that PH was affected by water stress. It was observed that PH increased in the DI soils for the first four weeks and beyond that, the FI soils increased relative to the DI. However this increment was only significant in weeks 5 and 6 and insignificant in week seven. The drop in plant height for the DI treatment was caused by water stress as a result of implementing deficit irrigation strategy on the fourth week.

Table 4.8 Plant height for the different irrigation levels.

<table>
<thead>
<tr>
<th>Maize Plant Height (cm)</th>
<th>Irrigation</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI</td>
<td>12.7</td>
<td>19.3</td>
<td>61.3</td>
<td>84.9</td>
<td>135.8a</td>
<td>220.4a</td>
<td>230.5</td>
<td></td>
</tr>
<tr>
<td>FI</td>
<td>12.4</td>
<td>19.0</td>
<td>56.5</td>
<td>83.6</td>
<td>147.8b</td>
<td>229.5b</td>
<td>237.9</td>
<td></td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.6</td>
<td>1.4</td>
<td>5.8</td>
<td>6.4</td>
<td>10.6</td>
<td>7.9</td>
<td>9.2</td>
<td></td>
</tr>
</tbody>
</table>

Column without the same alphabet are significantly different from each other (p<0.05) according to LSD test.
4.5.4 Effect of biochar amount on Stem Girth

Maize stem girth was observed to increase with increasing biochar amounts (Table 4.9). However, except for biochar amount of 40 tons/ha in week 2, the increase in maize stem girth was not significant relative to the control in the second and third weeks. In week 4 a significant difference was observed between the 80 tons/ha and the control only. But, in weeks 5 and 6, significant difference was observed between the 80 tons/ha and all treatments. However, in week 7, a significant difference relative to the control was observed for all biochar amounts.

Table 4.9 Stem girth for the different biochar amounts.

<table>
<thead>
<tr>
<th>Biochar (t/ha)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.52</td>
<td>0.79</td>
<td>1.22</td>
<td>1.62</td>
<td>1.96</td>
<td>2.11</td>
<td>2.15</td>
</tr>
<tr>
<td>20</td>
<td>0.51</td>
<td>0.83</td>
<td>1.31</td>
<td>1.76</td>
<td>2.04</td>
<td>2.14</td>
<td>2.11</td>
</tr>
<tr>
<td>40</td>
<td>0.52</td>
<td>0.78</td>
<td>1.23</td>
<td>1.74</td>
<td>2.01</td>
<td>2.16</td>
<td>2.22</td>
</tr>
<tr>
<td>80</td>
<td>0.47</td>
<td>0.80</td>
<td>1.24</td>
<td>1.78</td>
<td>2.13</td>
<td>2.26</td>
<td>2.31</td>
</tr>
<tr>
<td><strong>LSD</strong>&lt;sub&gt;(0.05)&lt;/sub&gt;</td>
<td><strong>0.07</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.21</strong></td>
<td><strong>0.15</strong></td>
<td><strong>0.09</strong></td>
<td><strong>0.06</strong></td>
<td><strong>0.06</strong></td>
</tr>
</tbody>
</table>

Column with same letters are not significantly different from each other (p<0.05) according to LSD test.

4.5.5 Effect of biochar particle size on maize stem girth

The results showed that maize stem girth generally increased with decreasing biochar particle size (Table 4.10). Data of the FBP (< 2mm) did not differ significantly from that of CBP (2-4mm). It was observed that maize stem girth increased in weeks 1 and 2 for the CBP soils whereas beyond week 2, the FBP had the highest stem girth increase.

Table 4.10 Stem girth for the different biochar particle sizes.

<table>
<thead>
<tr>
<th>Particle size</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBP</td>
<td>0.51</td>
<td>0.77</td>
<td>1.19</td>
<td>1.69</td>
<td>2.01</td>
<td>2.16</td>
<td>2.22</td>
</tr>
<tr>
<td>FBP</td>
<td>0.50</td>
<td>0.83</td>
<td>1.33</td>
<td>1.78</td>
<td>2.08</td>
<td>2.19</td>
<td>2.24</td>
</tr>
<tr>
<td><strong>LSD</strong>&lt;sub&gt;(0.05)&lt;/sub&gt;</td>
<td><strong>0.06</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.20</strong></td>
<td><strong>0.14</strong></td>
<td><strong>0.09</strong></td>
<td><strong>0.05</strong></td>
<td><strong>0.06</strong></td>
</tr>
</tbody>
</table>
4.5.6 Effect of irrigation on maize stem girth

DI showed significant increase in stem girth relative to FI soil in weeks 1 and 2 and increased insignificantly till week 6 and 7 where the FI soils had the highest increase (Table 4.11). This observation probably might be due to reduced frequency of irrigation for the DI soils as a result of implementing deficit irrigation strategy after week 3.

