UNIVERSITY OF CAPE COAST

INFLUENCE OF BIOCHAR AND IRRIGATION ON CROP PRODUCTION IN THE COASTAL SAVANNAH ZONE OF GHANA

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INFLUENCE OF BIOCHAR AND IRRIGATION ON CROP PRODUCTION IN THE COASTAL SAVANNAH ZONE OF GHANA

BY

KWADWO KUSI AMOAH

Thesis submitted to the Department of Crop Science of the School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Doctor of Philosophy degree in Crop Science

September 2019

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the results of my original research and that no part of it has been presented for another degree in this University or elsewhere. Materials previously published are duly referenced in the text.

Candidate's Signature……………………………… Date …………………

Name……………………………………………

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast

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ABSTRACT

A study was conducted during the major growing seasons of 2015 to 2017 to determine the integrated impact of corn cob biochar and irrigation on the growth and yield of maize, cowpea and tomato in the coastal savannah zone, Ghana. Preliminary pot experiments were set up to determine the appropriate biochar rates, biochar particle sizes and fertilizer to be used in subsequent field experiments. Completely randomized design with 4 levels of biochar (0, 20, 40, 80 t ha^{-1}), 2 levels of biochar particle sizes (< 2 mm and 2-4 mm) and 2 levels of irrigation regimes (full and deficit) was used. Irrigation generally did not have significant effect on maize growth. However, an increase in biochar significantly increased the fresh and dry above-ground biomass of maize. Generally, the < 2 mm biochar particle size improved maize growth compared to the 2-4 mm biochar particle size. There was a significant interactive effect of biochar rate, biochar particle size and irrigation on the above-ground biomass of maize. There was an increase in growth when phosphorus was loaded with biochar before application, compared to when phosphorus was applied in the form of NPK. Split plot design was used for the field experiments with irrigation and biochar as the main and sub-plots, respectively. There were 3 levels of irrigation (full, deficit and no irrigation) and 3 levels of biochar (0, 10, 20 and 20+P t ha^{-1} and 0, 20, 40 and 40+P t ha^{-1}) in 2016 and 2017, respectively. The results indicated that an increase in biochar significantly increased leaf area, leaf area index, above ground biomass and yield of maize. For instance, in 2016 maize yield obtained from plots treated with 20+P t ha^{-1} biochar was 8.1 t ha^{-1}, i.e. five times higher than yields from the control plots. Cowpea yield also increased with increasing rates of biochar. Full and deficit irrigation significantly improved maize growth and yield of maize and cowpea. In general, biochar treatments ladened with phosphorus performed better for maize, cowpea and tomato. There was a strong and positive correlation between maize grain yield and crown root diameter. An increase in biochar rate increased tomato fruit yield. Biochar and irrigation did not signficantly affect the quality of tomato fruits. Therefore, soil amendments with biochar, especially loading it with phosphorus before incooperating it in the soil and with supplemental irrigation even in the dry season, crop growth and yield will improve.

KEY WORDS

Corn cob biochar

Crop rotation

Deficit and full irrigation regimes

Maize-cowpea intercrop

Plant root

Shovelomics

Tomato

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DEDICATION

To my wife and sons: Dorcas, Kwaku and Kobby. Also to Kwadwo Konadu Amoah, Agnes Adutwumwa, Philip, Regina, Juliana, Faustina and Adonia.

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LIST OF ACRONYMS

CCI	Chlorophyll Content Index
CGR	Crop Growth Rate
CIMMYT	International Maize and Wheat Improvement Centre
CRI	Crop Research Institute
DAT	Days after transplanting
DI	Deficit irrigation
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization statistics
FI	Full irrigation
GHG	Greenhouse gas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ISODEC	International Social Development Centre
LAI	Leaf Area Index
MoFA	Ministry of Food and Agriculture
MOP	Muriate of Potash
NPK	Nitrogen Phosphorus Potassium
NI	No irrigation
PROTA	Plant Resources of Tropical Africa
SOP	Sulphate of Potash
SSA	sub-Saharan Africa
TDR	Time Domain Reflectometer
TSP	Triple super phosphate
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

USDA	United States Department of Agriculture
WAP	Weeks after planting
WEBSOC	cohesive Water, Energy from Biomass, Soil, Organics and Crops

CHAPTER ONE

INTRODUCTION

Background of the study

The need for increasing crop production is regaining public and policy attention. This is because according to the United Nations, the current world population of 7.2 billion is projected to increase by 1 billion over the next 12 years and reach 9.6 billion by 2050. This increase in population will be mainly in developing countries, with more than half in Africa (United Nations (UN), 2015). These figures indicate that the world, especially Africa, need to increase food production to be able to feed her ever increasing population. For example, in 2015, the World Population Review reported that Ghana's population ranks 48th in the world and it is estimated to be 27 million, up from the official 2010 census figure of 24.2 million (http://worldpopulationreview.com/, Accessed 21 June, 2016). Again, the United Nations Report (statistics of the world's projected populations) projected that Ghana would have a population of 33,678,000 million people by 2030 (https://populationpyramid.net /ghana/2025/, Accessed 30 June, 2016).

There is therefore an increasing concern about the prospects for food security over the next forty years to come (Bruinsma, 2009). It is feared that as populations grow, recent progress to reduce hunger will not be sustained and more people and animals will go hungry. This is much so because of the problems crop production has faced over the years, especially in Africa where there are land tenure disputes, soil infertility issues, pre and post-harvest losses due to pest infestation and storage problems, the use of farm lands for mineral mining and many other causes.

Attempts to increase food production to meet this enormous demand would generate more environmental damage, and this in turn will undermine our future capacity to produce food. To feed a fast growing world population, there is no option but to intensify crop production sustainably (FAO, 2011). This is the time to design concrete actions to improve agricultural productivity on a sustainable basis (Pisante, Stagnari & Grant, 2012). In this study, particular attention will be drawn more on the importance of biochar and irrigation on crop production. However, other principles and practices used in crop production will also be emphasized.

An important component of crop production is the soil fertility management. Most soils in Ghana are of low inherent fertility (Benneh, Agyepong & Allotey, 1990) and, therefore, require amendments to improve its fertility. However, fertilizer use in Ghana is low because most farmers cannot afford it and, therefore, do not use it or use less than the recommended rates (FAO, 2005). There has been so many remedies to combat soil infertility issues in Africa, especially in Ghana. Gyamfi, Loos and Anthofer, (2001) suggested that a remedy to nutrient deficiency and declining soil productivity may be to explore organic sources of fertilizers. With the rise in the cost of mineral fertilizer and the concern over sustainability of current cropping systems, green manures have also attracted new research interest (Hikwa & Mukurumbira, 1995). However, green manure production requires land that could often be used for food and cash crops (Giller, Cadisch, Ehaliotis, Adams, Sakala &

Mafongoya, 1997). On the other hand, a number of farmers cultivate legumes, including cowpea, soybean and groundnut, in rotation with upland crops, and these have beneficial effects on soil fertility. The levels of organic matter and most of the essential plant nutrients, particularly nitrogen and phosphorus are low in most Ghanaian soils (Dwomo & Dedzoe, 2010). Due to the poor nature of our soils, most farmers depend on external sources of fertilization to replenish the soil (FAO, 2004), though low rates are applied because of high cost of fertilizers. Chemical fertilizers mostly used in Ghana include ammonium sulphate (AS), muriate of potash (MOP), urea, single and triple superphosphate (SSP and TSP) (FAO, 2004). There has however been some significant successes in terms of crop yields when these chemical fertilizers were used. Albeit, these fertilizers are vital for high yields, their use is saddled with many ramifications such as soil acidification (Moore, Daniel, Gilmour, Shreve, Edwards, Wood, 1998).

Nutrient reserves in the soil can be of two forms, available or fixed (Francis, 1988). Crop plants usually get their nutrient requirement from the available pool. The rate of recharging of the available pool may however be too slow in some cases (Lehmann & Schroth, 2003). Biochar has been reported to facilitate the recharging of the available soil nutrients to make it readily available for plant use (Lehmann, Gaunt & Rondon, 2006). Biochar (soil amendment) similar to charcoal (fuel energy) is a carbon-rich solid material produced by heating biomass in an oxygen-limited environment (Lehmann *et al*., 2006).

Application of biochar to soils is currently gaining considerable interest globally due to its potential to improve soil nutrient retention capacity, especially in depleted tropical soils, water holding capacity, and also to sustainably store carbon, thereby reducing greenhouse gas (GHG) emissions (Bakewell-Stone, 2011; Verheijen, Jeffery, Bastos, van der Velde & Diafas, 2010; Lehmann et al., 2006; Downie, 2009). Enhanced nutrient retention and water holding capacity of soils reduce the total fertilizer requirements and environmental deterioration associated with fertilizers (Yeboah, Ofori, Quansah, Dugan & Sohi, 2009). Unlike fertilizers, biochar has an extremely long life in soils and it is not susceptible to biological degradation (Mutezo, 2013). Another significant effect of biochar is the ability of it to attract microbes and beneficial fungi which improves soil structure and texture and hence improves crop growth and yield (Verheijen *et al*., 2010). Biochar is also cited as a tool in agricultural waste management, thus, waste formerly difficult to dispose off can be used to produce biochar (Schouten, 2010). In addition, various types of biomass such as agricultural crop residues, forestry residues, wood waste, organic portion of municipal solid waste and animal manures have been proposed as feedstock for biochar production (Zheng, Guo, Chow, Bennett, & Rajagopalan, 2010).

In a sustainable crop production, one key input is water. Water has always been the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand and there is insufficient water for irrigation. While 2 litres of water are often sufficient for daily drinking purposes, it takes about 3,000 litres to produce the daily food needs of a person (FAO, 2011). It is reported that irrigated agriculture accounts for 20% of the total cultivated land but contributes 40% of the total food produced worldwide (FAO, 2011). This indicates that if the percentage irrigation is augmented worldwide then the total food production would increase to curb food insecurity issues. It is also estimated that irrigated land in developing countries will increase by 34% by 2030, but the amount of water used by agriculture will increase by only 14%, thanks to improved irrigation management and practices (FAO, 2011). With all these future prospects, access to water for productive agricultural use remains a challenge for millions of poor smallholder farmers, especially in sub-Saharan Africa, where the total area equipped for irrigation is only 3.2% of the total cultivated area (FAO, 2011).

Farmer-driven, informal irrigation is in many regions more prominent than formal irrigation (Heffer & Prud'homme, 2014). To alleviate this bane, FAO (2012), asserted that improved agricultural water use in irrigated and rainfed agriculture will play a key-role in coping with the expected water scarcity stress. Improving water use or water productivity is often understood in terms of obtaining as much crop as possible per volume of water - "more crop for the drop" (United Nations Information Service (UNIS), 2000).

Problem statement

Agriculture, especially crop production, has been the mainstay of many countries in the world. Bationo, Mokwunye, Vlek, Koala, Shapiro and Yamoah, (2003), asserted that regardless of the increasing global per capita food production, there has been an alarming decline in food production on the African continent over the past 25 years. Most analysts agree that African agriculture has been low and unsustainable for the past five decades or so. (Bationo *et al*., 2003). However, there is no consensus on the factors responsible for this low and unsustainable production (Pretty, 1999; Kuyek, 2002;

Bryceson, 2004). In view of this, agricultural productivity and food security in sub-Saharan Africa (SSA) are highly threatened.

There are many reasons accounting for the low and unsustainable crop production with the leading factors being nutrient depletion in the soil (Diagana, 2003). Soil fertility decline is a major problem confronting crop production in Ghana. According to Quansah, Safo, Ampontuah and Amankwah, (2000) Ghana has one of the highest rates of soil nutrient depletion among sub-Saharan African countries with annual projected losses of 35 kg N, 4 kg P and 20 kg K ha^{-1}. This is attributed to continuous cropping which has led to massive decline in soil fertility, crop nutrient removal and losses through soil erosion and worst still 'galamsey' (illegal mining) operations in Ghana, leading to low crop yields. For instance, maize yields has been in a range of 1.2 – 1.8 t ha^{-1} from 1961 to 2014 (FAOSTAT, 2017) compared to a potential yield of 4-6 t ha^{-1}. Most crop producers have tried to apply fertilizer to improve soil fertility but it is applied either in low quantities or without taking into consideration the nutrient removal pattern of crops grown. The impact of commonly practiced cropping systems on general soil fertility is also not checked (Pretty, 2007). The low or no fertilizer use is attributed to the fact that fertilizers are expensive in Ghana. Again, most soils in Ghana are of low in fertility with low water holding capacity due to parent materials, erosion, poor farming practices and leaching (FAO, 2005). The soils in sub-Saharan Africa also have high P-fixing capacities due to the pH ranges and impact of oxides of aluminum (Al) and iron (Fe) making P unavailable for plant use (Nwoke, Vanlauwe, Diels, Sanginga, Osonubi & Merckx, 2003).

In most developing countries like Ghana, crop production is predominantly practiced on smallholder, family-operated farms using rudimentary technology to produce about 80% of the total output. Most of these farmers, about 90% rely on rainwater for their crop production (MoFA-SRID, 2010). However, climate change is aggravating drought making rainfall more erratic. This will potentially affect the lives of people in Ghana where many poor smallholder farmers depend on crop production for their livelihood with very limited alternatives of earning a living (Jones & Thornton, 2003).

Justification

Climate is changing and this is leading to erratic rainfall, increased drought periods and increased temperature. Soil fertility and increase in population in Ghana is declining the size of arable land for crop production. Majority of farmers in Ghana are also resource poor. Crop production is mostly rainfed. The use of inorganic fertilizers is costly, unsustainable and may have adverse environmental implications. There is therefore the need to use biochar to amend the soil to improve its fertility. Biochar production and application may increase crop growth and yield and have fewer detrimental effects on the environment. Also average attainable yields can be increased using biochar as it improves fertilizer use efficiency. The application of biochar to arable fields will also increases carbon sequestration into the soil, improving the soil's carbon storage. These characteristics make biochar an exceptional soil amendment for use in improved crop production (Lehmann & Joseph, 2008; Verheijien *et al.*, 2010).

Climate change has alter the rainfall pattern in Ghana, making it more erratic. The effect of depending on an erratic rainfall pattern for crop production is in low crop productivity leading food insecurity and other societal impacts (Pereira, Oweis & Zairi, 2002). There is therefore a need to supplement rainwater with other sources of water for crop production, even in the rainy season in Ghana.

General objective

To generate knowledge that will improve growth and yield of cereal, legume and vegetable crops through the integrated use of corn cob biochar and irrigation.

Specific objectives

1. To evaluate the effect of corn cob biochar rates and particle sizes, fertilizer and irrigation regimes on the growth of pot grown maize.
2. To evaluate the influence of biochar and drip irrigation regimes on growth and yield of field grown maize in a maize-cowpea intercrop.
3. To determine the effect of biochar and drip irrigation on the root system architecture of maize and cowpea in a maize-cowpea intercropping system.
4. To determine the impact of biochar and drip irrigation on the growth, yield and quality of tomato.

Hypothesis

To achieve these objectives, the following hypotheses were tested:

1. Growth of maize is not influenced by different rates of biochar, particle size, fertilizer and irrigation regimes.
2. Biochar and drip irrigation regimes do not improve the growth and yield of field grown maize.

3. Root system architecture of maize and cowpea is not affected when biochar and irrigation are applied in a maize-cowpea intercropping system.
4. Tomato growth, yield and quality are not affected by biochar and drip irrigation.

Organization of the thesis

This thesis is divided into eight chapters. The first chapter is made up of five sections i.e. the background to the study, statement of the problem, justification and objectives. The second chapter reviews literature as it relates to the research as well as relevant literature from past studies. In chapter three, methodology of the research is presented. Chapters four, five, six and seven presents the results of the analysis of the data collected and the discussion of these results. Chapters 4-6, respectively corresponds to objectives 1-4 of the thesis. The final chapter, eight, presents the summary of major findings, policy implications, conclusion of the study, and recommendations for further studies.

CHAPTER TWO

LITERATURE REVIEW

The state of crop production in the world

Crop production demand is on the rise as a result of increasing human population, livestock production and biofuel use (Pingali, 2006; Godfray *et al*., 2010; Tilman, Balzer, Hill & Befort, 2011; Foley, Ramankutty, Brauman, Cassidy & Gerber, 2011). To meet these increasing demands, there is a need to increase crop production by 60% - 110% (Tilman *et al*., 2011). It has been suggested that increasing crop yields, is the most sustainable path for food security instead of increasing the land area for crop production (Godfray *et al*., 2010; Phalan, Onia, Balmford & Green, 2011; Matson & Vitousek, 2006).

Although crop yields vary from region to region, it is mostly low in sub-Saharan Africa compared to Eastern Asia. Insufficient adoption of more productive technologies, lack of market integration and gender inequalities in small-scale family farming (FAO, 2011) has been reported as constraints to the low crop yields in sub-Saharan Africa. Other constraints has been reported to be irrigation and soil fertility issues (Sosibo, Muchaonyerwa, Visser, Barnard, Dube & Tsilo, 2017, Bui, Saskia, Chu, & Leo, 2013). The adoption of improved crop production practices would contribute to increased crop yield. Some of the improved crop production practices include nutrient and water supply, and management of weeds and pests. Crops of higher yield and have increased resistance to drought, bacteria, fungi, and viruses, or other factors, such as optimal flowering time should be selected (Baltes, Gil-Humanes & Voytas, 2017). The synergistic effect of sustainable crop production practices on soil fertility do not only enhance crop yield, but also quality of crops (Tanaka *et al.*, 2007) and also lower the negative impact of the environment (Imadi & Kazi, 2015).

Benefits of crop production

According to Carolan, (2006), sustainable agriculture is associated with a decrease in rate of soil and nutrient loss, increase in levels of microorganisms in the soil, and reduction of amount of chemicals which leach into water table. Sustainable crop production ensures the production of quality and safe food, devoid of contamination by chemicals (Fowler & Rockstrom, 2001). Again, crop production practices ensure the conservation as well as enhancement of agro biodiversity for maintaining the security of food and agro-ecosystem which is sustainable in nature (Thrupp, 2000). On the other hand crop production are economical in nature but high with yields. Despite the fact that this system is best employed by small holder farmers, they still obtain high yield and use less water resources (Thrupp, 2000). Crop production not only contributes to the economy, but also has a huge function in the prevention of environmental degradation and climatic changes. Usage of biological pesticides and multiple cropping techniques further reduces the cost of sustainable crop production (Vermeir & Verbeke, 2006).

In most cases, what is termed as waste by most farmers could be used to replenish the soil for better crop yield. For example, biochar which is a form of charcoal could be produced from 'farm waste' for the remediation of the soil with no adverse effect on the soil and the environment. Singh, Baoule, Ahmed, Dikko, Aliyu, Sokoto, Alhassan, Musa and Haliru (2011) also affirm this fact that sustainable agriculture is a vital form of agriculture in today's world because it uses special techniques of farming in which environmental resources are fully utilized which also ensure no harm to soil and the environment. Fowler and Rockstrom (2001), also pointed out that sustainable crop production is practiced with the preservation of the biodiversity and that the world is moving towards sustainable agriculture and that is only due to the reason for saving the environment. All these factors make a sustainable agriculture system as a very affordable type of crop production. Pretty, Toulmin and Williams (2011), summed up the benefits of applications of sustainable agriculture as a way of improving crops, agroforestry, conservation of soil, conservation of agriculture, integrated pest management, horticulture, development of livestock and fodder crops, and aquaculture.

It is therefore very critical to include cropping systems such as crop rotation, multiple cropping, conservation agriculture, and cropping intensification approaches in daily agriculture to attain sustainable agriculture production systems (Yang, 2006). This research have considered the above facts and have incorporated some farming systems, irrigation, crop and soil management techniques that is cost effective and environmentally friendly. This will produce more food through less and low resources with more efficient usage of nutrients. This will have a minimal impact on environment and will also meet the demands of ever-growing population (Hobbs, Sayre, & Gupta, 2008).

Intercropping and crop production

Intercropping is one of the oldest practice of crop production which has proven very useful in sustainable crop production. Intercropping is a space-dependent form of multiple cropping system where two or more crops are cultivated simultaneously and in specific sequence on the same field. . Generally soil fertility is improved by biological nitrogen fixation (Lithourgidis, Dordas, Damalas, & Vlachostergios, 2011). For example, intercropping of maize and cowpea is more economical than maize monocropping when nitrogen fertilizer is not applied (Dahmardeh, Ghanbari & Ramroudi, 2009). A typical advantage of intercropping is that pest problems are curbed by the increased diversity attained in intercropping (Mousavi & Eskandari, 2011). It is noted that intercropping increase productivity per unit of land (Hardter, Horst, Schmidt & Frey, 2008) because the complementary effect between component crops is considered to be a major source of yield advantage from intercropping (Willey, 2006). Biologically, intercropping benefits include the efficient use of resources such as light, plant nutrients and water, nitrogen relations, yield stability (Willey, 2006) and more efficient use of the soil (Eskandari & Ghanbari, 2009). Intercropping increase crop canopy and this promote smothering of weeds and reduce evaporation. Recent interest has been the effect of environmental context on plant-plant interactions (Brooker *et al*., 2008). Complementarity effects are most relevant to improving intercropping systems, underlying transgressive over yielding and operating through processes such as niche complementarity, direct facilitative effects, e.g., hydraulic lift or N and P mobilisation, and increased abundance of insect pollinators or enemies of insect pests in diverse vegetation (Letourneau *et al*., 2011; Cardinale *et al*., 2012). Niche complementarity, which allows maximal exploitation of light and soil resources, is observed between species with contrasting short and tall shoot architectures, or shallow and deep root architectures (Hauggaard-Nielsen, Ambus & Jensen, 2001; Postma & Lynch, 2012). The net benefits are crop protection, pollination, greater photosynthetic carbon assimilation, greater acquisition of N, P, micronutrient and water, and sharing of these resources temporally to increase yield. Roots of complementary plant species can also improve soil stability and soil structure (Obalum and Obi, 2010), thereby improving resource acquisition (Hallett & Bengough, 2013). For instance, tap-rooted species can penetrate compacted soil layers to the benefit of fibrous-rooted species (Chen & Weil, 2010).