Table 4.11 Stem girth of maize for the different irrigation level

<table>
<thead>
<tr>
<th>Maize stem girth (cm)</th>
<th>Irrigation Regime</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DI</td>
<td>0.53a</td>
<td>0.83a</td>
<td>1.31</td>
<td>1.75</td>
<td>2.07</td>
<td>2.17</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>FI</td>
<td>0.48b</td>
<td>0.77b</td>
<td>1.20</td>
<td>1.73</td>
<td>2.02</td>
<td>2.18</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>LSD (0.05)</td>
<td>0.04</td>
<td>0.06</td>
<td>0.13</td>
<td>0.09</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Column with same letters are not significantly different from each other (p<0.05) according to LSD test.

4.5.7 Effect of biochar amount on maize leaf area

Results of leaf area measurement for maize (Tables 4.12-14) showed a general increase with increasing biochar amounts. However, this increment was only significant in week three for biochar concentration beyond 40 tons/ha relative to the control. Thus, increasing biochar amount beyond 20 tons/ha has the tendency of causing significant increase in maize leaf area measurements among biochar treatments.
Table 4.12 Leaf area of maize for the different biochar amount.

<table>
<thead>
<tr>
<th>Biochar (t/ha)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>103.9</td>
<td>554.6</td>
<td>2459.0a</td>
<td>4527.5</td>
<td>6650.0</td>
<td>7889.6</td>
<td>8408.4</td>
</tr>
<tr>
<td>20</td>
<td>106.2</td>
<td>610.6</td>
<td>3153.0</td>
<td>4830.3</td>
<td>6924.5</td>
<td>8177.7</td>
<td>8841.3</td>
</tr>
<tr>
<td>40</td>
<td>110.6</td>
<td>628.7</td>
<td>2388.0a</td>
<td>3970.6</td>
<td>6166.7</td>
<td>7462.4</td>
<td>9090.2</td>
</tr>
<tr>
<td>80</td>
<td>95.3</td>
<td>624.2</td>
<td>3229.0b</td>
<td>4820.5</td>
<td>7032.1</td>
<td>8444.4</td>
<td>9536.7</td>
</tr>
<tr>
<td><strong>LSD</strong>(0.05)</td>
<td><strong>18.28</strong></td>
<td><strong>177.42</strong></td>
<td><strong>718.8</strong></td>
<td><strong>860.5</strong></td>
<td><strong>1014.66</strong></td>
<td><strong>892.99</strong></td>
<td><strong>1031.81</strong></td>
</tr>
</tbody>
</table>

Column with same letters are not significantly different from each other (p<0.05) according to LSD test.

**4.5.8 Effect of biochar particle size on maize leaf area**

Leaf area for FBP increased insignificantly relative to CBP in weeks 1, 2, 4, 5 and 7 with respect to CBP (Table 4.13). Whereas in weeks 3 and 6, maize leaf area for CBP increased insignificantly with respect to FBP treatments.

Table 4.13 Mean leaf area of maize for the different biochar particle size.

<table>
<thead>
<tr>
<th>Particle size</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBP</td>
<td>100.6</td>
<td>572.5</td>
<td>2916.0</td>
<td>4528.2</td>
<td>6552.0</td>
<td>8151.0</td>
<td>8994.5</td>
</tr>
<tr>
<td>FBP</td>
<td>107.4</td>
<td>650.8</td>
<td>2798.0</td>
<td>4549.0</td>
<td>6846.9</td>
<td>7865.7</td>
<td>9104.0</td>
</tr>
<tr>
<td><strong>LSD</strong>(0.05)</td>
<td><strong>17.2</strong></td>
<td><strong>167.3</strong></td>
<td><strong>677.7</strong></td>
<td><strong>811.3</strong></td>
<td><strong>956.6</strong></td>
<td><strong>841.9</strong></td>
<td><strong>972.8</strong></td>
</tr>
</tbody>
</table>

**4.5.9 Effect of irrigation on maize leaf area**

Leaf area increased significantly in week 1 and insignificantly in week 2 for DI treatments relative to FI treatments, whereas it increased in favor of the FI treatments beyond week two (Table 4.14). However, the increment was only significant in week 4 through to week six and increased insignificantly in week 3 and 7.
Table 4.14 Leaf area of maize for the different irrigation levels

<table>
<thead>
<tr>
<th>Week</th>
<th>Leaf Area (cm²)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DI</td>
<td></td>
<td>110.4a</td>
<td>630.8</td>
<td>2704.3</td>
<td>3874.9a</td>
<td>6210.9a</td>
<td>7486.9a</td>
<td>8784.7</td>
</tr>
<tr>
<td>FI</td>
<td></td>
<td>97.6b</td>
<td>592.5</td>
<td>3009.8</td>
<td>5202.3b</td>
<td>7188.1b</td>
<td>8529.8b</td>
<td>9313.8</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td></td>
<td>11.3</td>
<td>109.5</td>
<td>443.7</td>
<td>531.1</td>
<td>626.3</td>
<td>551.2</td>
<td>636.9</td>
</tr>
</tbody>
</table>

Column with same letters are not significantly different from each other (p<0.05) according to LSD test.

4.5.10 Effect of biochar amount on chlorophyll content

Maize Chlorophyll content index (CCI) was observed to increase with increasing biochar amount (Table 4.15). However, except for biochar amount of 80 tons/ha in week 1, the CCI for the amended treatments were significantly different relative to the control in the first week. In week 3 to week 5, insignificant difference relative to the control was only observed for the 40 tons/ha biochar amount. Addition of biochar beyond 40 tons/ha did not increase maize CCI in the amended soils.

Table 4.15 Chlorophyll content index (CCI) of maize for the different biochar amounts.

<table>
<thead>
<tr>
<th>Biochar (t/ha)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.04a</td>
<td>9.88</td>
<td>26.70</td>
<td>31.27</td>
<td>35.30</td>
<td>38.10</td>
<td>37.90</td>
</tr>
<tr>
<td>20</td>
<td>17.62b</td>
<td>10.43</td>
<td>25.89</td>
<td>29.16</td>
<td>35.01</td>
<td>37.19</td>
<td>38.00</td>
</tr>
<tr>
<td>40</td>
<td>17.54b</td>
<td>10.08</td>
<td>27.35</td>
<td>32.02</td>
<td>38.54</td>
<td>39.97</td>
<td>36.80</td>
</tr>
<tr>
<td>80</td>
<td>15.29ab</td>
<td>9.64</td>
<td>24.94</td>
<td>30.12</td>
<td>35.10</td>
<td>37.41</td>
<td>35.40</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>2.39</td>
<td>2.02</td>
<td>4.31</td>
<td>4.78</td>
<td>6.14</td>
<td>6.45</td>
<td>7.58</td>
</tr>
</tbody>
</table>

Column with same letters are not significantly different from each other (p<0.05) according to LSD test.

The drop in CCI from week 1 to week 2 was caused by insufficient nitrogen in the soil which led to yellowing of leaves.
4.5.11 Effect of biochar particle size on chlorophyll content

The results in Table 4.16 show that CCI for FBP was higher compared to CBP from week 1 to week 5, and lower from weeks 6 and 7. The differences were insignificant in both treatments relative to the other. This sudden increase in CCI for CBP treatments may have been caused by late release of nitrogen by the biochar particles to the plant as compared to quick release of nutrient by the FBP in the early weeks.

Table 4.16 Chlorophyll content index (CCI) of maize for the different biochar particle size.

<table>
<thead>
<tr>
<th>Particle Size (mm)</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBP</td>
<td>16.32</td>
<td>9.42</td>
<td>25.20</td>
<td>30.14</td>
<td>35.17</td>
<td>39.00</td>
<td>38.70</td>
</tr>
<tr>
<td>FBP</td>
<td>16.81</td>
<td>10.63</td>
<td>27.10</td>
<td>30.97</td>
<td>37.00</td>
<td>37.36</td>
<td>35.10</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>2.25</td>
<td>1.90</td>
<td>4.07</td>
<td>4.51</td>
<td>5.79</td>
<td>6.08</td>
<td>7.15</td>
</tr>
</tbody>
</table>

4.5.12 Effect of irrigation on chlorophyll content

Results of Table 4.17 show that CCI was high in DI plants in weeks 2 to week 4, and in week 7. On the other hand, CCI was observed to be high in FI plants in week 1, 5 and 6. The differences were not significant relative to the other throughout the weeks. The fluctuations in the result may have been caused by the water stress. It was observed that the CCI for DI treatment fell below FI after deficit irrigation strategy was implemented after week 4, but increased again after recharge in week 7.

Table 4.17 Chlorophyll content index (CCI) of maize for the different irrigation levels.