Soil fertility and crop production

Soil infertility is the major constraint which limits the yield of crop worldwide. A "healthy" soil is a *critical* component of sustainable agriculture (Kassam, Friedrich, Shaxson & Pretty, 2009). Sustainably grown plants may be higher in vital macro and micronutrients, resulting from increased soil fertility as a direct consequence of sustainable practices (Halweil, 2007). Because the negative effects (enhanced due to changes in climatic conditions) of depletion of soil fertility on food security are of immense economic importance, it has now become crucial to develop options of gaining soil fertility without harmful effect. For example, soils which are low in nitrogen can be treated with crop rotation technique to enhance nitrogen concentrations in a sustainable system (Bakht, Shafi, Jan & Shah, 2009) and this will lead to higher agronomic nitrogen use efficiency (Spiertz, 2010). Efficient management practices can lower the use of nutrients (Tilman, Balzer, Hill & Befort, 2011).

The levels of organic carbon, nitrogen and available phosphorus in Ghanaian soils are very low (Tetteh, 2004). Usually figures are not shown for potassium because it is mostly abundant in the soils of Ghana. Phosphorus, a major soil nutrient which functions cannot be performed by any other nutrient is a major limiting nutrient in Ghanaian soils (FAO, 2004). This important nutrient is usually fixed by the soil decreasing its availability to plants. However, with the intervention of a sustainable crop production practices, like soil fertility management, irrigation and an improved cropping system, these important plant nutrients will be available for plant uptake (Withers, 2014).

At present, most traditional soil nutrient exhausting cultivation practices are still used extensively (Gerner, Asante, Owusu Bennoah, & Marfo, 1995). As a result of this almost all the crop balances in Ghana show a nutrient deficit, (i.e. the difference between the quantities of plant nutrients applied and the quantities removed or lost) (FAO, 2004). This represents a loss of potential yield and progressive soil impoverishment. Therefore, it is imperative that in any sustainable cropping system nutrients removed from the soil be balanced by nutrient replacement (Grant, Gary, & Campbell, 2002). With these caveats in mind, decreased CO_2 emissions and increased C sequestration can be a positive environmental externality of replenishing soil fertility (Sanchez, Shepherd, Soule, Place, Buresh, Izac, Mokwunye, Kwesiga, Ndiritu, & Woomer, 1997). Soil-fertility depletion decreases above and below ground biodiversity and increases the encroachment of forests and woodlands in response to the need to clear additional land (Sanchez, 1995).

Biochar and crop production

Definition of biochar

Biochar, also known by some as the 'black gold' of agriculture, is a black carbon manufactured through pyrolysis (the thermo-chemical degradation of biomass under anaerobic or oxygen-limited conditions) of biomass (Lehmann *et al.*. 2006; Lehmann, 2007a; Chan, Van Zwieten, Meszaros, Downie & Joseph, 2008b; Novak, Busscher, Laird, Ahmedna, Watts & Niandou, 2009). Biochar is a fine-grained and porous substance, similar in appearance to charcoal produced by natural burning or by the combustion of biomass under oxygen-limited conditions (Sohi, Loez-Capel, Krull & Bol, 2009). Biochar is a pyrogenic organic matter deliberately added to soil mostly for agricultural purposes. According to Lehmann and Joseph (2009), the char produced by pyrolysis is only called biochar when its application is towards environmental management and productivity benefits to soil.

Feedstock of biochar

Reports indicates that biochar can be produced from a wide range of organic materials and under different conditions resulting in products of varying properties (Baldock & Smernik 2002; Nguyen, Brown & Ball, 2004; Guerrero, Ruiz, Alzueta, Bilbao & Millera, 2005). Biochar is produced from sustainably procured waste biomass such as crop residues, manures, timber and forestry residues, and green waste (Chan *et al.*, 2007; Woolf, Amonette, Street-Perrott, Lehmann & Joseph, 2010) including woods and wood barks, olive husks, corncobs and tea waste (Demirbas, 2004; Ioannidou & Zabaniotou, 2007). Animal manures, poultry litter and other waste products can also be used to produce biochar (Downie, Klatt & Munroe, 2007; Chan *et al.*, 2008a; Lima, McAloon & Boateng, 2008; Revel, Maquire, & Agblevor, 2012). Sewage sludge (Khan, Chao, Waqas, Arp & Zhu, 2013), rice-husk (Lu, Sun & Zong, 2014), wheat straw (Junna, Bingchen, Ganga & Hongbos, 2014) are also used as feedstocks for biochar production. This therefore indicates that biochar properties are influenced by the feedstock, pyrolysis temperature and resident time (Ahmad *et al*., 2014; Sohi, Krull, Lopez-Capel & Bol, 2010).

Origin of biochar use

The oldest and most well-known use of biochar in agriculture dates back to the ancient Amazonians 7000 yr. BP. Interest in biochar grew out of research on rich, dark soils in the Amazon known as *Terra Preta* or Amazonia Dark Earth (ADE) (Neves, Petersen, Bartone & Heckenberger, 2001). It has been reported severally by some researchers that there is the occurrence of charcoal in '*Terra Preta*' (*'terra preta do indio'* or 'black-earth-like') in some soils found in the Amazon basin (Sombroek, 1966; Sombroek, Kern, Rodrigues, Cravo, Cunha, Woods & Glaser, 2002). The soil components revealed the presence of black carbon derived from incomplete combustion of cooking fires (Glaser, Haumaier, Guggenberger & Zech, 2001). This soil was possibly made by the several activities of pre-Columbian residents with their slash and char activities (Taylor, 2010) and also through the soil management practice of these ancient Amerindians of the Amazon region (Petersen, Neves, & Heckenberger, 2001; Lehmann & Joseph, 2012). These soils are highly fertile (Glaser *et al*., 2001), therefore very important for crop production. Due to a high proportion of aromatic structures, which results in resistance to chemical and biological decomposition, biochar can remain in the soil for hundreds to thousands of years (Schulz & Glaser, 2012; Lehmann, 2007a). Similar soils have been documented elsewhere within the region, namely Ecuador and Peru, in West Africa (Benin and Liberia), and the savanna of South Africa (Lehmann, de Silva, Steiner, Nehls, Zech & Glaser, 2003). Again the use of charring in traditional soil management in the past (Young, 1804) or at the current time (Lehmann & Joseph, 2009) has also been reported in other countries. Okimori, Ogawa and Takahashi, (2003), reported that Japan currently has the largest commercial production of charcoal for soil application, with about 15000 tons traded annually.

Effect of biochar on climate change

The effectiveness of biochar in mitigating climate change is mainly due to the greenhouse effect. Biochar can be used to reduce greenhouse gas emissions by sequestering atmospheric carbon into the soil and stores it for hundreds of years or more because of its relatively recalcitrant nature against microbial decay and slower return of carbon as carbon dioxide to the atmosphere (Lehmann, 2007b; Yanai, Toyota & Okazaki, 2007; Van Zwieten, *et al.*, 2010b; Schulz & Glaser, 2012). When charcoal which is similar to biochar was used as a soil amendment it was able to reduce the net fluxes of methane and nitrous oxide from pots cropped with soybean (Rondon, Ramirez & Lehmann, 2005; Renner, Sweeney & Kubit, 2007; Sohi *et al.*, 2009). Biochar also reduces the annual net emissions of carbon dioxide (Woolf *et al.*, 2010). As biochar increases soil pH, nitrous oxide produced from the top soil layer could be reduced (Deng, 2013). Day, Evans, Lee & Reicosky (2004) emphasized that using biochar to sequester carbon in soil and in the atmosphere to mitigate climate change could only be economical if the sequestered carbon has beneficial soil amendment and fertilizer value.

Nutrient content of biochar

Though biochar is not a fertilizer it usually contains N, P and basic cations like Ca, Mg and K (Major, Rondon, Molina, Riha & Lehmann, 2010b). It has been reported that biochar produced from plant materials often have lower concentration of nutrients and minerals such as N and P, but a higher C content when compared to biochar based on manure (Lehmann *et al*., 2003; Chan *et al*., 2008a; Chan *et al*., 2008b; Waters *et al*., 2011). In general, the actual nutrient content of biochar and its bioavailability is highly dependent on the feedstock used and pyrolysis conditions. Information on the bioavailability of nutrients contained in biochar is however rare (Gaskin, Steiner, Harris, Das & Biben, 2008; Singh *et al*., 2010a).

Effects of biochar on soil health

In every crop production enterprise, soil fertility management is a crucial yet under-appreciated dimension of sustainable productivity growth. Most of the soils in Ghana are suitable for agriculture but most of the soils are of low inherent fertility. Ghana has one of the highest rates of soil nutrient depletion among sub-Saharan African countries with annual projected losses of 35 kg N, 4 kg P and 20 kg K ha^{-1} (Quansah *et al*., 2000). The soil are old and have been leached over a long period of time (Bationo *et al*., 2015). Therefore, the sustainability of good crop yields is closely linked with the careful management of the soils. This will require explicit attention to soil nutrient replacement for a reliable agricultural intensification in Ghana.

Biochar could be beneficial as soil amendment for improving the quality of agricultural soils (Glaser *et al*., 2002; Lehmann *et al*., 2003). It has been reported that biochar application to soils has positive influences on improving soil quality and plant growth (Chan *et al*., 2007; Chan *et al*., 2008a). When used as a soil amendment, biochar has been reported to boost soil fertility and improve soil quality by raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity (CEC), and retaining nutrients in soil (Lehmann *et al*., 2006) durability of soil aggregates, reduce leaching (Brandstaka *et al*., 2010). Another major benefit associated with the use of biochar as a soil amendment is its ability to sequester carbon from the atmosphere-biosphere pool and transfer it to soil (Winsley, 2007; Laird, 2008). One good reason why biochar is important for sustainable agriculture is because of its ability to persist in soil for millennia because it is very resistant to microbial decomposition and mineralization (Woolf *et al*., 2010).

Activated carbon like charcoal and biochar usually has a greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge, and charge density (Liang *et al*., 2006). Therefore, to prevent the loss of nutrients and also to protect water resources from contamination, addition of biochar to soil is very important. Reports suggest that soils containing biochar have a strong affinity for organic contaminants (Yang and Sheng, 2003a; 2003b; Yu, Ying, & Kookana, 2009). The use of biochar as a cost-effective sorbent is an emerging research topic, especially where phosphorus and nitrogen is always fixed and leached respectively from the soils in Ghana and other parts of Africa. Though some reports indicate that significant biochar effects on some soil properties will not be seen few months after application (Hardie *et al*., 2014) others reports shows that when biochar was applied at a rate of 0, 5, 10, 20 and 30 t ha^{-1} with or without inorganic fertilizer for two years, nitrate content, water retention capacity, soil organic carbon and K content was improved significantly (Tammeorg *et al*., 2014).

Another important property of biochar is the nutrient retention and plant uptake of nutrients which has also been found to improve due to increase in overall net soil surface area in soil after application of biochar (Chan *et al*., 2008a; Downie *et al*., 2009; Lehmann & Joseph, 2009). Also, long-term effects like stabilisation of organic matter, slower release of nutrients from organic matter and increased retention of cations are assumed to have a major impact on yield (Lehmann & Rondon, 2006; Brady & Weil, 2008). According to Nelson *et al*. (2011), biochar produced from corn cobs increased nitrate N in the first ten days of crop growth and thereafter it decreased; while it decreased P content when biochar was applied solely and increased it after addition of nitrogenous or phosphate fertilizer. This finding indicates the use of biochar combined with application of other sources of fertilizers (organic or inorganic) could be beneficial for improving plant growth and soil nutrient status.

Influence of biochar on crop growth and yield

There are varied responses of crops to biochar (Chan *et al*., 2008a) because effects are reliant on a number of factors including, biochar feedstock material, processing temperature biochar concentration, soil conditions and type and the nature of crops. Whether in greenhouse or field studies, several research have been conducted to examine the effect of biochar on crop yields (Glaser *et al*., 2002; Yamato *et al*., 2006; Chan *et al*., 2007, 2008a). Most studies showed that biochar addition increased crop yields (Lehmann & Joseph, 2009; Sara *et al*., 2018). For instance, it is indicated in some field experiments where the soil was amended with biochar that there was an improvement in the soil quality and substantially increased crop yield (Glaser *et al*., 2002; Yamato, *et al*., 2006). That notwithstanding, there has been some few cases with either no difference or negative results on the use of biochar as a soil amendment (Laird *et al*., 2009).

A study by Van Zwieten *et al*. (2010a), for example, reported that biochar produced from paper mill waste and used incorporation with fertilizer, significantly increased biomass in wheat, soybean and radish in ferrosol soil but reduced wheat and radish biomass in calcaresol soil. A significant decrease in dry matter content of radish was obtained when biochar was applied at a rate of 10 t ha^{-1} (Chan *et al*., 2008a). In soils with low P availability, biochar has increased rice grain yields probably due to improved saturated hydraulic conductivity of the top soil, xylem sap flow of the plant and response to N and NP chemical fertilizer treatments (Asai *et al*., 2009). As indicated earlier, biochar application promotes sustainable crop yield when it is applied in combination with other nutrients. For example, when biochar was applied in combination of mineral fertilizer to a nutrient-poor, slightly acidic loamy sand soil, it produced wheat yield of 20-30% more than mineral fertilizer alone (Alburquerque *et al*., 2014).

Biochar at different concentrations has been reported to have no significant difference in root elongation of pea and wheat (Borsari, 2011). However, a rice-husk biochar tested in lettuce-cabbage-lettuce cycle increased final biomass, root biomass, plant height and number of leaves in comparison to no biochar treatments (Carter *et al*., 2013). This has brought about another significant component of sustainable crop production where it is vital to include crop rotation and intercropping. For example, an oak biochar derived from a slow pyrolysis process was tested for four years at 0 t ha 5 t ha^{-1} and 25 t ha^{-1}

with 100% and 50% of N fertilizer on a maize-soybean rotation in an alfisol soil, resulting in an overall positive trend in total above-ground biomass and grain yield (Hottle, 2013).

In another example, biochar at the rates of 20 and 40 t ha^{-1} without N fertilization in a carbon poor calcareous soil of China increased maize yield by 15.8% and 7.3% while the rates with 300 kg ha^{-1} N fertilization enhanced yield by 8.8% and 12.1% respectively (Zhang *et al*., 2012). The yield of tomato fruit was significantly higher in beds with charcoal than without charcoal (Yilangai *et al*., 2014). Biochar application also increased vegetable yields by 4.7-25.5% as compared to farmers' practices (Vinh *et al*., 2014).

It should be noted that increased yield is likely to be observed more in highly degraded soils, particularly acid soils in the tropics, and in those with low CEC or SOC contents (Lehmann, 2007b). Relatively small increases in crop yield was observed when soils were amended with biochar alone. However, it did not generally provide significant input of plant nutrients, unless it is derived from a nutrient-rich source such as poultry litter (Chan *et al*., 2008b).

It is also important to note that biochar is not an actual fertilizer, although, at times it can supply some major (N, P, K) and minor (calcium, potassium and magnesium etc.) plant nutrients (Chan *et al*., 2008a). According to Steiner *et al*. (2007) yield of sorghum and rice increased moderately with application of biochar alone, whereas the application of biochar plus mineral fertilizer or chicken manure increased yields significantly.

Effect of biochar on root system architecture

Root system architecture is the spatial configuration of the entire root system in the soil (Fitter 1987; Lynch 1995). Root architecture can be looked at as the geometric arrangement of the individual roots within a root system in the soil volume the root system occupies (Lynch, 1995). A good soil environment is key to an optimum growth of plant root because of its direct contact with the soil. In particular, the way in which the plant root system adapts to the prevailing soil conditions reflects the limitations of resources that the plant experienced. For example, maize plants root growth angles have been shown to become steeper under low nitrogen conditions (Trachsel *et al*., 2013). Root system architecture is one major factor determining the biomass productivity, particularly under edaphic stress. For example, a deep rooting system may be beneficial during droughts (Benjamin & Nielsen, 2006), while a system exploring the topsoil may be useful to collect immobile nutrients, especially phosphorus (Ho *et al*., 2005). Describing the root system architecture remains a technical challenge since its access is constrained by the soil. However under laboratory conditions (soil columns), one study observed significantly larger barley root biomass in sandy soils after the amendment of biochar, by grid net counting after trimming by brushing (Bruun *et al*., 2014).

Though it has been stated by Bruun *et al*. (2014) that biochar effects on root system architecture are poorly understood at the moment, can confidently say that the effect of biochar on root architecture could be two sided, (1) a negative and (2) a positive effect. There will be negative effect when plants are forced to develop more root to uptake the water and nutrients and a positive effect when the biochar improve the soil properties and promote root development. For example, larger root proliferation may indicate more available water locally in the basins. However, for mobile nutrients and water rather induces an elongation of the root system (Bengough *et al*., 2011). There is also a specific development of roots, particularly observable for immobile nutrients like phosphorus (Lynch, 2011). When nutrients are mobile and highly available, the root system developed is deeper and numerous primary and secondary roots are produced (Hodge, 2004; Peng *et al*., 2010) for the uptake of water and nutrients. Lehmann *et al*. (2011) have also reported that a positive effects of biochar amendment on root growth especially on uncontaminated agricultural soils. This indicates that attention should be drawn to the use of biochar on soils that are contaminated. Because of the high root proliferation in the presence of biochar, plants develop the ability to resist environmental stress factors such as drought (Malamy, 2005) because their roots are able to absorb water to improve on root biomass. Lehmann *et al*. (2011) reviewed the changes of root biomass induced by the application of biochar as compared to a non-amended control and observed that in most cases, an increase in root biomass was related to an increase in shoot biomass. This could ultimately affect the yield of crops.

Importance of irrigation in crop production

Crop production practices include methods of water conservation and irrigation. Severe water shortage problems are developing in arid regions (FAO, 2002). Scarcity and increasing competition for fresh water decrease water accessibility for irrigation (Panda *et al*., 2003). Therefore, use of water to produce higher agricultural crops, in particular, in water scarcity regions, requires innovative strategies to promote the efficiency of available water (Pereira *et al*., 2002; Kirda, 2002).

Most agricultural nations have adopted strategies to curb the problems of water scarcity to promote crop production. In Iran, considerable arable lands are dominated with arid and semi-arid climate so that use of deficit irrigation is inevitable (Gheysari *et al*., 2009). In Ghana, Climate change scenarios developed based on the forty-year data (1960-2000) from the Ghana Meteorological Agency revealed that there will be a continuous rise in temperature with an average increase of about 0.6, 2.0 and 3.9°C by the year 2020, 2050 and 2080, respectively. Rainfall was also predicted to decline on average by 2.8, 10.9 and 18.6% by 2020, 2050 and 2080, respectively in all agro-ecological zones (EPA, 2007). These predicted changes can have impact on the pattern of agricultural production in Ghana, especially in the regions where the agro-ecological systems are in transition. Small holder farmers in Ghana who produce the bulk of the food and cash crops are the most vulnerable to the various manifestations of climate change. Irrigated agriculture has therefore become the key contributor to food security, producing 40% of food and agricultural commodities on 17% of agricultural land (FAO, 2012). Yet water use efficiency should be considered when irrigated agriculture should be adopted. There are numerous strategies available for improving water use efficiency, including the use of improved irrigation methods (Huang *et al.*, 2007) like drip irrigation. For example, it has been stated that water use efficiency for surface or furrow irrigation is 60-90%, sprinkler irrigation is 65-90% and drip irrigation is 75-90% (Fairweather *et al.*, 2003). However, irrigation water use efficiency has been always regarded as superior for drip irrigation compared with furrow irrigation (Nazirbay *et al.*, 2005).

Deficit irrigation can promote crop water productivity, sometimes even up to twice or more (Zwart and Bastiaanssen, 2004). Because drip irrigation is regulated, it cannot only reduce water consumption but also minimize adverse effects on yield (Panda *et al*., 2003). This was confirmed by Jinxia *et al*., (2012) when they stated that in maize production a certain degree of deficit irrigation in seedling stage is recommended to significantly improve water use efficiency.