<table>
<thead>
<tr>
<th>Week</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI</td>
<td>16.50</td>
<td>10.32</td>
<td>27.05</td>
<td>30.67</td>
<td>35.57</td>
<td>37.20</td>
<td>37.40</td>
</tr>
<tr>
<td>FI</td>
<td>16.63</td>
<td>9.73</td>
<td>25.25</td>
<td>30.44</td>
<td>36.60</td>
<td>39.16</td>
<td>36.40</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>1.47</td>
<td>1.25</td>
<td>2.66</td>
<td>2.95</td>
<td>3.79</td>
<td>3.98</td>
<td>4.68</td>
</tr>
</tbody>
</table>
CHAPTER FIVE

5.0 DISCUSSION

5.1 Bulk Density

Biochar addition significantly reduced soil bulk density (BD). Reduction in soil bulk density leads to improve aeration, infiltration and root growth in the soil. The bulk density measured for the amended soils were lower than the unamended soils. This observation is consistent with the findings of some researchers (Jein and Wang, 2013; Karhu et al., 2011; Vaccari et al., 2011; Major et al., 2010). Reduction in BD as a result of biochar addition might have been caused by the physical dilution effect, which agrees with Busscher et al. (2011) who reported that increasing total organic carbon by the addition of organic amendments in soils could significantly decrease bulk density. Also, biochar has been found to have a lower bulk density than soil and therefore, reduces soil bulk density (Verheijen et al., 2009) over time. In addition, the reduction in BD of the amended soils may be linked to alteration of soil aggregate sizes caused by biochar-soil interaction, as reported by Tejada and Gonzalez (2007).

5.2 Soil Water Retention

Water retention in the soil is determined by the pore distribution and connectivity within the soil matrix. This effect is controlled by soil texture and structural characteristics (aggregation), and the soil organic matter content. Soil aggregation can be improved by addition of biochar. The results showed increased moisture retention for biochar amended soils for a given matric potential as compared to the unamended soils. This implies more water was retained within the biochar as matric potential increased and the soil dried up. This finding is consistent with the result of Laird et al. (2010). Gaskin et al. (2007) found a significant increase
in water holding capacity of biochar when he measured the water release curve at pressures of 20–100 kPa. Other researchers (Githinji, 2013; Mukherjee and Lal, 2013; Herath et al., 2013; Dugan et al., 2010; Tryon, 1948) have also reported improvement in soil physical properties such as bulk density and water holding capacity with as low as 1% addition of biochar.

The mechanism behind this improved water retention capacity of the sandy loam soil may have been caused by factors such as the hydrophobic nature of the cob biochar, high surface area, and organic matter content of the corn cob biochar and alteration in soil pore size distribution (PSD). According to literature, biochar amendment enhances the formation and stabilization of soil macro-aggregates, especially in sandy loam soil (Ouyang et al., 2013; Liu et al., 2011). Biochar surfaces are commonly hydrophobic, and their negative surfaces charge oxidize over time in the soil leading to accumulation of carboxylic and hydroxyl functionalities in the surface of biochar particles (Jein and Wang, 2013). This creates a condition which possibly enhances the interactions between biochar and other soil components, such as organic and mineral matter. In other words, when biochar is incorporated into the soil, it could function as a binding agent that connects soil micro-aggregates to form macro-aggregates. This ultimately increases the diameter of the soil aggregates of biochar amended soils (Cheng et al., 2006), and therefore, leads to changes in pore-size distribution and aggregate stability which affect water retention potential in biochar amended soils.

Fine biochar particle sizes have high surface area than the large grain particle size. It was observed in this study that the treatment with fine grains hold more water than the treatment with large grain particles when the suction pressure was low. However, as suction increases above -300 kPa the large grain particles tend to hold more water than the fine grains. The possible reason for this response may be attributed to particle size distribution and total surface area.
Water holding capacity of the soil is controlled mainly by the number of pores, pore-size distribution, and the specific surface area of the soil particles. Amending soil with biochar may increase aggregation by increasing the total pore spaces (Mukherjee and Lal, 2013). Also, reduction in bulk density alters the pore-size distribution and thus, increases the relative number of small pores especially for coarse textured soils. The tension which causes a particular pore to drain is dependent on the effective diameter of the pore, so greater tension is required to drain small pores, compared to large pores (Vengadaramana et al., 2012). Increased WHC at lower tensions such as at field capacity is mainly the result of an increase in number of small pores. But, at higher tensions close to wilting range, almost all the pores are filled with air, and the moisture content is determined primarily by the specific surface area and the thickness of water films on these surfaces (Vengadaramana et al., 2012). The coarse grain biochar particle sizes (2-4 mm) have much less surface area than the fine grain biochar particles (<2 mm), and thus retain much more water at higher tensions.

5.3 Water use Efficiency

The result of this study showed that addition of biochar to sandy loam soil increased the water retention. This finding is consistent with findings of other researchers (Novak et al., 2009; Artiola et al., 2012; Basso et al., 2013) who have reported increased water holding capacity linked to high adsorption capacity and porous structure of biochar. The addition of biochar significantly increased the available water for the plants as clarified by the improved dry matter yield (DMY), and water use efficiency (WUE). This improvement in available water may have contributed to the increased biomass yield in the biochar treated soils. It was observed that the largest increase in DMY was among the FI treated pots. However, the dry matter yield of biochar
amended DI pots were close to the FI control by approximately 6 g difference. Water use efficiency was higher in DI compared to FI, and this is consistent with the finding of other studies (Kammann et al., 2011; Aktar et al., 2014). DI is better than FI in terms of improving crop WUE (Aktar et al., 2014). Kammann et al. (2011) also reported of increased WUE with biochar addition.

In this study, reduction in leaf area (LA) and plant height (PH) was observed in DI compared to FI, whilst chlorophyll content index (CCI) and stem girth (SG) were higher in DI relative to FI. An interesting observation in this study is how SG for DI increased over FI. This result is in absolute contrast to general consensus, because growth rate decreases under drought condition, and cells become smaller and thus should affect SG in DI. However, the result proved different. This effect might have been caused by improved plant water status as a result of biochar addition in amended DI regime and reduced N uptake by plants under FI regime.

Furthermore, CCI results for biochar treated soils were not different compared to the control, and there was no significant effect of irrigation treatments on CCI. Two possible reasons may have accounted for this observation of CCI under biochar treatment. First, it might be attributed to NH$_4^+$ adsorption on the surface of biochar (Lehmann et al., 2002), which may lead to reduced N availability to the maize plants. Kammann et al. (2011) observed decreased leaf N content with biochar amendment in his study and saw reduction in CCI, a finding consistent with our result. Literature has shown that CCI may reduce with decreasing leaf N content and that may lead to reduction in plant growth. Secondly, there is a possible increase in soil C/N ratio with respect to biochar addition leading to soil N immobilization (Lehmann et al., 2002) and consequently, reduced N uptake by the maize plants. Despite the observation on CCI, biomass
yield (BY) was not affected negatively which was probably due to increased uptake of water and improved plant physiology and soil physical properties as a result of biochar addition.
CHAPTER SIX

6.0 CONCLUSION

The following conclusions are drawn based on the results from the study:

1. Addition of corn cob biochar amount of 80 tons/ha had significant effects on the maize biomass yield, bulk density and water retention potential of a sandy loam soil. Biochar application rate of 20 tons/ha had no significant effect on the soil physical properties and on maize biomass yield relative to the no biochar treatment. It was discovered that, corn cob biochar applied at a rate beyond 20 tons/ha improved soil bulk density, water retention, and maize biomass yield. Thus, it is concluded that corn cob biochar amount beyond 20 tons/ha should be applied to sandy loam soil for effective response.

2. Corn cob biochar particle size less than 2 mm reduced soil bulk density lower than biochar particle size of 2-4 mm, and improved water retention in the soil. Thus, it is concluded that less than 2 mm corn cob biochar particle size will have greater effect on the physical properties of a sandy loam soil if applied at a higher rate beyond 20 tons/ha.

3. The addition of corn cob biochar to sandy loam soil under deficit irrigation improved maize physiology and biomass yield. Transpiration efficiency for DI treatment was statistically significant compared to FI treatments. The DI plants under biochar amendment produced yield closer to FI control. Thus, it is concluded that in the case of limited water availability, biochar in combination with deficit irrigation should be
practiced as a strategy for conserving water and enhancing crop productivity, hence, improving crop water use efficiency.

6.1 RECOMMENDATION

1. Further research should be carried out with more particle size factors to help determine the particle size appropriate for use in sandy loam soil.

2. It is recommended that 80 tons/ha of less than 2 mm corn cob biochar particle size should be applied by farmers to sandy loam soils to help improve the properties of the soil and achieve high yielding results. Some amount of fertilizer should be added to boost performance of the biochar in the soil.

3. It is recommended also that, farming areas with problems of limited water availability should start practicing biochar in combination with deficit irrigation as a strategy for conserving water and enhancing crop productivity.
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