It has been noted by Norman, (1992), that deficit irrigation (through drip irrigation) is relevant for crops in which flowering and fruit development take place in the dry season. Due to the application of relatively small amounts of water, the harvest can be stabilized over time and it improves economic planning for farmers, which is increasingly interesting under climate change conditions where water resources are becoming scarce and rains unpredictable (Sadras *et al*., 2007). There is also emerging research and development on precision irrigation for sustainable agriculture where automated systems are used. A developing country like Ghana could in the future use precision irrigation but now others are being used.

Tomato production

Tomato (*Solanum lycopersicum*) is cultivated as an annual crop in most regions of the world and is a valuable source of several minerals and vitamins (Vossen van der, 2004). It has the highest acreage of any vegetable crop in the world (Jensen *et al*., 2010). In Ghana, it is almost an indispensable ingredient in the daily diets of people across all regions (Ellis *et al.*, 1998). According to Alam *et al.* (2007), tomato is botanically a fruit but classified as vegetable in trade.

Tomato is cultivated mostly by farmers often in peri-urban areas to supply local demand. In most cases, field production is much less intensive, and is the most common system in tropical and subtropical areas. However the method of production is not sustainable because in most cases pesticides are widely used by tomato growers in developing countries, generally without training in application or identification of need, leading to several environmental burdens (Penning & Conrad, 2007; Zou *et al.*, 2007; Daker *et al.*, 2008; Tao *et al.,* 2008). Another production drawback is the over reliance of farmers on rains. These had led to a decline in production of tomato in Ghana, specifically in terms of attaining its potential or achievable yields of 15 t ha^{-1} (International Social Development Centre (ISODEC), 2004). There has been government interventions that include the establishment of a number of tomato processing factories (Ablorh-Odjidia, 2003) to purchase the produce when there is a glut but the production is still unsustainable (Asuming-Brempong and Asuming Boakye 2008). Because of the drastic decline of tomato production in Ghana, Burkina Faso supply almost all the fresh tomato in the country.

Moreover, Lopes *et al*. (2005) remarked that good productivity requires availability of water throughout the cycle, as the tomato plant is very sensitive to water stress. The commercial value of the table tomato is defined by the characteristics and quality of the fruit (Ferreira *et al*., 2004). The quest of producing tomato in a sustainable manner has led researches and some farmers to the use biochar for soil amendment (Chan *et al*., 2008a; Verheijen *et al*., 2010; Ahmad *et al*., 2012). Moreover, converting organic waste to biochar provides a beneficial way of recycling waste materials (Al Wabel *et al*., 2013; El-Mahrouky *et al*., 2015).

Tomato production in Ghana is highly seasonal and mostly rainfed. The erratic nature of rainfall recently has partly reduce tomato production in Ghana (Robinson & Kolavalli, 2010). It has become necessary to use irrigation because lack of water greatly affect the quality and quantity of production (Pires *et al*., 2009). According to Monte *et al*. (2013), among the different irrigation systems used in tomato growing, drip irrigation has become a viable option in Brazil (Marouelli *et al*., 2011) for its many advantages, such as the possibility to grow in areas of low water availability, high levels of efficiency (Bernardo *et al*., 2008), and lower incidence of diseases of plant aerial parts, leading to high yield and fruit quality. Although drip irrigation requires a high initial capital investment, it is one of the best techniques to use in applying water to vegetables (Cetin & Uygan, 2008). When compared to sprinkler irrigation, drip irrigation can distribute water uniformly, increases plants yield, reduces evapotranspiration, and decreases the use of water and fertilizer (Ozbahce & Tari, 2010). Furthermore, its pumping requires less energy, it potentially minimizes negative irrigation impacts on soil, and facilitates the use of fertigation (Nascimento *et al*., 2009). Nonetheless, a study of the basic principles of water and fertilizer management is essential for sustainable irrigated agriculture (Bernardo *et al*., 2008), as well as the amount of water required for best efficiency (Harmanto *et al*., 2005). When water is a limiting factor for agricultural production, irrigation with water deficit index provides greater economic return than total irrigation (Zegbe-Domíngues *et al*., 2003). Deficit irrigation management is possible when crop production function is estimated. When properly applied, the technique shows great potential to increase water use efficiency (Meric *et al*., 2011), especially in areas of low water availability (Lorite *et al*., 2007). The deficit irrigation could be used for tomato without reduction in yield and also with increase in fruit quality parameters, such as the content of sugar and antioxidants moieties (Favati *et al*., 2009).

Maize production

Maize (*Zea mays* L.) is a multipurpose crop that provides food for human, feed for animals especially poultry and livestock and raw material for the industries (Khaliq *et al*., 2004). It is the third most important cereal crop after wheat and rice in the world (IITA, 1991). Maize is the most widely consumed staple food in Ghana. A nationwide survey carried out in 1990 revealed that 94% of all households had consumed maize during an arbitrarily selected two-week period (Alderman & Higgins, 1992). Maize production in Ghana and most countries is now limited by several challenges related to soil degradation such as erosion, decline of soil organic matter content, drought, low soil fertility, diseases and pests (Edmeades, 2013; Ngoko *et al*., 2002) and ever escalating prices of chemical fertilizers (Farhad *et al*., 2009). Surprisingly while the average yield of maize in developed countries can reach up to 8.6 t ha^{-1} and over, production per hectare is still very low (1.3 t ha^{-1}) in Ghana (FAO, 2005).

In order to address the challenges facing maize production in Ghana, researchers have considered organic farming, integrated soil fertility management and efficient weed control. (Huang *et al*., 2007; Rasool *et al*., 2007). To ensure increased yield of maize, there is need to intensify soil fertility improvement and water management. This is for the reason that maize may thrive well in most soils but Twenebaoh (2000) stated that maize usually requires well-drained, deep loams or silty loams with high to moderate organic matter and nutrient content and pH 5.5 – 8.0 for best production.

Recently biochar has been used to improve the production of maize (Major *et al*., 2010b; Jeffery *et al*., 2011). It has been reported that yield characteristics and water use efficiency of maize were increased from 50 to

100% when biochar application rate was increased from 15 to 20 t ha^{-1} (Uzoma *et al*., 2011). Maize yield and yield components have also showed positive response when biochar was used to amend the soil (Steiner, *et al*., 2007; Uzoma *et al*., 2011)

Water management is also critical in the sustainable production of maize. The schedule of agricultural activities from land preparation, through crop selection and planting, to the time of harvesting for a developing country like Ghana, is rainfall dependent. The assessment and prediction of the onset and cessation dates of the rainy season is therefore crucial to the success of agricultural activities in Ghana (Amekudzi *et al*., 2015). Due to the possibility that rainfall in tropical climatic regions can be erratic due to climate change, it is essential that at least, there is adequate soil moisture at the time of anthesis in order to have a full set of kernels on the ear at harvest time. According to Fageria *et al*. (1997), maize is very sensitive to drought during the time of silk emergence. In general, maize needs at least 500-700 mm of well-distributed rainfall during the growing season (International Maize and Wheat Improvement Centre (CIMMYT), 2005) depending on the location. Hence the need to improve the water use efficiency through irrigation.

Cowpea production

Cowpea (*Vigna unguiculata* (L.) Walp) is an important grain legume in the dry savannah of the tropics covering 12.5 million hectares with annual production of about 3.million tons (FAO, 2005). It is a major staple food crop in sub-Saharan Africa, especially in the dry savannah regions of West Africa. The seeds are a major source of plant proteins and vitamins for man, feed for animals, and also a source of cash income (Thomas Jefferson Agricultural

Institute (TJAI), 2010). Nigeria is one of the world's largest producer of cowpea with an average production of 2.92 million tons followed by Niger with 1.1 million tons (FAO, 2012) while Ghana produces about 57,000 tons (FAOSTAT, 2017). Despite the dramatic increase in cowpea production in the sub-Saharan Africa, cowpea yields remain one of the lowest among all food legume crops, averaging at 450kg ha^{-1} in 2006-2008, which is half of the estimated yields in all other developing regions. Its yields are very low due to several constraints including poor soil and use of low yield variety of seeds as planting material (Ecocrop, 2009). Cowpea also plays an important role in providing soil nitrogen to cereal crops when grown in rotation, especially in areas where poor soil fertility is a problem. It does not require a high rate of nitrogen fertilization. Its roots have nodules in which soil bacteria called Rhizobia inhabit and help to fix nitrogen from the air into the soil in the form of nitrates (Sheahan, 2012).

Cowpea can be grown under rain fed conditions as well as by using irrigation or residual moisture along river or lake flood plains during the dry season. It performs well in agro ecological zones where the rainfall range is between 500 and 1200 mm per year (Madamba *et al*., 2006). Cowpea as a legume is a phosphorus loving crop; it require phosphorus for growth and seed development and most especially in nitrogen fixation up to 11-20 kg N ha^{-1} (Sanginga *et al*., 2000)

The demand for cowpea in Ghana is estimated to be 169,000 tons thereby giving a deficit of 112,000 tons, making importation inevitable (Langyintuo *et al.*, 2003). This has come about as a result of some major constraints to cowpea production in Ghana which are insect pests, diseases, drought and low soil fertility (International Crops Research Institute for the

Semi-Arid Tropics (ICRISAT), 2013). Cowpea can fix about 240 kg ha^{-1} of atmospheric nitrogen and make available about 60-70 kg ha^{-1} nitrogen for succeeding crops grown in rotation with it (Crops Research Institute (CRI), 2006; Aikins & Afuakwa, 2008).

The integration of biochar into cowpea cropping systems is expected to augment the beneficial effects of the crop rotation systems in the long term by improving nutrient availability, N recovery efficiency, and crop performance (Steiner *et al*., 2008; Major *et al*., 2010a). Because biochar can stay in soils for several decades without decomposing, its application could guarantee a long-term benefit for soil fertility improvement and crop production (Lehmann *et al*., 2006; Steiner *et al*., 2008). As mentioned before in this review, biochar use is new to most farmers in sub-Saharan Africa. This project aims to improve sustainability of cowpea in Ghana through the use of biochar and application of water through drip irrigation to augment the amount of water received from rains in a growing season. Also to sustainably use cowpea as a component crop in crop rotation and intercropping systems.

CHAPTER THREE

MATERIALS AND METHODS

Introduction

To achieve the objectives and to test the proposed null hypotheses, pot and field experiments were carried out. The detailed general methodologies used in these experiments are outlined in the following sub-sections, however, other materials and methods specific to experiments are outlined in each chapter.

Experimental site description

The experiments were carried out at the Alexander Carson Technology Centre (ACTC), University of Cape Coast, Cape Coast (latitude 05°7'47.07'' N and longitude 01°17'14.58'' W, from December, 2015 to April, 2018. The site is located in the coastal savannah agro-ecological zone which runs along the coast, widening toward the east of the country. Most farmers in this zone grow maize and often intercrop with cassava. Rainfall in this area ranges between 800 mm and 1000 mm annually. The annual rainfall of the experimental site is bimodally distributed. The major season starts from March to July, with maximum in June and minor season from September to November, with maximum in October. Between 60-70% of the total annual rain falls in the major season and 30-40% in the minor season. The mean monthly temperature is about 26.5 $^{\circ}$C. The soils of the area are sandy clay loam, belonging to Benya series, which is a member of the Edina-Benya-Udu compound association, developed under Sekondian material. They are classified as Ultisols (Typic Haplustult) (USDA Soil Taxonomy) and Haplic Acrisol (FAO/UNESCO). The soils are generally light in texture and also low in fertility leading to low crop productivity.

Experimental details

Test crops

The crops used in the pot and field experiments were those that are widely cultivated and used in Ghana. They present an ideal opportunity for the rural poor in developing countries like Ghana to increase their income sustainably.

Maize (*Zea mays*): The maize variety used was Obatanpa released in the year 1992. It takes about 55 days to silk and 105-110 days to mature. It has a plant height of 175 cm and an average grain yield of 5.5 t ha^{-1}. Maize tolerates dry period better during the first 3-4 weeks of growth (CRI, 2005).

Cowpea (*Vigna unguiculata*): The cowpea variety used was asontem. Asontem is adapted to all five major agroecological zones in Ghana and as such can flourish in these zones, but it is more popular in the coastal savannahs for both the major and minor seasons. Due to its adaptability and early maturity, '*Asontem'* is currently the most widely cultivated improved cowpea variety in Ghana occupying 44% of area planted to improved cowpea in the Guinea savannah zone (Abatania *et al.*, 2000 cited in Asafo-Adjei *et al.*, 2005).

Tomato (*Solanum lycopersicum*): The Pectomech variety used in this experiment is a recommended variety used in Ghana. Robinson and Kolavalli (2010) described the Pectomech variety as suitable for processing and preferred by consumers. Though it requires high management on the field, farmers prefer it because it is high yielding, depending on the locality in Ghana. For example in 2008/2009 season, Greater Accra (irrigated) recorded a yield of 8.8 t ha^{-1}, Brong Ahafo (rainfed) recorded a yield of 10.1 t ha^{-1} and Upper East (irrigated) recorded a yield of 13.8 t ha^{-1} (Clottey *et al*., 2009).

Experimental design and treatments

Pot and field experiments to test the effect of biochar and irrigation on the sustainability of some high value horticultural crops production were conducted during the 2015 to 2018 planting seasons. A completely randomised design with four corn cob biochar levels (control, 10, 20, 40 and 80 t ha^{-1}), two biochar particle sizes (>2 mm and 2-4 mm) and two irrigation levels (full irrigation (FI) and deficit irrigation (DI)) was used in the pot experiment. For the field experiments, there were four corn cob biochar levels (control, 10, 20 and 20 + phosphorus t ha^{-1} and control, 20, 40 and 40+phosphorus t ha^{-1} in 2016 and 2017, respectively) and three irrigation levels (FI, DI and no irrigation (DI)) arranged in a split plot design and replicated four times. Irrigation regimes were the main plots and biochar as sub-plots. However, the irrigation levels for the tomato experiments were two (FI and DI).

Experimental field layout

The total experimental plot size was 106.2 m × 17.4 m (1847.88 m^2). There were 80 plots each measuring 3 m × 6 m (18 m^2). The field layout is shown in Figure 3.1.

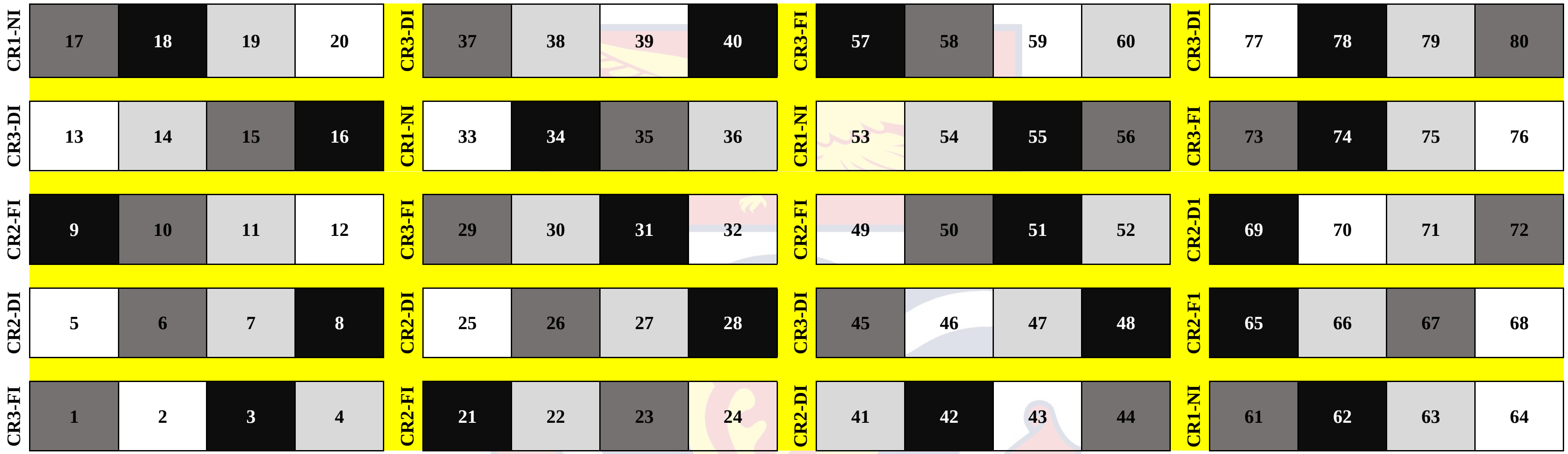

Figure 3.1: Field experiment layout showing the main and sub-plots

Legend

No Biochar
20 t/ha biochar
40 t/ha biochar
40 t/ha biochar + P
Pathways

Cropping history of experimental field

The land had been fallowed for about 10 years and weeds like *Panicum maximum, Sida acuta, Mimosa peduca, Centrosema pubescens, Ageratum conizoides, Cyperus rotundus, were* growing on it. After the land was ploughed and harrowed, maize was planted on it to homogenize the field for the subsequent experiments.

Land preparation

The experimental field was cleared of all weeds, ploughed and harrowed twice to achieve fine tilth followed by the removal of stubble and weeds. The field was laid out as per the design and treatments which were four blocks each having 20 plots, hence 80 plots in all. The plots were demarcated and raised to 30 cm above the natural soil surface (Figure 3.2).

Figure 3.2: Field layout

Biochar production and application

Biochar used in all experiments was produced from corn cobs. It was pyrolysed at 600°C at the Soil Research Institute, Kumasi. The charred corn cobs were milled and sieved to particle size of < 2 mm. Before application the biochar was slightly moistened to prevent drift after application. It was applied to the soil, first by spreading the calculated amounts of biochar evenly on the soil surface and then thoroughly incorporated into the top 20 cm depth of the soil using a hoe (Figure 3.3). The required amount of biochar to be applied per treatment was divided into 4 and applied in batches, thus, four times in four seasons (Table 3.1). Biochar, as per treatment details, was incorporated in the soil 14 days prior to sowing and/or transplanting.

Table 3.1: Rates of biochar to be applied per plot per season

Rate of Biochar (t ha^{-1})	Rate of biochar (%)	Amount of biochar applied per plot (kg)	No. of plots	Total biochar amount (kg)	Amount of biochar (t)
0	0	0	20	0	0
20	0.685	9	20	180	0.18
40	1.37	18	20	360	0.36
40 + P	1.37	18	20	360	0.36
				Total	**0.9**

Triple supper phosphate (TSP) was used and the amount needed for each plot was calculated and added to the biochar by dissolving the P in water. The biochar was soaked and thoroughly mixed with the P solution. After six days of incubation it was then dried, weighed and then applied to their respective plots.

Figure 3.3: Incorporating biochar into the top 20 cm depth of the soil

The corn cob biochar and soil used in the experiments were analyzed by Wessling Hungary Ltd., Budapest, in 2015. The physicochemical characteristics of the biochar and soil are shown in Tables 3.2 and 3.3 respectively.

Table 3.2: Physicochemical characteristics of the corn cob biochar used

Component	Results	Limit value
Dry matter	85.35%	
Organic matter (loss on ignition)	61.50%	
pH	10.2	
Ammonium	3 mg kg^{-1}	
Nitrate	120 mg kg^{-1}	
Total carbon	38.80%	
Total nitrogen	0.90%	
Calcium	8690 mg kg^{-1} 1.22% CaO	
Cadmium	<1 mg kg^{-1}	1.5 mg kg^{-1}
Chromium	14 mg kg^{-1}	100 mg kg^{-1}
Copper	9 mg kg^{-1}	100 mg kg^{-1}
Iron	3920 mg kg^{-1}	
Mercury	<1 mg kg^{-1}	
Potassium	31800 mg kg^{-1} 3.83% K_2O	
Magnesium	4510 mg kg^{-1} 0.75% mg kg^{-1}	
Manganese	1250 mg kg^{-1}	
Sodium	2160 mg kg^{-1} 0.29% Na_2O	
Nickel	7 mg kg^{-1}	50 mg kg^{-1}
Phosphorus	3150 mg kg^{-1} 0.72% P_2O_5	
Lead	3 mg kg^{-1}	120 mg kg^{-1}
Sulphur	874 mg kg^{-1}	
Selenium	< 1 mg kg^{-1}	
Zinc	73 mg kg^{-1}	400 mg kg^{-1}

Table 3.3: Physicochemical characteristics of the soil used

Component	Unit	Value
pH_H_2O		6.12
Electrical conductivity	mS cm^{-1}	0.20
Phosphorus	mg $100g^{-1}$	<0.4
Potassium	mg $100g^{-1}$	11.90
Magnesium	mg $100g^{-1}$	9.30
Total nitrogen	%	0.07
Organic Matter	%	1.60
Clay (<0.002 mm)	%	17.33
Silt (0.002-0.02 mm)	%	8.63
Fine Sand (0.02-0.2 mm)	%	57.33
Coarse Sand (0.02-0.2 mm)	%	15.00

Drip irrigation kits installation and management

The irrigation scheme used for the experiments was FI, DI and NI. All the three irrigation regimes were tried in the major season but only two of the regimes, FI and DI, were practiced in the dry season. Netafim Uniram® drip lines with 16 mm diameter and a distance of 30 cm between emitters were used. The installation was done at 50 cm distance between drip lines. The lines have a discharge rate of 1 L per hour. Irrigation water was through the drip lines by gravity from two 10,000 litres water reservoirs (Figure 3.4). Treated tap water was used.

Figure 3.4: Irrigation water applied by gravity from water reservoirs

Soil water content measurement

Moisture content of the field was based on the field capacity of the soil. Moisture content was initially measured to determine the field capacity of the various plots before sowing or transplanting of crops. Two Time Domain Refractometer (TDR) probes of 0.8 m in length was inserted in each plot. A transmission cable (4.5 m in length) was connected to the probes. Soil water content was then measured by connecting the transmission cable to the TDR central processing unit. The necessary data (cable and TDR probe length) needed for the determination of the amount of moisture in the soil were inputted in the TDR data logger. The displayed volumetric soil water content was recorded. The volumetric soil water content measured was then converted to depth of water in millimetres by dividing the volumetric water content value by the area covered by probes in the soil. After sowing or transplanting, moisture content was measured every other day to determine the soil water depletion level for irrigation scheduling.

Irrigation scheduling

Irrigation scheduling was based on the methodologies of the FAO 56 publication (Allen *et al.*, 1998). For the full irrigation (FI) treatment, irrigation was initiated when the crop has depleted a fraction (p) of the total available soil water (TAW) in the root zone thus the readily available soil water (RAW) in the root zone was set as p x TAW. p is defined as average fraction of TAW that can be depleted from the root zone before drought stress occurs. For the deficit irrigation (DI) treatment, pdi was set to 1.4 × p such that RAW = 1.4 × p × TAW. After an initial plant establishment period of 20 days, where crops were irrigated daily, irrigation according to the schedules (FI, DI, and NI) was initiated (Allen *et al.*, 1998).

TAW was calculated as:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r$$

where θ_{FC} is the soil water content at field capacity (m^3 m^{-3}), θ_{WP} is the soil water content at wilting point (m^3 m^{-3}), Z_r is the rooting depth (m) as indicated by Allen *et al*. (1998). However, since the TDR-probes are only 0.80 m long, Z_r was not estimated as more than 0.80 m.

Soil moisture content was monitored by manual time domain reflectometry (TDR) measurements on probes that were installed to a depth of 80 cm in the soil in three replicates (60 plots) of the treatments once or twice a week depending on the environmental conditions before irrigation was initiated (Plauborg *et al.*, 2005). The measurement of soil moisture content enabled the determination of moisture depletions within the root zone and subsequent calculation of actual crop evapotranspiration (ET_a). Actual crop evapotranspiration was calculated using the following equation:

$$ET_a = (\theta_{i-1} - \theta_i) + \mathrm{I} + \mathrm{P} - \mathrm{D}$$

where θ is the volumetric water content within 0–80 cm depth (mm) of the soil, i is day of TDR measurements, i-1 is previous time of TDR measurements, I is irrigation amount (mm), P is effective precipitation (mm) and D is drainage (mm).

Time domain reflectometry output is volumetric water content (%). To convert volumetric water content (%) to mm of soil water, the volumetric water content was multiplied by the length of the probe in decimetre. It was noted that irrespective of the depletion level in the deficit irrigation treatments, the length of the drying cycle should be the same for treatments with and without biochar to reveal the beneficial effect. Therefore the DI treatment was defined as irrigation of both plus biochar and minus biochar when the deficit has reached 1.4 × p × TAW in the minus biochar plots. The FI treatment was defined as irrigation of both plus biochar and minus biochar plots when the deficit has reached p × TAW in the minus biochar plots. The idea was just to have some drought stress that can show the beneficial effect of biochar addition if any. The drip irrigation kits (Netafim Uniram ®) were installed on plots to be irrigated as shown in Figure 3.5.

Figure 3.5: Installation of drip irrigation kits on the experimental plots. (**A**): Fixing of sub-main line, (**B**): flushing valve connected to the sub-main line and flushing manifold, (**C**): connecting dripper lines to the flushing manifold and (**D**): installed drip irrigation kits connected to a filtration unit.

Agronomic practices

Nursery

After preparing nursery beds of size 1 m × 2 m, tomato and lettuce were nursed to synchronize the planting dates. Nursery beds were raised close to the experimental field and seeds were sown in drills created on nursery beds. After germination, all the necessary nursery practices such as pricking out, thinning out, hardening off, weeding and watering were done to obtain healthy seedlings to be transplanted to the field. Seedlings were transplanted after four weeks of establishment at the nursery.

Planting and transplanting

The method of planting depended on the crops used in each experiment. Maize, cowpea and okra were sown at stake at 2 seeds per hill and thinned to one plant per hill a week after emergence. Planting depth ranged from 3-5 cm. Okra seeds was primed overnight to ease germination. After 4 weeks at the nursery, lettuce and tomato seedlings were transplanted to the experimental plots.

Fertilizer application

The soil used in the field experiments was low in organic carbon (<1.5%), total nitrogen (<0.2 %), potassium (<100 mg kg^{-1}) and phosphorus (<10 ppm). The inherent soil fertility was low. Fertilizers were applied according to the fertilizer requirements of the crop. Nitrogen, potassium and phosphorus fertilizers were applied based on the crop's nutrient requirements at two growth stages of the crop, early growing stages and vegetative stages (Norman, 1992). Band placement was used to apply the fertilizers.

Weeding

In order to ensure a clean experimental field and most importantly to prevent the invasion of pest and diseases, hand weeding was done first at two weeks after planting and subsequently when necessary.

Data collection

From each plot, randomly selected plants were tagged and used as sample plants for growth data collection. Observations were made weekly or biweekly depending on the crop and data to be collected starting from one week after planting and continued until termination of each of the experiments. Data were collected based on the objectives of each experiment. The following indicators of plant growth, development, yield and quality of the test crops as affected by the applied treatments were measured. The following sections describe the general parameters measured in the experiments.

Plant height

Plant height of tested crops was measured with a meter rule from base of the shoot at the soil surface to the tip of the apical meristem of the plant to be measured. This was done from two weeks after planting till flower initiation. Average plant height was expressed in centimetres.

Number of leaves

The number of fully developed leaves were counted starting from two weeks after sowing or transplanting to flower initiation.

Leaf area

The leaf area was measured from tagged plants by using a flexible tape measure to measure leaf length and width which was then multiplied by a correction factor of the tested crop under investigation.

Stem girth

Stem diameter was measured using a pair of Vernier callipers at 5 cm above the collar at 2 weeks interval starting from 2 weeks after planting or transplanting till flower initiation.

Number of days to 50% flowering

The number of days to 50% flowering was monitored and calculated. This was determined when about 50% of the plants had flowered.

Chlorophyll content Index

Chlorophyll content meter (CCM-200 plus, Apogee® Instruments Inc., USA) was used to measure the amount of chlorophyll present in the leaves as affected by the applied treatments. It was measured two weeks after planting and discontinued after 50% flower initiation.

Leaf area index (LAI)

The LAI was calculated by dividing the measured leaf area per crop by the land area occupied by the crop (Sestak *et al.*, 1971). Leaf area was measured at 15, 30, 45 and 60 days after planting.

$$Leaf\ Area\ Index = \frac{Leaf\ Area}{Land\ Area}$$

Crop growth rate (CGR)

Crop growth rate is the rate of dry matter production per unit ground area per unit time (Watson, 1952). It was calculated by using the following formula and expressed in g m^{-2} day^{-1}. Crop growth rate was measured at 15, 30, 45 and/or 60 days after planting depending on the crop.

$$CGR = \frac{W2 - W1}{A(t2 - t1)}$$

where,

W1 = Dry weight of the plant (g m^{-2}) at time t1

W2 = Dry weight of the plant (g m^{-2}) at time t2

t2-t1 = Time interval in days

A = Unit land area

Statistical analysis

The data collected was subjected to statistical analysis using GenStat version 12. The effect of biochar and irrigation was determined by two way analysis of variance (ANOVA) and the means were separated using the least significant difference (LSD) method. Correlation analysis was performed where necessary to examine degree of associations among parameters measured. *P*-values of less than or equal to 0.05 indicates significant statistical difference between treatments.

CHAPTER FOUR

EFFECT OF CORN COB BIOCHAR PARTICLE SIZE, RATE OF APPLICATION AND IRRIGATION REGIMES ON THE GROWTH AND DEVELOPMENT OF POT GROWN MAIZE IN THE COASTAL SAVANNAH ZONE OF GHANA

Introduction

There is a steady rise in global food insecurity due to unstainable food, feed and fibre production compared with increasing population. Currently, actual crop yields are less than 10% of potential yields in low-input agricultural production systems characteristic of many developing countries (Lynch & Brown, 2012). To be able to feed the estimated 9 billion people in the world by 2050, it has been estimated that global agricultural productivity must increase by 70%, or 100% in the case of developing countries (Tilman *et al*., 2011; Fischer, Nachtergaele, Prieler, Teixeria, Toth, van Velthuizan, Verelst, & Winerg, 2012; Alexandratos & Bruinsma, 2012).

This productivity target would be met if the challenges facing crop production could be tackled in a sustainable manner. Crop production requires various inputs, of which nutrients (e.g., nitrogen, phosphorus, and potassium) and water are crucial. Low soil fertility and limited water supply are the primary yield constraints for smallholder farmers in tropical countries who have limited access to fertilizers and irrigation (Lynch & Brown, 2012). The problem is further aggravated by increasing soil nutrient depletion through deforestation, desertification, erosion, soil and water pollution (Fischer *et al*., 2012), as well as, soil nutrient depletion through harvesting of crops.

Attempts to achieve rapid increase in food production in many African countries, including Ghana, have basically relied on the expansion of the area of land under cultivation, but cropland expansion is unsustainable and has negative impact on biodiversity and ecosystem services (Nelson, Rosegrant, Palozzo, Gray, Ingersoll, Robertson, & You, 2010). With or without increasing the land area for cultivation, it is clear that the soil is more vulnerable than is generally thought. Yet the soil remains the very basis of human existence and the foundation of our food chain. Soils of tropical Africa have inherently low soil fertilities under extreme weather conditions. This is because they have been exposed to long periods of weathering which results in highly depleted soils with low organic matter, low cation exchange capacities.

Biochar is a pure carbon base product obtained from the pyrolysis of organic materials (Lehman & Joseph 2009; Lehman *et al*., 2011). Application of biochar as agricultural soil amendment has been shown to positively alter soil's physical (Laird *et al*., 2010; Lehmann *et al*., 2011; Mukherjee & Lal, 2013), hydrological, chemical (Major *et al*., 2009; Sohi *et al*., 2010; Atkinson *et al*., 2010; Deal *et al*., 2012; Liu *et al*., 2012) and biological properties (Saito & Muramoto, 2002; Warnock *et al*., 2007). The agricultural sector directly contributes about 10% to 12% of the total anthropogenic greenhouse gas (GHG) emissions (Smith *et al*., 2014) but biochar reduces the amount of theses greenhouse gasses by sequestering them into the soil (Molina *et al*., 2009; Woolf *et al*., 2010). This indicates that amending soil with biochar is an approach to mitigate climate change (Woolf *et al*., 2010). The overall fertility, water holding capacity and soil biotic activity is greatly improved by biochar application, thereby increasing crop growth and subsequently yields (Sohi *et al*., 2010; Lehman *et al*., 2011). Biochar application may increase or decrease the pH of the soil and this depends on the feedstock used (Laird *et al*., 2010). When biochar increase pH especially in acid soils (van Zwieten *et al*., 2010) it leads to improved nutrient retention through cation adsorption (Liang *et al*., 2006). Biochar obtained from crop residues such as rice husk and corn cob have high mineral ash content and high in pH and therefore, increase the pH of soils into which they are applied. For instance, Cheng *et al*. (2006) reported an increase of pH from 6.7 to 8.1 in corn stover biochar over the course of one year incubation. Biochar application has also been shown to greatly increase the CEC of soils (Cheng *et al*., 2008; Nguyen *et al*., 2010) improving nutrient availability and uptake by plants. Application of biochar has also been shown to supply high levels of P for optimum plant growth (Sohi *et al*., 2010). Another critically important characteristic of biochar is the increased water holding capacity of soils making water available for use by plants, hence increased plant growth (Dugan *et al*., 2010; Mukherjee & Lal, 2013; Yu *et al*., 2013) and yield. This is very critical especially in tropical regions where water shortage can be experienced during the growing season (Akhtar *et al*., 2014). Biochar is also known to enhance soil nutrient availability (Glaser *et al*., 2002; Liang *et al*., 2006; Karhu *et al*., 2011).

When biochar is to be used to remediate soil fertility, an important area to look at is the rate of application and particle size of the biochar before its application. It is known that the rate and particle size of biochar has effect on the soil and hence the crops (Liu *et al*., 2017). Biochar's particle size, shape, and internal structure likely play important roles in controlling soil water storage because they alter soil pore characteristics. For instance, biochar has pores (intrapores), which may provide additional space for water storage beyond the pore space between biochar particles (interpores) (Masiello *et al*., 2015). The addition of fine biochar particles may increase soil porosity (Boadu, 2000) and over time the applied biochar will degrade into silt-sized particles changing the porosity and saturated hydraulic conductivity of the amended soil (Brodowski *et al*., 2007). Though the ideal biochar particle sizes to improve soil moisture retention have not been determined (International Biochar Initiative (IBI), 2010), Lehman *et al*. (2009) suggested 2 mm biochar particle size as the most suitable for application to agricultural soils. The rate of biochar applied to agricultural soils could influence the soil's physicochemical properties and hence crop productivity. The recommended application rates of biochar as a soil amendment varies based on soil type and crops. It is also dependent on the type of feedstock used for the production of the biochar. Lehmann *et al*. (2006) noted that crops responded positively to biochar application rates up to 55 t ha^{-1}, showing growth reductions only at very high applications. In an experiment where the equivalent of 165 t ha^{-1} of biochar was applied to a poor soil in a pot experiment (Rondon *et al*., 2007), yields decreased to the level of the control. Biederman and Harpole (2013) also confirm instances of decreasing yield due to a high biochar application rate. Kammann *et al*. (2011) also found that quinoa growth was retarded when biochar was applied at the rate of 100–200 t ha^{-1}.

The present study therefore seeks to determine the influence of the application rate of corn cob biochar, its particle sizes (<2 mm and 2-4 mm) in combination with two irrigation regimes (deficit and full) on the growth of maize. This was a preliminary experiment to provide further insight into the selection of appropriate rate of biochar, the particle size and proper irrigation scheduling to be applied in subsequent field experiments. In this experiment, the validity of the hypothesis that biochar particle size and rate of application with irrigation regimes will not enhance growth of maize in comparison to the soils with no biochar amendment (controls) was tested.

Materials and Methods

Experimental site, soil and biochar description

The study was carried out in 2015 (December) and repeated in 2016 (March) at the Alexander Carson Technology Centre near the Teaching and Research Farm of the University of Cape Coast (latitude 05°7'47.07'' N and longitude 01°17'14.58'' W. The Cape Coast metropolis has a bimodal rainfall pattern, the major season (April to July) and the minor season (August to November). The mean monthly temperature of about 26.5^{o}C. The soil used in filling the pots were characterized for its physical and chemical properties at the Department of Agro-ecology, Aarhus University Denmark before the commencement of the study. The soil used in the experiment was sandy loam, made up of about 72.3% sand (57.3% fine sand and 15.0% coarse sand) (Table 3.6). Inherently the nutrient content was low with total nitrogen and phosphorus 0.073% and >0.4 mg/100g respectively. The pH of 6.1 was slightly acidic but good for most vegetable crop production. The electrical conductivity (EC) of the soil was 0.20 mS cm^{-1}. The corn cob biochar used was pyrolysed at 600°C at Soil Research Institute (SRI), Kumasi, Ghana. The pH of the biochar was 10.2 with total carbon of 38.8%. Total N and P was 0.9% and 3150 mg kg^{-1} respectively (Table 3.5).

Experimental procedure

The experiment was conducted in polyvinyl chloride (PVC) pipes with a diameter of 25 cm and 75 cm in height. The experiment was set up under a shed covered with a transparent plastic roofing to prevent rain water from entering the set up and also for easy access of crops to sunlight (Figure 4.1).

Figure 4.1: Experimental set up (**A)**: PVC pipes used as pots ready to be filled with soil, **B**: Pots filled with soil and maize planted (about 14 DAP), **C**: Maize plants about 28 DAP and **D**: Maize plants ready to be harvested for biomass yield determination.

Filling of pots

The pots were filled with representative soil samples obtained from 0-20 cm depth as top soil and 20-50 cm depth as sub-soil from soil to be used for the successive field experiments. The soil was then sieved through a 20 mm mesh screen to get rid of non-soil materials. The first 50 cm from the base of the pots was filled with the subsoil and 20 cm was filled with the top soil leaving a head space of 5 cm. The topsoil was then mixed with the corn cob biochar at different application rates and particle sizes according to the experimental treatments. The soil was packed in the pot in a way to obtain the accurate bulk density of the field where the soil was taken. The base of the pots were lined with filter paper and covered with a net and a wire gauze to hold the soil in the pots.

Soil moisture content determination

Soil moisture content was measured using time domain reflectometer (TDR) with two probes of 65 cm in length placed near the centre of the pots whiles taking into account the possible effect of biochar on the calibration curve (Figure 4.2). The pots were slightly overwatered so that gravitational drainage takes place. After adding water, the pots were covered with plastic sheets to prevent evaporation. Time domain reflectometry measurements were taken after 24, 48, 72 and 96 hours until the drainage had virtually stopped. After planting, soil water deficit was measured using the TDR every other day.

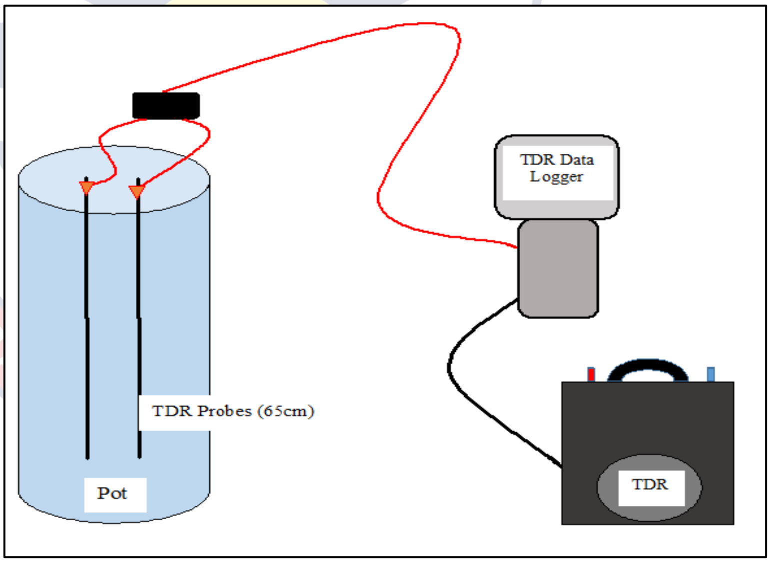

Figure 4.2: An illustration of a pot with TDR probes inserted and connected to the TDR data logger for the measurement of moisture content in the pots (Image source: Kusi Amoah, 2018)

Biochar and fertilizer application

After sieving the biochar to the required particle sizes, the rate of biochar to be applied per pot was mixed with the amount of soil within the top 20 cm depth of the pot. Nitrogen (urea) was applied to all the pots at a rate of 150 kg

ha^{-1} and potassium at a rate of 90 kg ha^{-1}. Phosphorus was applied at a rate of 60 kg ha^{-1}. Based on the treatments some of the phosphorus were mixed with the biochar before application, while others were applied later after planting. The fertilizer was mixed evenly within the first 10-20cm depth of the soil. One third of the nutrients were basally applied to stimulate early growth and the remaining two-thirds was applied as side dressing when the plants were at about 40 cm high, the period when the plant's demand for fertilizer is high. Amount of fertilizer applied per plot is shown in Table 4.1.

Table 4.1: Fertilizer application rates

Fertilizer	Nutrient	Rate (kg ha^{-1})	Amount of fertilizer/ pot (g)	Amount of nutrient per pot (g)
Urea	Nitrogen	150	3.75	1.725
Triple super phosphate (TSP)	Phosphorus	30	5.11	1.04
Muriate of Potash (MOP)	Potassium	90	2.08	1.035

Experimental design and treatments

The experiment was divided into two but was done simultaneously. The first was to determine the effect of corn cob biochar rates and particle sizes, and irrigation on the growth of maize. There were 16 treatments consisting of a combination of three factors, i.e. four biochar rates (0, 20, 40, and 80 t ha^{-1}), two biochar particle sizes (<2 mm, 2-4 mm) and two irrigation levels, FI and DI irrigation. There were 4 replications. The second was to determine the effect of fertilizer, especially phosphorus on the growth of maize. There were 8 treatments combination of three factors, i.e. 2 fertilizer levels (NPK and NP + P mixed with biochar before application to the soil, 2 biochar particle sizes and 2 levels of irrigation. They were replicated four times. The columns were arranged in a completely randomized design (CRD). The rates of biochar applied per pot is shown in Table 4.2.

Table 4.2: Rate of biochar applied per pot per treatment

Biochar rate (t ha^{-1})	Rates applied per pot (kg)
0	0
20	0.94
40	1.88
80	3.76

Planting and thinning out

Two seeds of 'Obatanpa' maize variety were planted per pot at an average depth of 3 cm. One week after emergence (WAE) the seedlings were thinned to one plant per pot. Seeds that could not germinate were refilled a week after planting.

Irrigation procedure

After 20 days of maize establishment, the plants were subjected to two, FI and DI, irrigation regimes. For the FI pots, irrigation was applied after the plants had used 30% of the moisture at field capacity in the pot according to TDR measurements. Irrigation was done for the DI pots by irrigating after the plants have used 70% of moisture at field capacity in the pot. Moisture readings were taken by the TDR instrument which was connected to two probes at 65 cm inserted at the centre of each pot. The result was used to compute to get the required moisture needed to get the soil back to field capacity.

Crop growth parameters assessed

Growth data was taken from each pot every week after planting (WAP) starting from the second week after planting. The following growth data were taken. Plant height was measured using a meter rule from the soil surface to the arch of the uppermost leaf. Number of fully opened leaves were counted on each plant. Leaf area was determined based on linear measurement. The length and widest breath of a leaf was measured and multiplied by a correction factor 0.75 (Kvet and Marshall, 1971). Area of the leaf was then determined by using the formula:

$$L_A = (L \times B) \times N$$

where L is the length of the leaf and B is the widest breadth of the leaf multiplied by a correction factor, N = 0.75.

At harvest, the fresh and dry above-ground biomass were determined by cutting the above-ground part of the plant from about 5 cm above the soil surface and the fresh weight taken. The dry weight was taken after drying the in an oven at 80°C for 48 hours.

Statistical analysis

The data was subjected to analysis of variance (ANOVA) and the means were separated using the Tukey's honest significant difference (HSD) method. GenStat edition 12.1 was used for the statistical analysis.

Results

Effect of biochar rates, biochar particle size and irrigation on maize leaf number

In 2015, biochar rates significantly influenced maize leaf number only in the 3rd and 7th WAP (Table 4.3a). Biochar particle size did not have a significant effect on leaf number. Generally, irrigation had no effect on leaf number. There was a significant biochar rate and particle size interaction effect on leaf number in the 4^{th} (P = 0.004) and 6^{th} (P = 0.004). WAP. There was a significant (P = 0.049) biochar rates, particle size and irrigation interaction effect on leaf number in the 3^{rd} WAP (Figure 4.3). A treatment combinations of biochar rates at 20 t ha^{-1} × <2 mm biochar particle size × FI increased the number of leaves significantly compared to the number of leaves produced from the control pots.

In 2016, there were no significant differences observed among the biochar rates, biochar particle size and irrigation applied (Table 4.3b). There were significant biochar rate × biochar particle size interaction effect on maize leaf number in the 6^{th} (P = 0.012) and 7^{th} (P = 0.009) WAP. There was significant (P = 0.014) BR × BS × I treatment interactions at the 3^{rd} WAP.

Table 4.3a: Effect of Biochar rate, biochar particle size and irrigation on maize leaf number in 2015

	Leaf number					
Treatment	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	2.0	3.0	5.0	6.0	6.0	7.0
20	2.0	4.0	5.0	5.0	7.0	9.0
40	2.0	4.0	5.0	6.0	7.0	9.0
80	2.0	4.0	5.0	6.0	7.0	9.0
P-value	0.262	<0.001	0.396	0.145	0.249	<0.001
S.E.D	0.21	0.27	0.28	0.40	0.46	0.45
Biochar particle size						
control	2.0	4.0	5.0	6.0	7.0	9.0
< 2 mm	2.0	4.0	5.0	6.0	7.0	9.0
2-4 mm	2.0	4.0	5.0	6.0	7.0	9.0
P-value	0.663	0.181	1.000	0.733	0.102	0.318
S.E.D	0.19	0.25	0.27	0.37	0.43	0.42
Irrigation						
DI	2.0	4.0	5.0	6.0	7.0	9.0
FI	2.0	4.0	5.0	6.0	7.0	9.0
P-value	0.577	0.281	0.685	0.771	0.049	0.025
S.E.D	0.13	0.16	0.18	0.24	0.28	0.28
BR*BS (*P*-value)	0.205	0.154	0.004	0.376	0.004	0.052
S.E.D	0.24	0.31	0.33	0.46	0.53	0.52
BR*I (*P*-value)	0.658	0.157	0.732	0.451	0.204	0.894
S.E.D	0.29	0.38	0.40	0.56	0.64	0.63
BS*I (*P*-value)	0.955	0.895	1.000	0.547	1.000	0.785
S.E.D	0.27	0.35	0.38	0.53	0.61	0.60
BR*BS*I (*P*-value)	0.038	0.049	0.592	0.243	0.739	0.203
S.E.D	0.34	0.43	0.46	0.65	0.74	0.73

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

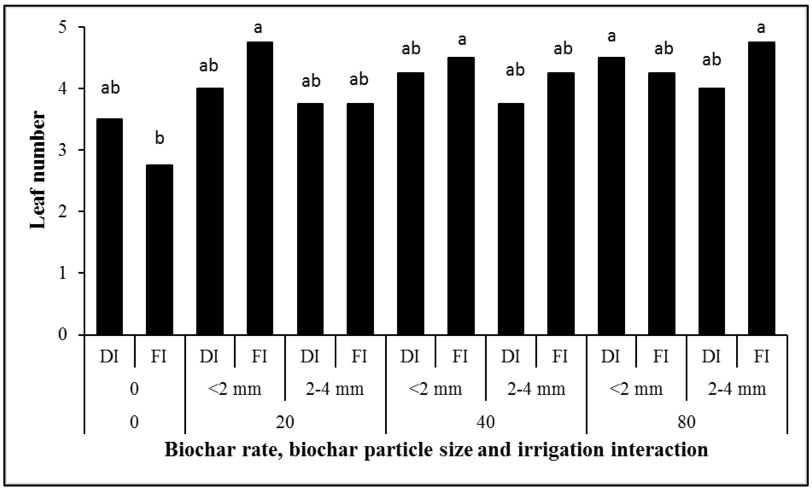

Figure. 4.3: Interaction effect of biochar rate, particle size and irrigation on maize leaf number at 3 weeks after planting in 2015. DI and FI are deficit and full irrigation regimes applied.

Table 4.3b: Effect of Biochar rate, biochar particle size and irrigation on maize plant height in 2016

Treatment	Leaf number					
	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	3.00	4.00	5.00	5.00	6.00	7.00
20	3.00	4.00	5.00	6.00	7.00	8.00
40	3.00	4.00	5.00	6.00	7.00	8.00
80	3.00	4.00	5.00	6.00	8.00	9.00
P-value	0.094	0.637	0.417	0.187	0.308	0.176
S.E.D	0.25	0.36	0.29	0.45	0.66	1.03
Biochar particle size						
control	3.00	4.00	5.00	6.00	7.00	8.00
< 2 mm	3.00	4.00	5.00	6.00	7.00	8.00
2-4 mm	3.00	4.00	5.00	6.00	7.00	8.00
P-value	0.605	0.949	0.071	0.705	0.851	0.861
S.E.D	0.234	0.363	0.273	0.421	0.621	0.966
Irrigation						
DI	3.00	4.00	5.00	6.00	7.00	9.00
FI	3.00	4.00	5.00	6.00	7.00	8.00
P-value	0.487	0.457	0.842	0.7	0.663	0.402
S.E.D	0.153	0.238	0.179	0.276	0.407	0.633
BR*BS (*P*-value)	0.351	0.106	0.277	0.077	0.012	0.009
S.E.D	0.286	0.445	0.334	0.516	0.761	1.183
BR*I (*P*-value)	0.619	0.973	0.623	0.768	0.95	0.836
S.E.D	0.350	0.545	0.409	0.632	0.932	1.449
BS*I (*P*-value)	0.605	0.811	0.811	0.705	0.982	0.998
S.E.D	0.330	0.514	0.386	0.596	0.879	1.366
BR*BS*I (*P*-value)	0.351	0.014	0.169	0.077	0.055	0.065
S.E.D	0.405	0.629	0.473	0.730	1.076	1.673

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Biochar and irrigation effect on plant height

The effect of biochar and irrigation on maize plant height is shown in Table 4.4a and Table 4.4b. The ANOVA showed that biochar at the rate of 80 t ha^{-1} increased maize plant height significantly (P = 0.033). Irrigation and biochar particle size did not show any significant effect on plant height in all weeks after planting (Table 4.4a).

Table 4.4a: Effect of Biochar rate, biochar particle size and irrigation on maize plant height in 2015

	Plant height (cm^2)					
Treatment	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	21.09	33.30	49.00	74.90	97.80	119.20
20	22.38	39.00	64.10	84.70	104.10	129.30
40	22.82	41.40	63.50	86.00	103.20	130.50
80	24.59	45.50	72.50	92.70	115.10	139.40
P-value	0.522	0.121	0.033	0.063	0.148	0.105
S.E.D	2.505	5.12	7.61	6.42	8.24	8.14
Biochar particle size						
Control	22.95	40.80	64.20	86.00	106.10	131.10
< 2 mm	24.21	44.70	67.50	89.20	108.70	133.10
2-4 mm	21.70	36.80	60.90	82.70	103.50	129.10
P-value	0.332	0.079	0.432	0.319	0.646	0.763
S.E.D	2.362	4.82	7.17	6.05	7.77	7.67
Irrigation						
DI	22.24	39.60	62.10	82.00	103.70	128.10
FI	23.67	41.90	66.20	89.90	108.50	134.10
P-value	0.361	0.469	0.391	0.053	0.356	0.24
S.E.D	1.546	3.16	4.70	3.96	5.08	5.02
BR*BS (*P*-value)	0.064	0.612	0.506	0.984	0.437	0.35
S.E.D	2.892	5.91	8.79	7.41	9.51	9.4
BR*I (*P*-value)	0.332	0.014	0.059	0.204	0.52	0.597
S.E.D	3.542	7.24	10.76	9.08	11.65	11.51
BS*I (*P*-value)	0.878	0.981	0.628	0.159	0.487	0.702
S.E.D	3.34	6.82	10.14	8.56	10.98	10.85
BR*BS*I (*P*-value)	0.201	0.026	0.068	0.08	0.074	0.026
S.E.D	4.09	8.36	12.42	10.48	13.45	13.29

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Figure 4.4 shows the significant interaction effect of biochar rates × biochar particle size × irrigation on maize plant height. A treatment combination of 20 t ha^{-1} biochar × <2 mm biochar particle size × FI had a significant effect on plant height compared to the plant height obtained from the control pots. However, it was not significantly different from the plant height obtained from pots treated with 80 t ha^{-1} biochar rate × <2 mm biochar particle size × DI.

In 2016, there was no significant effect of biochar rates, biochar particle sizes and irrigation on maize plant height. There were also no significant interaction effect between Biochar rates × irrigation, biochar particle size × irrigation on plant height. All the treatments that showed a significant effect on plant height in the ANOVA did not show significant difference in the multiple comparisons (Table 4.4b).

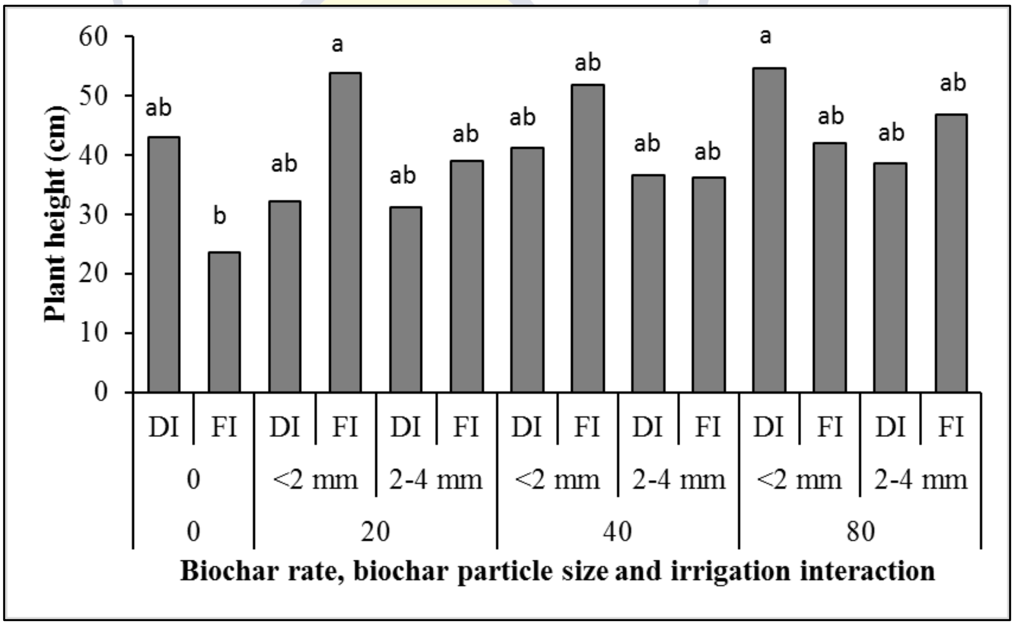

Figure 4.4: Interaction effect of biochar rate, particle size and irrigation on maize plant height at 3 weeks after planting in 2015.

Table 4.4b: Effect of Biochar rate, biochar particle size and irrigation on maize plant height in 2016

	Plant height (cm)					
Treatment	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	20.75	30.90	41.20	57.90	75.80	96.40
20	21.09	33.50	46.60	64.50	89.60	122.30
40	19.47	30.20	45.10	62.30	84.20	109.60
80	24.19	35.90	50.80	69.90	96.90	132.30
P-value	0.101	0.187	0.316	0.317	0.177	0.142
S.E.D	2.308	3.370	5.310	6.800	9.990	16.600
Biochar particle size						
control	21.46	32.90	46.60	64.50	88.20	117.80
< 2 mm	22.4	33.50	47.90	66.30	92.60	126.90
2-4 mm	20.53	32.30	45.30	62.60	83.70	108.80
P-value	0.482	0.874	0.754	0.712	0.422	0.275
S.E.D	2.176	3.180	5.000	6.410	9.420	15.650
Irrigation						
DI	20.96	32.30	46.30	62.90	86.40	114.10
FI	21.96	33.50	46.90	66.00	89.90	121.60
P-value	0.487	0.574	0.845	0.474	0.577	0.465
S.E.D	1.425	2.08	3.27	4.2	6.17	10.25
BR*BS (*P*-value)	0.066	0.024	0.194	0.096	0.025	0.041
S.E.D	2.666	3.890	6.130	7.850	11.530	19.170
BR*I (*P*-value)	0.202	0.468	0.905	0.856	0.838	0.816
S.E.D	3.265	4.760	7.500	9.620	14.130	23.480
BS*I (*P*-value)	0.641	0.500	0.478	0.77	0.823	0.824
S.E.D	3.078	4.490	7.070	9.070	13.320	22.130
BR*BS*I (*P*-value)	0.032	0.121	0.268	0.357	0.275	0.221
S.E.D	3.770	5.500	8.66	11.110	16.310	27.110

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on leaf area

The results of the main and interactive effect of biochar particle size, rate of application and irrigation obtained in 2015 is shown in Table 4.5a. The result showed that, generally, leaf area increased with increase in biochar rate although not significantly different from each other. Generally there were no significant main and interactive effect of biochar rates, particle size and irrigation on leaf area. However, the <2 mm and the FI treatments increased leaf area compared to the control and 2-4 mm and DI treatments.

Similar trends were recorded in 2016 (Table 4.5b) where an increase in biochar rates increased maize leaf area although not significantly different from each other. Similarly a decrease in biochar particle size increased the leaf area. Full irrigation increased leaf area of maize.

Table 4.5a: Effect of Biochar rate, biochar particle size and irrigation on maize leaf area in 2015

	Leaf area (cm^2)					
Treatment	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	34.32	76.58	166.74	368.27	648.77	748.68
20	38.23	101.58	219.80	434.7	680.34	785.12
40	40.28	102.43	262.67	467.11	756.57	873.08
80	45.89	102.09	261.58	482.18	768.17	886.47
P-value	0.568	0.164	0.020	0.052	0.185	0.185
S.E.D	8.84	12.47	33.26	41.86	67.83	78.28
Biochar particle size						
control	40.45	98.40	236.41	448.04	722.71	834.00
< 2 mm	42.78	102.29	253.49	480.32	753.97	870.08
2-4 mm	38.11	94.51	219.32	415.75	691.44	797.93
P-value	0.732	0.648	0.315	0.08	0.393	0.393
S.E.D	8.33	11.76	31.36	39.46	63.95	73.80
Irrigation						
DI	40.12	93.78	236.94	443.12	696.97	804.30
FI	40.77	103.01	235.87	452.96	748.44	863.70
P-value	0.907	0.237	0.959	0.705	0.226	0.226
S.E.D	5.46	7.70	20.53	25.84	41.87	48.31
BR*BS (*P*-value)	0.328	0.326	0.258	0.657	0.249	0.249
S.E.D	10.21	14.40	38.41	48.33	78.33	90.39
BR*I (*P*-value)	0.411	0.317	0.214	0.636	0.828	0.828
S.E.D	12.50	17.63	47.04	59.20	95.93	110.70
BS*I (*P*-value)	0.953	0.894	0.832	0.859	0.484	0.484
S.E.D	11.78	16.62	44.35	55.81	90.44	104.37
BR*BS*I (*P*-value)	0.135	0.338	0.397	0.065	0.454	0.454
S.E.D	14.43	20.36	54.31	68.35	110.77	127.83

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 4.5b: Effect of Biochar rate, biochar particle size and irrigation on maize leaf area in 2016

	Leaf area (cm^2)					
Treatment	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP
Biochar rate						
Control	80.20	139.50	245.60	331.00	527.00	729.00
20	79.80	161.80	276.80	347.60	585.00	810.00
40	82.90	165.10	254.20	357.30	573.00	793.00
80	92.20	174.90	282.30	384.90	630.00	872.00
P-value	0.625	0.397	0.336	0.332	0.057	0.057
S.E.D	12.59	20.47	24.93	31.96	37.80	52.30
Biochar particle size						
control	84.30	163.30	267.50	358.70	586.00	811.00
< 2 mm	91.40	177.90	289.80	383.90	585.00	810.00
2-4 mm	77.20	148.70	245.10	333.40	587.00	812.00
P-value	0.247	0.114	0.035	0.072	0.998	0.998
S.E.D	11.87	19.3	23.51	30.13	35.60	49.30
Irrigation						
DI	87.10	166.30	267.60	347.90	583.00	807.00
FI	81.50	160.30	267.40	369.40	589.00	815.00
P-value	0.468	0.641	0.990	0.280	0.800	0.800
S.E.D	7.77	12.64	15.39	19.72	23.30	32.30
BR*BS (*P*-value)	0.047	0.783	0.123	0.538	0.059	0.059
S.E.D	14.53	23.64	28.79	36.90	43.60	60.40
BR*I (*P*-value)	0.199	0.340	0.347	0.582	0.753	0.753
S.E.D	17.8	28.95	35.26	45.19	53.40	740
BS*I (*P*-value)	0.825	0.247	0.652	0.747	1.000	1.000
S.E.D	16.78	27.30	33.24	42.61	50.40	69.70
BR*BS*I (*P*-value)	0.382	0.306	0.022	0.045	0.468	0.468
S.E.D	20.55	33.43	40.71	52.18	61.70	85.40

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect biochar and irrigation on biomass yield

The results of the effect of biochar rates, particle size and irrigation obtained in 2015 on maize fresh and dry above ground dry matter yield is shown in Table 4.6a. There were significant effect of biochar rates on the fresh (*P* = 0.05) and dry (*P* = 0.002) above-ground biomass of maize. It was observed that the fresh and dry biomass increased with increased biochar rates. However, biochar particle size did not show any significant effect on biomass yield. The FI regime increased the amount of fresh and dry biomass yield compared to the DI regime. The interactive effect of biochar rates, biochar particle size and irrigation on dry biomass yield is shown in Figure 4.6b. Generally the treatment combinations with <2 mm biochar particle size increased the dry biomass compared to treatment combinations with 2-4 mm biochar particle size. The control pots treated with FI produced maize above-ground biomass that was significantly lower compared to the other treatment combinations (Figure 4.5).

The trend was different in 2016 (Table 4.6b) where no significant effect of the treatments on maize above-ground biomass was found with the exception of the interactive effect of biochar rate × biochar particle size × irrigation which showed significant (*P* = 0.016) effect on fresh biomass yield.

Table 4.6a: Effect of Biochar rate, biochar particle size and irrigation on maize biomass in 2015

Treatment	Fresh maize above-ground biomass (g plant^{-1})	Dry maize above-ground biomass (g plant^{-1})
Biochar rate		
Control	183.1	59.9
20	210.4	67.8
40	233.1	75.1
80	236.2	73.6
P-value	0.050	0.002
S.E.D	20.63	4.02
Biochar particle size		
Control	220.4	70.4
< 2 mm	229.0	72.1
2-4 mm	211.7	68.7
P-value	0.459	0.469
S.E.D	19.45	3.79
Irrigation		
DI	207.0b	66.2b
FI	233.8a	74.6a
P-value	0.041	0.002
S.E.D	12.73	2.48
BR*BS (*P*-value)	0.712	0.954
S.E.D	23.82	4.65
BR*I (*P*-value)	0.091	0.129
S.E.D	29.17	5.69
BS*I (*P*-value)	0.082	0.026
S.E.D	27.5	5.37
BR*BS*I (*P*-value)	0.016	0.005
S.E.D	33.68	6.57

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

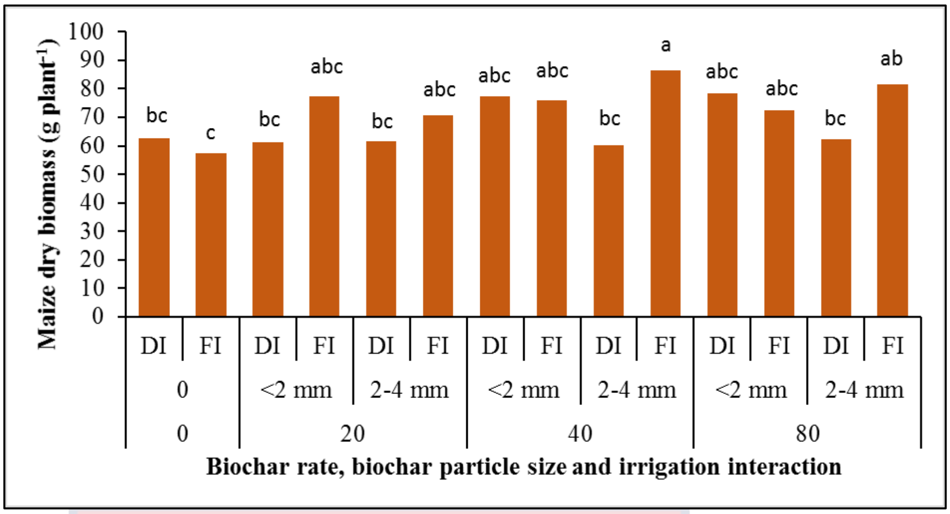

Figure 4.5: Biochar rate, particle size and irrigation interaction effect on maize dry biomass in 2015

Table 4.6b: Effect of Biochar rate, biochar particle size and irrigation on maize biomass in 2016

Treatment	Fresh maize above-ground biomass (g plant^{-1})	Dry maize above-ground biomass (g plant^{-1})
Biochar rate		
Control	245.00	53.80
20	275.00	60.40
40	264.00	57.40
80	336.00	65.60
P-value	0.392	0.481
S.E.D	61.80	8.31
Biochar particle size		
Control	285.00	60.10
< 2 mm	321.00	65.30
2-4 mm	248.00	54.90
P-value	0.220	0.182
S.E.D	58.30	7.84
Irrigation		
DI	291.00	60.20
FI	278.00	60.00
P-value	0.739	0.977
S.E.D	38.10	5.13
BR*BS (*P*-value)	0.177	0.212
S.E.D	71.40	9.60
BR*I (*P*-value)	0.434	0.316
S.E.D	87.40	11.76
BS*I (*P*-value)	0.668	0.289
S.E.D	82.40	11.09
BR*BS*I (*P*-value)	0.016	0.075
S.E.D	100.90	13.58

P: phosphorus, BR: biochar application rate, BS: biochar particle size, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Discussion

Plant height, leaf number, leaf area and above-ground biomass are important parameters in measuring crop growth. In both experiments in 2015 and 2016, the general observation was that an increase in the biochar application rate improved the measured parameters. For instance, though there was no significant difference in plant height and number of leaves among the treatments, it was observed that an increase in biochar increased plant height and number of leaves. Uzoma *et al.* (2011) reported similar results which indicated a significant increase in maize plant height and number of leaves with the addition of biochar. Biochar at a higher application rate is reported to have a positive and or negative impact on plant growth and development. Lehmann *et al.* (2006) indicated that crops respond positively to biochar additions up to 55 t ha^{-1}, showing growth reductions only at very high applications. Although 80 t ha^{-1} was used in this experiment, it did not show a negative impact on maize growth and development. Generally, the effect of biochar at the rate of 20, 40 and 80 t ha^{-1} on the measured parameters were not significantly different from each other. Generally, biochar application rate at 20 t ha^{-1} performed significantly better than the control for the parameters measured. This confirms the report that growth reaches it threshold even with much lower levels of biochar. For instance, Asai *et al.* (2009) confirmed that an application rate of 4 t ha^{-1} biochar performed better when compared with 8 and 16 t ha^{-1} of biochar. Interestingly, Lehmann *et al*. (2007) concluded that biochar at the rate of 50 MgC ha^{-1} was able to improve crop growth but may show growth reductions only at very high applications rates. Winsley, (2007) and Major, (2013) have also supported this assertion that even low rates of biochar application can significantly increase crop productivity. At a high rate of 80 t ha^{-1} there was no negative growth on maize in this experiment. However, 80 t ha^{-1} was not added to the treatments in the field experiment since its effect on maize growth was found to be significantly similar to 20 and 40 t ha^{-1}.

It must however be noted that growth and yield of a crop may differ in relation to the type of biochar feedstock, application rate, the type of soil and the climatic conditions. In this study, it was observed that application of corn cob biochar of <2 mm particle size improved the measured growth parameters. Biochar with <2 mm particle size was hence selected as the optimum particle size to be used in the subsequent field experiments. It was also generally observed that full irrigation improved crop growth compared to the deficit irrigation. Previous studies also found positive responses of maize and other cereals to fertilizers and biochar amendments (Asai *et al.*, 2009; Partey *et al.*, 2015; Zhang *et al.*, 2012), which are consistent with the observations made in this study. Interestingly, growth was improved when phosphorus was added to the biochar before its application, compared to when it was added in the form of NPK. This could be due to the fact that biochar adsorbed the phosphorus making it unavailable for the aluminium and ferrous oxides in the soil to fix (Chng, *et al*., 2014).

Conclusion

The study revealed that biochar and fertilizer influenced the growth of pot grown maize. The <2 mm particle size biochar was found to be the appropriate particle size of biochar for a better growth and development of maize. Phosphorus fertilizer added to biochar before application increased maize growth compared to when it was applied after sowing in the form of NPK.

CHAPTER FIVE

INFLUENCE OF BIOCHAR AMENDMENTS ON GROWTH AND YIELD OF MAIZE (*Zea mays*) UNDER DRIP IRRIGATION REGIMES IN A MAIZE-COWPEA INTERCROP

Introduction

Maize (*Zea mays*) is the world‘s third most important crop after rice and wheat (Ofori and Kyei-Baffour, 2006). In West Africa, maize is a major cereal crop accounting for a little over 20% of the domestic production in the sub-region (IITA, 2000) and it remains the most important food security crop for millions of rural households (Larson, Keijiro, Kei, Jonna, & Aliou, 2010). It is the most important cereal crop in Ghana and it is cultivated in all the agro-ecological zones (Fening, Ewusi-Mensah & Safo, 2011) and domestic demand for it is growing. Globally, average maize yield is about 4.9 t ha^{-1} (Edgerton, 2009). Nevertheless, maize yields in major growing areas in developing countries still lag behind the world average (Pixley, Banziger, Cordova, Dixon, Kanampiu, Srivastava, Waddington & Warburton, 2009). This is highly evident comparing maize yields in North America and sub Saharan Africa, which were 2.2 t ha^{-1} and 0.8 t ha^{-1} in 1961 and 7.3 t ha^{-1} and 1.4 t ha^{-1} in 2016, respectively. In 2016 United States of America produced 8.1 t ha^{-1} of maize, but, Ghana produced 1.8 t ha^{-1} (FAOSTAT, 2017). However, the potential for expanding maize production in sub-Saharan Africa is huge. It has been reported that there is a possibility of achieving yields of about 6 t ha^{-1} (MoFA, 2011).

There are various reasons why Ghana's maize production remains below the potential yield. Maize production in Ghana is largely rainfed and subsistence. With the insurgence of climate change, rainfall is currently erratic. Production is also threatened by practices, such as burning of bush, and improper use of modern technologies such as irrigation and agro-chemicals, including fertilizers. Most soils are inherently infertile and also prone to erosion (Oppong-Anane, 2006; MoFA, 2007).

For a sustainable maize production, biochar has been suggested to act as a soil conditioner enhancing plant growth by retaining water and nutrients, hence, improving soil physical and biological properties (Glaser *et al*., 2002; Lehmann *et al*., 2003). Because of it recalcitrant nature (Glaser *et al*., 2002) the benefits of biochar could be sustained to improve crop production.

Climate change has increased the periods of drought and reduced the amount of rainfall in the African continent, and hence increased food shortage problems. A technology that may contribute to efficient water management is drip irrigation. Drip irrigation is capable of applying small amounts of water precisely when and where it is needed and with a high degree of uniformity and frequency, hence it has proven to be an effective method for increased water use efficiency than other irrigation methods (Hanson *et al*., 1997). That notwithstanding, the degree of efficiency may be linked essentially to the regularity of irrigation. Regularity of irrigation affects soil water regime, plant root distribution around the emitter, amount of water uptake by roots and the amount of water percolation under the root zone (Assouline 2002, Wang *et al.*, 2005, El-Hendawy *et al.*, 2008). Generally, drip irrigation system uses water efficiently, provides precise water control, provides better control of saline water, and improves fertilization. It also saves time and labour, reduces disease problems and increase yield.

Intercropping has been practiced for a long time in the developing countries, including Central America, Asia and Africa (Altieri & Liebman, 1994; Bekunda & Woomer, 1996; Grossman & Qualles, 1993). The advantages of intercropping surpass the disadvantages. Intercropping minimise risk, uses available resources effectively, also use labour efficiently, crop productivity is increased, food security and erosion is controlled (Bekunda & Woomer, 1996; Owuor, Tenywa, Muwanga, Woomer, & Esele, 2002). It provides a good soil cover regulating soil temperature to a relatively low level. After the intercrop is harvested, decaying roots and fallen leaves provide nitrogen and other nutrients for the next crop. More importantly, legumes used as an intercrop enhance biological atmospheric nitrogen fixation (Li *et al*., 2009). When fertilizers are used in intercropping system they are more efficient because of the increased amount of humus and the different rooting systems of the crops and also the differences in the amount of nutrients uptake (Rahman *et al.*, 2006; Rukazambuga *et al.*, 2001; Sakala *et al*., 2000). Again, intercropping plays an important role in reducing the hunger gap as a result of stable yield and it is therefore by its nature a sustainable way of food production and a strategy for resource poor farmers.

It is against this background that objective of this chapter was set to determine the effect of intercropping, corn cob biochar and irrigation regimes on maize growth and yield in the coastal savannah zone of Ghana.

Materials and methods

Experimental design and field layout

The experiment was laid out in a split-plot design with four replications with irrigation regimes as the main plots and biochar levels as subplots. The net experimental plot size was 864 m^2 made up of 48 plots each measuring 3 m × 6 m (18 m^2). The detailed field layout is found in chapter three (Figure 3.1).

Experimental treatment

The experiment was conducted in June 16, 2016 to September 20, 2016 and repeated in July 5, 2017 to October 15, 2017. All treatments were made up of a combination of corn cob biochar with <2 mm particle size and irrigation regimes. There were four levels of biochar and three levels of irrigation. In 2016, biochar was applied at the rate of 0 (no biochar), 10, 20 and 20+P t ha^{-1} (where P is phosphorus mixed with biochar before application). The biochar rates applied in 2017 were increased to 0, 20, 40 and 40+P t ha^{-1}. The irrigation regimes used in these experiments were full (FI), deficit (DI) and no irrigation (NI).

Agronomic practices

Planting of maize and cowpea

Maize (Obatanpa) and cowpea (Asontem) seeds were purchased from an agricultural input shop (Tina Farmers' shop) in the Cape Coast Kotokoraba market. The seed were sown on June 16, 2016 and July 5, 2017. Sowing was done using a dibber to create holes and two seeds were placed per hole with a spacing of 50 cm × 30 cm. At 7 days after sowing (DAS) the maize plants were thinned out to one plant per stand. The same procedure was repeated in 2017. Cowpea was sown as an intercrop in between two rows of maize two weeks after sowing of maize. Cowpea seedlings were thinned out a week after sowing to maintain one plant per hill.

Pest and disease control

Pest and disease symptoms were monitored and controlled throughout the experiments using the recommended pesticides (organic and inorganic). In 2017 there was fall army worm (FAW) infestation at the vegetative stage of the maize growth. Recommended pesticides such as K-Optimal EC, Sumitox and Lambda Super were used to control the FAW. Neem leaf and mahogany bark extract were later used when the pesticides were not effective.

Fertilizer application on the experimental plots

Recommended rate of fertilizer for maize, 100 kg N ha^{-1}, 60 kg P ha^{-1} and 40 kg K ha^{-1} was applied at different stages of growth. Fifty percent (50 %) of the nitrogen and all the phosphorus and potassium were applied two weeks (14 days) after sowing. The remaining 50% nitrogen was applied six weeks after sowing. All fertilizers were banded. There was no fertilizer application for cowpea.

Data collection

Each experimental plot was divided into two sub plots, measuring (A) ($6m^2$) and (B) ($12m^2$). Plants in the sub plot (A) was sampled and tagged for data collection on destructive growth parameters. Six plants were tagged in the subplot (B) for non-destructive crop growth data to be collected. Yield data was also taken from the subplot (B).

Meteorological data

Standard meteorological data were obtained from an automatic weather station (Campbell Scientific, Logan, Utah) located at the experimental site at a distance of about 200 m away from the main plots. Data taken included daily maximum and minimum air temperatures, relative humidity and rainfall.

Plant shoot characteristics

Data taken on plant height, number of leaves, leaf area, leaf area index (LAI), stem girth (cm), number of days to 50% flowering, chlorophyll content index (CCI), and crop growth rate (CGR) are described in chapter three under data collection.

Above and below-ground biomass

The fresh and dry weights of maize shoot, were recorded at 14, 28, 42 and 56 days after planting (DAP). Two plants were randomly selected and harvested from each plot and their fresh weight was recorded. It was then dried in an oven at 80^{o}C to a constant weight and weighed again to determine dry weight. The above ground biomass (fresh and dry) was determined for cowpea at 60 DAP. Above ground biomass of maize and cowpea was reported in gram per plant. The below-ground biomass was taken after the roots were excavated by the shovelomics technique (Trachsel *et al*., 2011) at anthesis stage of the plant growth.

Yield parameters

Ear length and diameter

After harvest eight maize ears were randomly selected from each treatment and the length and diameter were measured from the base to the tip and at approximately the middle of the ear after harvest using a ruler and a pair of digital Vernier callipers respectively. Measured values were reported in centimetres.

Number of rows per ear and number of grains per row

Number of rows per ear and number of grains per ear were determined by counting the number of rows and the number of grains per row respectively, and the average for each plot was determined. The number of grains per ear was determined by multiplying the number of rows by the number of grains per row.

Thousand seed weight (TSW)

Grains from each treatment were composited and a thousand seeds counted and weighed and was then recorded in grams.

Grain, cob, stover and husk yield

Maize ears from plants in the plot area (12 m^2) were harvested and used for the determination of grain, cob and stover yield. Maize grains and cobs were weighed after shelling and drying to a moisture content of 12.5%. Ten plants were used to determine stover yield. Cowpea grains and husks were weighed and the grain yield was converted to kg ha^{-1}.

Data analysis

Data on all growth and yield parameters measured were subjected to analysis of variance (ANOVA) using the GenStat statistical package edition 12.1 (GenStat, 2007). Means were separated using the Tukey's HSD test at 5 % level of probability.

Results

Effect of biochar and irrigation on maize leaf number

Table 5.1a shows the results obtained for the effect of biochar application rates, irrigation regimes and their interactions on maize leaf number in the 2016 growing season. Biochar significantly affected the number of leaves. The general trend was that the control plots significantly produced low number of leaves. Biochar applied at the rate of 20+P t ha^{-1} produced significantly the highest number of leaves. At 28 DAP there were no significant effect of biochar on the number of leaves of maize. Irrigation regimes generally had a significant effect on the number of leaves. However, at 28 DAP irrigation had no significant impact on the number of leaves. The number of leaves produced on FI and DI plots were no significantly different from each other, however, they were significantly different from the number of from the control plots. Maize number of leaves had no biochar and irrigation interaction effect (Table 5.1a).

In the 2017 growing season (Table 5.1b), there were significant (P <0.001) effect of biochar on maize leaf number. The trends obtained in 2016 were similar to 2017 in the sense that the higher the amount of biochar, the higher the number of leaves. The effect of irrigation regimes on the number of leaves followed similar trends in 2016, that, FI and DI plots produced significantly more number of leaves compared to those produced from the control plots. The number of leaves did not have biochar and irrigation interaction effect from 14 DAP to 42 DAP, however, at 56 DAP biochar and irrigation had significant (P <0.001) interaction effect on maize leaf number.

Table 5.1a: Effect of biochar and irrigation on number of leaves (2016)

	Number of leaves			
Treatment	14	28	42	56
Biochar rate				
Control	4b*	6	9b	13b
10	4ab	6	9b	14ab
20	4a	6	10b	16a
20+P	4a	6	10a	15ab
S.E.D	0.133	0.148	0.205	0.995
P-value	0.018	0.017	<0.001	0.041
Irrigation regimes				
DI	4a	6	10a	17a
FI	4a	6	10a	116a
NI	4b	6	8b	10b
P-value	<0.001	0.079	0.004	0.002
S.E.D	0.072	0.282	0.538	1.093
B*I *(P-value)*	0.576	0.498	0.532	0.435
S.E.D	0.2115	0.360	0.620	1.85

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.1b: Effect of biochar and irrigation on number of leaves (2017)

	Number of leaves			
Treatment	14	28	42	56
Biochar rate				
Control	4b	6b	9c	11c
20	4ab	6b	9bc	11c
40	4a	6ab	10b	12b
40+P	4a	6a	10c	14a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.107	0.129	0.225	0.214
Irrigation regime				
DI	4a	6a	10a	12a
FI	4a	6a	10a	13a
NI	4b	5b	8b	10b
P-value	0.001	0.014	0.002	<0.001
S.E.D	0.092	0.226	0.477	0.305
B*I (*P*-value)	0.200	0.496	0.633	<0.001
S.E.D	0.185	0.297	0.584	0.442

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize plant height

The effect of irrigation and biochar on maize plant height are shown in Tables 5.2a (2016) and 5.2b (2017). From the 14 DAP to 42 DAP, biochar had a highly significant (*P* <0.001) impact on maize plant height. Biochar did not have a significant (*P* = 0.148) effect of plant height at 56 DAP. Generally, it was observed that plant height increased with an increase rate of biochar, with the tallest and the shortest plants emanating from plots treated with 20+P t ha^{-1} and the control plot respectively. Though the first 14 DAP did not show significant (*P* = 0.204) effect of irrigation on plant height, the 28 DAP to 56 DAP also showed a significant effect it. Generally, the height of the plants were significantly higher on the DI and FI irrigated plots compared to those from the no irrigated plots. There was no biochar and irrigation effect on maize plant height in the 2016 growing season (Table 5.2a).

Similar trends were realized in the 2017 growing season (Table 5.2b). There was a highly significant (*P* <0.001) effect of biochar on plant height. Irrigation regimes also had a significant effect on plant height. There was no significant biochar and irrigation interaction effect on plant height from 14 DAP to 42 DAP, however, there was a significant (*P* = 0.044) biochar and irrigation interaction effect on plant height at 56 DAP.

Table 5.2a: Biochar and irrigation effect on maize plant height (2016)

Treatment	Plant height (cm)			
	14	28	42	56
Biochar rate				
Control	22.94c*	44.9c	123.4b	196.8
10	24.14bc	47.25bc	131.9b	198.6
20	26.05ab	53.53ab	138.4ab	204.7
20+P	27.76a	59.03a	154.1a	223.3
P-value	<0.001	<0.001	<0.001	0.148
S.E.D	0.842	2.746	6.81	12.31
Irrigation regime				
DI	26.17	58.02a	162.8a	247.5a
FI	25.99	57.4a	166.7a	243.0a
NI	23.51	38.11b	81.3b	127.0b
P-value	0.204	0.002	<0.001	<0.001
S.E.D	1.452	3.428	11.34	13.62
B*I (*P*-value)	0.446	0.486	0.875	0.415
S.E.D	1.924	5.359	15.27	22.94

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.2b: Biochar and irrigation effect on maize plant height (2017)

Treatment	Plant height (cm)			
	14	28	42	56
Biochar rate				
Control	23.04c*	45.71c	108.9c	163.0c
20	24.9b	49.79bc	119.2bc	176.5bc
40	26.4b	54.15b	123.4ab	178.7b
40+P	28.69a	60.95a	135.7a	201.1a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.651	2.024	5.1	4.94
Irrigation regime				
DI	26.56a	59.18a	139.5a	207.5a
FI	27.4a	58.26a	141.9a	204.2a
NI	23.31b	40.51b	84.0b	127.8b
P-value	0.017	<0.001	<0.001	<0.001
S.E.D	1.032	2.285	5.44	4.73
B*I (*P*-value)	0.567	0.755	0.766	0.044
S.E.D	1.421	3.8	9.39	8.79

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize leaf chlorophyll content index

, Biochar significantly influenced the leaf chlorophyll content in all WAP in the 2016 season, except on the 28th DAP. Chlorophyll content varied considerably among the biochar application rates (Table 5.3a). Generally, plots that received 20+P t ha^{-1} biochar rate recorded the highest value of chlorophyll which differed significantly from those plots that received 20, 10 and 0 t ha^{-1} biochar rates. However, in most cases chlorophyll content obtained from plots amended with 20+P and 20 t ha^{-1} were similar. With the exception of the 56 DAP, irrigation did not have significant effect on chlorophyll content in maize leaves. At the 56 DAP, DI and FI treatments significantly increased the chlorophyll content compared to the NI treatment. There was no interaction effect of biochar and irrigation on chlorophyll content in the 2016 growing season (Table 5.3a).

During the 2017 season, biochar significantly influenced the amount of chlorophyll present in the maize leaves (Table 5.3b). Plots treated with 40+P t ha^{-1} biochar increased the chlorophyll content compared to the other biochar treatment applied. Irrigation had a significant effect on chlorophyll content. Deficit and full irrigations regimes had a significant increase in the amount of chlorophyll compared to the chlorophyll content from the plots with no irrigation. There was no biochar and irrigation interaction effect on the chlorophyll content at 14, 28 and 42 DAP except at 56 DAP (P = 0.004) (Table 5.3b).

Table 5.3a: Biochar and irrigation effect on chlorophyll content index (2016)

Treatment	Chlorophyll content index			
	14	28	42	56
Biochar rate				
Control	14.61b*	18.53	20.76b	20.99b
10	16.57ab	19.81	23.64b	25.57b
20	16.05ab	19.58	23.71b	27.53ab
20+P	18.25a	21.39	29.25a	33.55b
P-value	0.018	0.203	<0.001	0.001
S.E.D	0.75	0.98	1.37	2.55
Irrigation regime				
DI	16.83	20.32	24.94	30.99a
FI	17.56	20.49	25.68	31.45a
NI	14.72	18.66	22.4	18.29b
P-value	0.309	0.403	0.281	0.017
S.E.D	1.23	0.92	1.188	1.992
B*I (*P*-value)	0.121	0.243	0.462	0.712
S.E.D	1.67	1.7	2.247	3.926

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.3b: Biochar and irrigation effect on chlorophyll content index (2016)

Treatment	Chlorophyll content index			
	14	28	42	56
Biochar rate				
Control	14.73b*	18.86b	15.93b	18.11c
20	16.55b	20.89ab	19.00ab	21.53bc
40	17.69b	24.17a	22.57a	24.84b
40+P	21.82a	25.92a	22.93a	30.82a
P-value	<0.001	0.003	0.002	<0.001
S.E.D	1.168	1.848	1.842	1.846
Irrigation regime				
DI	18.73ab	22.18b	20.60ab	22.83b
FI	21.2a	25.31a	24.79a	32.56a
NI	13.17b	19.89b	14.92b	16.08b
P-value	0.044	0.004	0.039	0.002
S.E.D	2.485	0.969	2.893	2.663
B*I (*P*-value)	0.181	0.262	0.529	0.004
S.E.D	3.041	2.937	4	3.841

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize leaf area

In the 2016 growing season, biochar generally influenced maize leaf area significantly (Table 5.4a). The effect of biochar on maize leaf area was significant at the 14th DAP to the 42nd DAP except at the 56th DAP which showed no significant (P = 0.228) difference. The higher the biochar application rate the higher the leaf area obtained. For example, at 28 DAP plots treated with 20+P t ha^{-1} biochar had significantly higher leaf area (211.1 cm^2) compared to leaf area obtained from plots treated with 20 t ha^{-1} (186.2 cm^2) and plots with no biochar plots (148.9 cm^2). There was a significant effect of irrigation on maize leaf area of maize. The plots that were not irrigated had significantly lower leaf area compared to the leaf area obtained from plots treated with irrigation (DI and FI). However, there was no biochar and irrigation effect on leaf area (Table 5.4a).

The effect of biochar on leaf area was highly significant (P <0.001) in the 2017 growing season (Table 5.4b). Leaf area increased with increased biochar application rate with the higher leaf area obtained from plots treated with 40+P t ha^{-1} biochar compared to the leaf area obtained from 40 t ha^{-1}, 20 t ha^{-1} and control plots. There was a highly significant (P <0.001) effect of irrigation on maize leaf area. There was no significant difference between leaf area obtained from the DI and FI treated plots, however, there was a significant difference between leaf area from DI and FI compared to those from the no irrigation plots (Table 5.4b).

Table 5.4a: Effect of biochar and irrigation on leaf area (2016)

	Leaf area			
Treatment	14	28	42	56
Biochar rate				
Control	91.4	148.9b*	412.6b	545.1
10	103.3	164.4ab	437.5b	500.8
20	124.2	186.2ab	435.0b	513.4
20+P	136.0	211.1a	519.9a	550.4
P-value	<0.001	0.007	0.002	0.228
S.E.D	8.88	17.08	26.39	27.49
Irrigation regime				
DI	123.7a	201.2a	521.1a	622.9a
FI	133.2a	214.9a	548.9a	609.8a
NI	84.2b	116.8b	283.6b	349.6b
P-value	0.008	0.006	0.013	0.007
S.E.D	10.73	20.21	66.52	61.37
B*I (*P*-value)	0.881	0.79	0.414	0.248
S.E.D	17.1	32.63	77.4	73.93

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.4b: Effect of biochar and irrigation on leaf area (2017)

	Leaf area			
Treatment	14	28	42	56
Biochar rate				
Control	93.4b	168.5d	244.2c	356.8c
20	107.4b	193.3c	299.7b	433.9b
40	129.8a	223.8b	319.6b	451.9b
40+P	145.6a	252.1a	388.4a	529.6a
P-value	<.001	<.001	<.001	<.001
S.E.D	6.13	8.97	12.8	13.82
Irrigation regime				
DI	134a	247.4a	360.8a	515.1a
FI	145.5a	251.6a	385.2a	526.1a
NI	77.8b	129.3b	192.9b	287.3b
P-value	<.001	<.001	<.001	<.001
S.E.D	9.47	15.69	17.25	25.15
B*I (*P*-value)	0.663	0.679	0.872	0.739
S.E.D	13.2	20.67	25.81	32.59

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize leaf area index

In the 2016 growing season, biochar rates significantly increased leaf area index (LAI). From the 14^{th} DAP to the 42^{nd} DAP LAI obtained from each treatment was significantly different from each other. However, there was no significant effect of biochar on the LAI of maize in the 56^{th} DAP. Generally, plots treated with 20+P t ha^{-1} produced maize leaves that had a higher LAI compared to that of the plots treated with 20, 10 and 0 t ha^{-1} biochar. In most cases, the LAI obtained from plots treated with 20, 10 and 0 t ha^{-1} were similar. This shows the effect of P on leaf area index of maize. Irrigation generally had a significant effect on the leaf area index of maize. Leaf area index from deficit and full irrigated plots were not significantly different from each other, however, they were significantly higher compared to the control plots. There were no biochar and irrigation interaction effect on the LAI of maize in the 2016 growing season (Table 5.5a).

In the 2017 growing season, the effect of biochar on maize leaf area index was highly significant in all the weeks measurements were made. However, similar trends in 2016 growing season were observed, that, as the amount of biochar increased the leaf area index also increased. Generally, plots amended with 40+P t ha-^{1} came out with high leaf area index compared to the 40, 20 and 0 t ha-^{1}. The effect of irrigation regimes on leaf area index was highly significant with the DI and FI having the highest LAI compared to the control. There was however no biochar and irrigation interaction effect on LAI except on the 56^{th} DAP which showed a significant (P = 0.044) interaction effect (Table 5.5b).

Table 5.5a: Effect of biochar and irrigation on leaf area index (2016)

	Leaf area index			
Treatment	14	28	42	56
Biochar rate				
Control	0.26c	0.60b	2.60b	5.15a
10	0.31bc	0.66b	2.80b	4.84a
20	0.36ab	0.77ab	2.90b	5.13a
20+P	0.38a	0.90a	3.71a	5.64a
P-value	<0.001	0.005	<0.001	0.077
S.E.D	0.026	0.073	0.175	0.297
Irrigation regime				
DI	0.35a	0.83a	3.63a	6.53a
FI	0.39a	0.90a	3.83a	6.42a
NI	0.24b	0.46b	1.55b	2.62b
P-value	0.008	0.005	0.005	0.003
S.E.D	0.03	0.089	0.477	0.762
B*I (*P*-value)	0.533	0.667	0.268	0.214
S.E.D	0.05	0.141	0.545	0.883

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.5b: Effect of biochar and irrigation on leaf area index (2017)

	Leaf area index			
Treatment	14	28	42	56
Biochar rate				
Control	0.243b	0.66c	1.53c	2.76c
20	0.296b	0.75c	1.89b	3.16c
40	0.369a	0.90b	2.11b	3.59b
40+P	0.416a	1.07a	2.78a	4.86a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.02	0.042	0.091	0.151
Irrigation regime				
DI	0.38a	1.03a	2.512a	4.19a
FI	0.42a	1.03a	2.674a	4.51a
NI	0.20b	0.47b	1.05b	2.07b
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.026	0.059	0.141	0.26
B*I (*P*-value)	0.942	0.468	0.125	0.044
S.E.D	0.04	0.089	0.196	0.345

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize above-ground biomass

Table 5.6a indicate the effect of irrigation and biochar on maize above-ground biomass in the 2016 growing season. Biochar significantly (*P* <0.001) increased the dry above-ground biomass from 14 DAP to 56 DAP. Generally, there was a significant increase in biomass with an increase in the rate of biochar applied. However, plots amended with 20+P t ha^{-1} biochar significantly increased the biomass weight compared to plots with no biochar. Irrigation also affected the above-ground biomass of the maize significantly (*P* = 0.035 and *P* <0.001 for 14-28 DAP and 42-56 DAP, respectively). Generally, there were no significant difference between the above ground biomass obtained from DI and FI treated plots. However, DI and FI treated plots significantly increased the above-ground biomass compared to the biomass obtained from the NI plots. There was significant (*P* = 0.018) interaction effect of biochar and irrigation on the maize above ground biomass only at 42 DAP.

Table 5.6b indicate the effect of irrigation and biochar on maize aboveground biomass in the 2017 growing season. From 14 DAP to 56 DAP, biochar significantly (*P* <0.001) increased the dry above-ground biomass. Similar trends in 2016 occurred in 2017 where an increase in biochar application rates significantly increase the biomass. Generally, irrigation significantly affected the above-ground biomass at all stages, except for the 42^{nd} DAP which showed no significant (*P* = 0.053) difference among the irrigation treatments applied. Where there were significant difference DI and FI treated plots significantly increased the above-ground biomass compared to the biomass obtained from the NI plots. There was no significant interaction effect of biochar and irrigation on the maize above ground biomass in the 2017 growing season (Table 5.6b).

Table 5.6a: Effect of biochar and irrigation on above-ground biomass (2016)

	Dry above-ground biomass (g plant^{-1})			
Treatment	14	28	42	56
Biochar rate				
Control	10.46d	18.60d	50.50c	87.90c
10	12.67c	22.54c	59.00bc	105.20bc
20	14.23b	25.31b	65.60b	112.60b
20+P	19.30a	34.33a	102.30a	142.20a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.563	1.001	5.16	7.64
Irrigation regime				
DI	14.61ab	25.99ab	88.00a	139.20a
FI	15.66a	27.85a	82.80a	138.50a
NI	12.23b	21.75b	37.30b	58.30b
P-value	0.035	0.035	<0.001	<0.001
S.E.D	1.002	1.783	5.64	8.02
B*I (*P*-value)	0.074	0.074	0.018	0.460
S.E.D	1.311	2.332	9.58	13.99

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.6b: Effect of biochar and irrigation on above-ground biomass (2017)

	Dry above-ground biomass (g plant^{-1})			
Treatment	14	28	42	56
Biochar rate				
Control	13.38d	19.18d	46.80c	83.10b
20	16.10c	22.99c	55.40bc	94.30b
40	18.08b	25.76b	65.30ab	105.20ab
40+P	24.52a	34.78a	76.40a	121.50a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.719	1.007	5.60	8.08
Irrigation				
DI	18.56ab	26.44ab	76.20a	115.30a
FI	19.89a	28.3a	63.10ab	103.00ab
NI	15.6b	22.29b	43.60b	84.70b
P-value	0.038	0.038	0.053	0.009
S.E.D	1.277	1.787	10.4	6.44
*B*I (P-value)*	0.06	0.06	0.786	0.168
S.E.D	1.671	2.34	13.36	13.72

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on maize below-ground biomass

Results of the effect of biochar, irrigation and biochar-irrigation interaction on the below-ground biomass obtained in the 2016 growing season is shown in Table 5.7a. Biochar had a highly significant (*P* <0.001) effect on the below-ground biomass. Generally, the below-ground biomass obtained from the control (no biochar) plots and the 10 t ha^{-1} biochar treated plots were significantly lower than those obtained from plots treated with 20 and 20+P t ha^{-1} biochar. However, plots amended with 20+P t ha^{-1} biochar produced significantly higher below ground biomass (23.06 g) compared to the biomass obtained from the rest of plots. Irrigation regimes also affected the maize below ground biomass significantly (*P* = 0.009). Although the below-ground biomass obtained from the FI and DI treated plots were not significantly different from each other, they were significantly different from the below ground biomass produced from plot that were not irrigated (14.26 g). There was a significant (*P* = 0.017) biochar and irrigation interaction effect on maize below-ground biomass (Table 5.7a).

Similar results were obtained in 2017 (Table 5.7b), where biochar and irrigation showed a significant (*P* <0.001 and *P* = 0.024, respectively) effect on dry root biomass, however, there was no significant (*P* = 0.120) biochar and irrigation interactive effect on dry root biomass (Table 5.7b).

Table 5.7a: Effect of biochar and irrigation on below-ground biomass (2016)

Treatment	Dry below-ground biomass (g)
Biochar rate	
Control	11.42c
10	14.59c
20	18.94b
20+P	23.06a
P-value	<0.001
S.E.D	1.403
Irrigation regime	
DI	18.26a
FI	18.48a
NI	14.26b
P-value	0.009
S.E.D	1.002
B*I (*P*-value)	0.017
S.E.D	2.331

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.7b: Effect of biochar and irrigation on below-ground biomass (2017)

Treatment	Dry below-ground biomass (g)
Biochar rate	
Control	14.64c
20	18.33b
40	19.55b
40+P	25.26a
P-value	<0.001
S.E.D	1.182
Irrigation regime	
DI	20.73a
FI	19.89ab
NI	17.72b
P-value	0.024
S.E.D	0.807
B*I (*P*-value)	0.120
S.E.D	1.948

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on days to 50% tasselling of maize plants

In the 2016 growing season, biochar significantly (P <0.001) affected the days to 50% tasselling of the plants (Table 5.8a). Number of days to 50% tasselling increased with decreased biochar application rates. Plots treated with 20+P t ha^{-1} had significantly took less number of days to reach 50% tasselling compared to plots treated with 20, 10 and 0 t ha^{-1} biochar. There was no significant (P = 0.064) difference in the number of days to 50% tasselling among the irrigation regimes applied. Again there was no significant (P = 0.124) interaction effect of biochar and irrigation on the number of days to 50% tasselling (Table 5.8a).

Similar trends were followed in the 2017 growing seasons in the sense that biochar significantly (P <0.001) reduced the number of days 50% of the maize plants tasselled (Table 5.8b). Maize plants on plots treated with 40+P and 40 t ha^{-1} took less number of days to tassel compared to maize grown on plots treated with 20 and 0 t ha^{-1}. Irrigation regimes did not significantly affect the number of days to 50% tasselling. There was also no significant (P = 0.085) interaction effect of biochar and irrigation on the number of days to 50% tasselling of maize plants (Table 5.8b).

Table 5.8a: Effect of biochar and irrigation on days to 50% tasselling of maize (2016)

Treatment	Days to 50% tasselling
Biochar rate	
Control	60a
10	58a
20	55b
20+P	52c
P-value	<0.001
S.E.D	0.61
Irrigation regime	
DI	56
FI	54
NI	59
P-value	0.064
S.E.D	0.97
B*I (*P*-value)	0.124
S.E.M	1.33

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.8b: Effect of biochar and irrigation on days to 50% tasselling of maize (2017)

Treatment	Days to 50% tasselling
Biochar rate	
Control	59.42a
20	58.42a
40	54.42b
40+P	54.58b
P-value	<0.001
S.E.D	0.892
Irrigation regime	
DI	56.56
FI	54.69
NI	58.88
P-value	0.093
S.E.D	1.559
B*I (*P*-value)	0.085
S.E.D	2.055

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on crop growth rate of maize

The rate at which the maize plants were growing as affected by biochar is shown in Figures 5.1a and 5.1b in 2016 and 2017 growing seasons, respectively. In 2016 (Figure 5.1a), crop growth rate (CGR) showed a significant difference between the biochar rates applied. Crop growth rate increased with increasing biochar application rate (Figure 5.1a). There were no significant (P = 0.637) biochar effect on CGR at 28 DAP. Plots treated with biochar at the rate of 20+P t ha^{-1} generally produced significantly higher dry matter compared to the control. There was a sharp increase in dry matter produced between 28 DAP and 42 DAP, but from 42 to 56 DAP dry matter production reduced.

The trend was different in 2017 (Figure 5.1b) where biochar significantly (P <0.001) affected CGR at the first two sampling stages (14 and 28 DAP) but did not significantly affect CGR at the last two sampling stages (42 DAP (P = 0.059) and 56 DAP (P = 0.738)). However, the general trend was similar to that of 2016 where CGR increased with increasing biochar application rate. Biochar applied at the rate 40+P and 40 t ha^{-1} produced higher amount of dry matter per unit time compared to biochar applied at 20 and 0 t ha^{-1}.

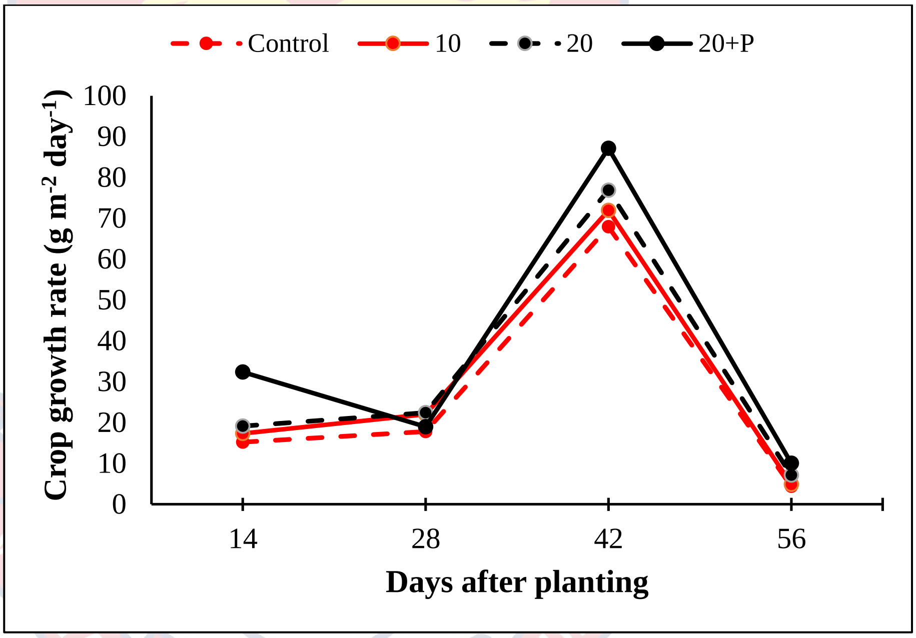

Figure 5.1a: Crop growth rate (CGR) of maize as affected by biochar in 2016. Biochar was applied in 0, 10, 20 and 20+P t ha^{-1}.

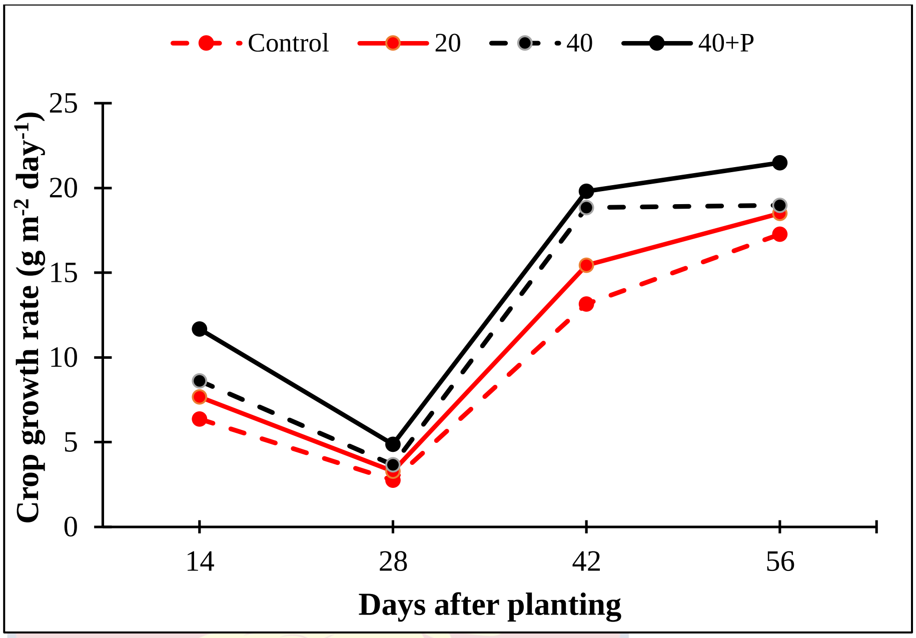

Figure 5.1b: Crop growth rate (CGR) of maize as affected by biochar in 2017. Biochar was applied in 0, 10, 40 and 40+P t ha^{-1}.

The effect of irrigation regimes on CGR is shown in Figures 5.2a (2016) and 5.2b (2017). In 2016, full and deficit irrigated plots significantly increased CGR compared to CGR obtained from the no irrigated plots. Crop growth rate was low at the initial stages (14 - 28 DAP) but increased steadily from the 28 to 42 DAP till it dropped at the 56 DAP when plants had started tasselling. The effect of irrigation regimes on CGR was significant at the 14, 28 and 42 DAP but not at 56 DAP (P = 0.089) (Figures 5.2a). In 2017, the CGR obtained from the no irrigation plots were significantly lower compared that obtained from the full and deficit irrigated plots. The rate of dry matter accumulation reduced from the 14 to 28 DAP but increased from 28 DAP steadily to the last sampling stage (56 DAP). Statistically the difference between the effect of irrigation on CGR at 14 and 28 DAP were the same (P = 0.038), but was the effect of irrigation on CGR was not significant at 42 DAP (P = 0.113) and at 56 DAP (P = 0.988) (Figure 5.2b).

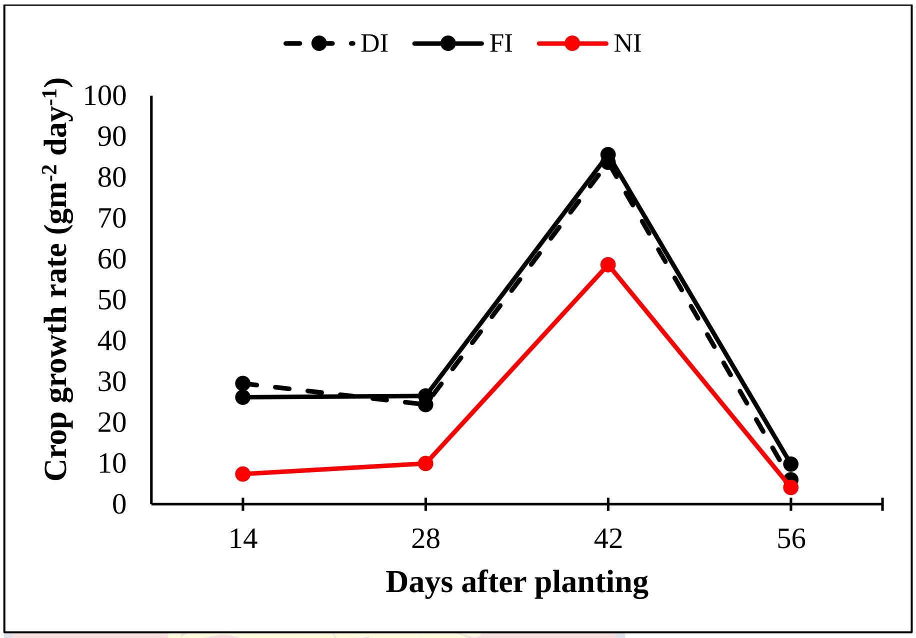

Figure 5.2a: Crop growth rate (CGR) of maize as affected by irrigation regimes in 2016. Irrigation regimes used were DI - deficit irrigation, FI – full irrigation and NI – no irrigation.

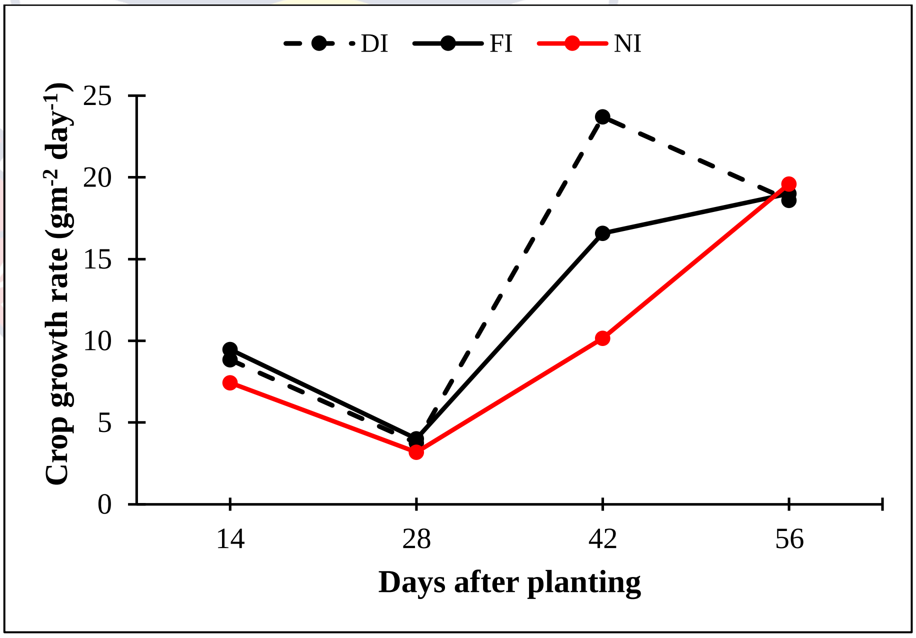

Figure 5.2b: Crop growth rate (CGR) of maize as affected by irrigation regimes in 2017. Irrigation regimes used were DI - deficit irrigation, FI – full irrigation and NI – no irrigation.

Effect of biochar and irrigation on maize yield parameters

The results of the maize yield traits obtained in the 2016 and 2017 growing seasons are shown in Table 5.9a and Table 5.9b, respectively. In 2016, biochar significantly affected all yield traits measured. Generally, plots treated with 20+P t ha^{-1} recorded higher and significant values compared to the other biochar treatment applied. That notwithstanding, maize grain yield, ear equatorial diameter, number of grains per row and number of rows per cob produced under plots treated with 20+P and 20 t ha^{-1} biochar were not significantly different from each other. Generally, plots with no biochar produced the lowest yield traits measured compared to plots treated with biochar. Irrigation significantly improved all yield parameters measured. Generally, FI and DI plots produced statistically the same values for all yield parameters measured but produced significantly high values for all yield traits compared to the NI plots. There were no significant biochar and irrigation interaction for maize 1000 seed weight (P = 0.108), ear equatorial diameter (P = 0.527), ear length (P = 0.698), number of grains per row (P = 0.574) and number of rows per ear (P = 0.648). However, biochar and irrigation interaction showed a significant interaction on cob yield (P <0.001), grain yield (P = 0.002) and stover yield (P = 0.001). The effect of biochar and irrigation interaction on maize grain yield is shown in Figure 5.3. The plots amended with 20+P t ha^{-1} with FI produced significantly higher maize grain yield (8.06 t ha^{-1}). This was not significantly different from plots amended with 20 t ha^{-1} with FI (7.81 t ha^{-1}), 20+P t ha^{-1} with DI (7.73 t ha^{-1}) and 20 t ha^{-1} with DI (7.56 t ha^{-1}). However, the lowest maize grain yield (1.38 t ha^{-1}) was obtained from the no biochar no irrigation plot (Table 5.9a).

In 2017, biochar significantly affected all yield parameters measured with the exception of number of rows per cob was not significantly (P = 0.413) affected by biochar. For all yield parameters measured in 2017, plots treated with 40+P and 40 t ha^{-1} produced significantly better results compared to plots with no biochar. All parameters measured were significantly affected by irrigation, where the NI plots produced lower maize yield traits compared to plots treated with FI and DI. In 2017, there was significant biochar and irrigation interaction effect on maize cob, grain and stover yields which were similar to the 2016 results (Table 5.9b).

Table 5.9a: Effect of biochar and irrigation on maize yield parameters (2016)

Treatment	1000 seed weight (kg)	Cob yield (t ha^{-1})	Grain yield (t ha^{-1})	Ear equatorial diameter (cm)	Ear length (cm)	Number of grains per row	Number of rows per ear	Stover yield (t ha^{-1})
Biochar rate								
Control	0.26d	1.26d	4.20c	4.51b	14.10c	30b	13b	8.22d
10	0.29c	1.49c	4.78b	4.95a	15.24bc	32ab	15a	10.61c
20	0.32b	1.92b	5.92a	4.93a	16.38ab	34a	15ab	12.67b
20+P	0.36a	2.19a	6.16a	5.06a	17.57a	34a	14ab	17.94a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.018	<0.001
S.E.D	0.007	0.064	0.132	0.11	0.59	1.436	0.48	0.49
Irrigation								
DI	0.332a	2.11a	6.65a	5.13a	17.09a	35a	15a	15.13a
FI	0.346a	2.18a	7.08a	5.17a	17.67a	36a	15a	15.63a
NI	0.243b	0.85b	2.07b	4.30b	12.71b	25b	13b	6.33b
P-value	<0.001	<0.001	<0.001	0.004	0.002	0.002	0.009	<0.001
S.E.D	0.0118	0.043	0.256	0.169	0.857	1.918	0.519	0.663
B*I (*P*-value)	0.108	<0.001	0.002	0.527	0.698	0.547	0.648	<0.001
S.E.D	0.016	0.105	0.323	0.236	1.232	2.884	0.888	0.99

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

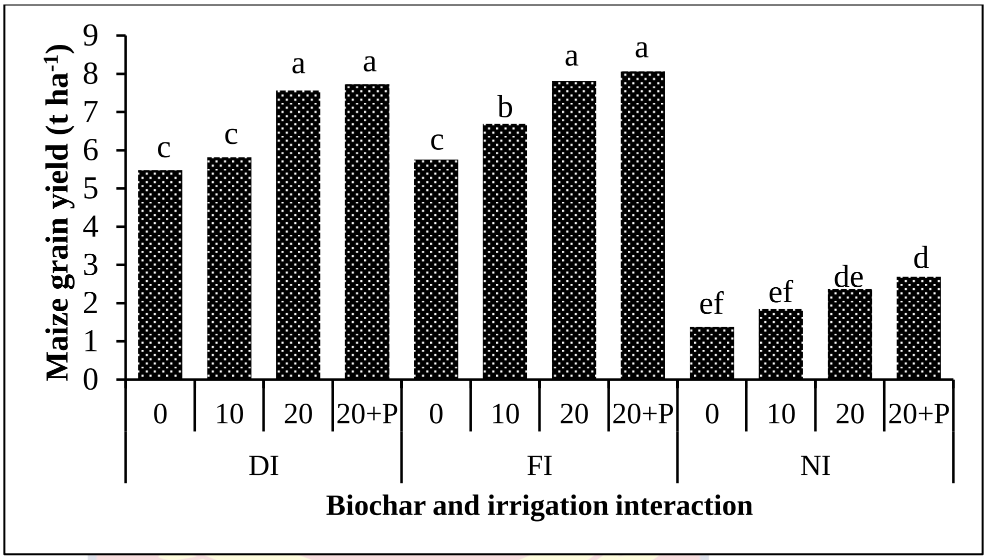

Figure 5.3: Maize yield as affected by biochar and irrigation interactions in 2016. DI - deficit irrigation, FI – full irrigation and NI – no irrigation.

Table 5.9b: Effect of biochar and irrigation on maize yield parameters (2017)

Treatment	1000 seed weight (kg)	Cob yield (t ha^{-1})	Grain yield (t ha^{-1})	Ear equatorial diameter (cm)	Ear length (cm)	Number of grains per row per cob	Number of rows per cob	Stover yield (t ha^{-1})
Biochar rate								
Control	0.25c	1.20c	4.40c	4.57b	13.47c	27.42b	13.54a	8.50d
20	0.26c	1.44b	4.86b	5.02a	14.8bc	30.29ab	13.96a	10.67c
40	0.29b	1.93a	5.62a	4.95a	15.78ab	32.08a	14.25a	12.67b
40+P	0.34a	1.99a	5.79a	5.13a	16.85a	32.21a	14.04a	17.00a
S.E.D	0.008	0.066	0.128	0.124	0.65	1.5	0.423	0.492
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.012	0.413	<0.001
Irrigation								
DI	0.30a	1.97a	6.31a	5.34a	16.60a	33.09a	14.03ab	14.75a
FI	0.33a	2.07a	6.53a	5.04a	17.15a	34.56a	14.56a	14.62a
NI	0.23b	0.88b	2.66b	4.37b	11.93b	23.84b	13.25b	7.25b
S.E.D	0.011	0.081	0.156	0.178	0.736	1.807	0.304	0.858
P-value	<0.001	<0.001	<0.001	0.004	<0.001	0.002	0.014	<0.001
B*I (*P*-value)	0.264	<0.001	0.002	0.549	0.853	0.821	0.793	<0.001
S.E.D	0.017	0.128	0.248	0.257	1.216	2.884	0.703	1.131

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Influence of irrigation regimes and biochar application rates on cowpea growth and yield in a maize-cowpea intercrop

The main and interactive effect of biochar and irrigation on cowpea growth and yield are shown in Tables 5.10a (2016) and 5.10b (2017). In the 2016 (Table 5.10a) growing season biochar significantly affected all growth and yield parameters measured. The general trend was that plots amended with 20+P t ha^{-1} performed significantly better than plots amended with 20, 10 and 0 t ha^{-1}. Plots with no biochar generally performed poorly compared to plots treated with biochar. For instance, cowpea grain yield was significantly higher on plots amended with biochar at the rate of 20+P t ha^{-1} (491.7 kg ha^{-1}), 20 t ha^{-1} (457.1 kg ha^{-1}) and 10 t ha-1 (419.2 kg ha^{-1}) compared to the grain yield obtained from the control plots (395.4 kg ha^{-1}). Apart from stem girth, all measured growth and yield parameters were significantly affected by irrigation regimes. The growth and yield traits observed on the no irrigated plots generally performed poorly compared to the traits observed from the full and deficit irrigated plots. There were significant interactive effect of biochar and irrigation on days to 50% flowering (*P* <0.001), dry above-ground biomass (*P* <0.001), stem girth (*P* <0.001), husk weight (*P* <0.001), number of grains per pod (*P* = 0.036) and grain yield (*P* <0.001). However, there were no significant biochar and irrigation interactive effect on number of leaves (*P* = 0.765), plant height (*P* = 0.536) and number of nodules per plant (*P* = 0.098).

Similar trends were observed in the 2017 growing season (Table 5.10b). The effect of biochar application rates was only not significant (*P* = 0.073) on the number of grains per pod. It was realised that an increase in the rate of application of biochar increased the performance of the growth and yield of cowpea. Irrigation significantly affected all measured parameters except for days to 50% flowering (P = 0.267) and stem girth (P = 0.064) which were not significantly affected by irrigation. There was a significant interactive effect only on stem girth (P = 0.002), number of nodules per plant (P = 0.013) and cowpea husk weight (P <0.001) (Table 5.10b).

Table 5.10a: Impact of biochar and irrigation on cowpea growth and yield of cowpea in 2016

Treatment	Number of leaves	Plant height (cm)	Days to 50% flowering	Above-ground biomass (g)	Stem girth (cm)	Number of nodules per plant	Husk weight (g)	Dry root weight (cm)	Number of grains per pod	Cowpea grain yield (kg ha^{-1})
Biochar										
0	48c	85.0b	38c	41.01d	0.76b	11d	0.34c	6.10b	10c	395.4d
10	51c	83.3b	39bc	47.86c	0.80b	13c	0.35c	6.00b	12b	419.2c
20	56b	94.9ab	41b	70.94b	0.91a	16b	0.52b	6.71a	13a	457.1b
20+P	64a	100.5a	48a	82.86a	0.93a	21a	0.60a	6.93a	14a	491.7a
P-value	<0.001	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<.001
S.E.D	1.46	5.05	0.845	0.973	0.014	0.602	0.014	0.162	0.341	3.85
Irrigation regime										
DI	59a	95.0a	42b	66.48b	0.84a	16b	0.49a	6.57a	14a	503.8b
FI	66a	109.0a	41b	69.04a	0.87a	18a	0.51a	6.74a	14a	534.2a
NI	38b	68.7b	43a	46.49c	0.84a	11c	0.35b	5.99b	9b	284.5c
P-value	<0.001	0.004	0.003	<0.001	0.085	<0.001	<0.001	0.004	<0.001	<0.001
S.E.D	2.913	7.15	0.245	0.504	0.0112	0.482	0.009	0.137	0.544	2.68
B*I (P-value)	0.765	0.536	<0.001	<0.001	<0.001	0.098	<0.001	0.005	0.036	<0.001
S.E.D	3.644	10.42	1.291	1.544	0.024	1.024	0.023	0.278	0.747	6.37

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 5.10b: Impact of biochar and irrigation on cowpea growth and yield of cowpea in 2017

Treatment	Number of leaves	Plant height (cm)	Days to 50% flow	Dry above-ground biomass (g plant^{-1})	Stem girth (mm)	Number of nodules per plant	Husk weight (g)	Dry root weight (g)	Number of grains per pod	Cowpea grain yield (kg ha^{-1})
Biochar rate										
0	70c	108.3b	39c	86.02a	9.36b	11d	0.34c	5.85c	12a	551.9b
20	74bc	118.4ab	42b	98.48ab	9.70b	13c	0.35c	6.46b	13a	603.8a
40	79b	135.8a	44a	96.24b	10.90a	16b	0.52b	6.59b	14a	598.1ab
40+P	93a	139.5a	46a	102.25a	11.27a	20a	0.60a	7.16a	13a	640.3a
P-value	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.073	<0.001
S.E.D	2.544	8.85	0.567	1.741	0.217	0.608	0.014	0.173	0.762	18.48
Irrigation regime										
DI	86a	139.1a	42	105.32a	10.36a	16b	0.49a	6.89a	15a	677.1a
FI	95a	142.1a	44	107.42a	10.65a	18a	0.51a	7.15a	14a	721.4a
NI	57b	95.2b	42	74.51a	9.91a	11c	0.36b	5.51b	10b	397.0b
P-value	<0.001	0.005	0.267	0.043	0.064	<0.001	<0.001	<0.001	0.002	<.001
S.E.D	5.084	9.81	0.91	11.029	0.245	0.438	0.009	0.224	0.873	15.81
B*I (*P*-value)	0.567	0.667	0.9	0.179	0.002	0.013	<0.001	0.686	0.686	0.499
S.E.D	6.356	16.5	1.246	11.334	0.409	1.011	0.023	0.343	1.438	31.91

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

General observations made in the experiments

Cowpea was cultivated as an intercrop. As it grew it covered the soil surface and hence smothered weeds and reduced evaporation, especially on plots amended with biochar and irrigated. This decreased the number of times weeding was done from 3 times to 2 times in the growing season. However, the control plots were weeded 4 times. Another observation is that most of the maize plants cultivated on the control plots (no biochar and no irrigation) produced multiple number of ears from a node or from different nodes (Figure 5.4), a condition that promoted the malformation of the ears, hence a reduction in yield.

Figure 5.4: Maize plant on control plot showing multiple ears on one plant.

Discussion

Maize production in Ghana is mainly done by smallholder farmers. The consideration of the impact of biochar, an important resource for small holder farmers (Partey *et al.*, 2015) and irrigation for crop production is critical in achieving a sustainable growth and yield of maize in Ghana. This is supported by Lehmann and Joseph (2015) who stated that biochar application may substantially improve soil fertility and crop productivity. In this experiment, two major treatments were applied, corn cob biochar and irrigation to determine its influence on maize and cowpea growth and yield. There has been many reports that states that using biochar as soil amendment enhances crop productivity through improving soil quality (Sohi *et al.*, 2010; van Zwieten *et al*., 2010b; Major *et al*., 2010a; Haefele *et al.*, 2011).

The impact of biochar and irrigation on the growth of maize

Chlorophyll is very important in the production of assimilates through photosynthesis. In this experiment, it was observed that chlorophyll content index increased with increasing biochar. The general trend was that, CCI obtained from plots with no biochar under no irrigation were significantly lower compared to CCI obtained from treatments with high rates (20 and 40 t ha^{-1}, plus or minus P) of biochar and under irrigation. For example, in 2017, the treatment 40+P t ha^{-1} under irrigation produced CCI which was about 73% more than that of no biochar and no irrigation treatments. This was a clear indication that there was a negative effect of water stress on chlorophyll content, hence the negative impact on photosynthesis and yield. This in line with observations made by Khayatnezhad *et al.* (2011) who testified that the total yield of maize decreased with increasing water deficit. Under severe drought, Farooq et al.

(2009) stated that chlorophyll production may perhaps stop. Massacci et al. (2008) also stated that cotton production was reduced under drought stress.

Leaves of maize was significantly affected by the interaction between biochar and irrigation in this experiment. The number of leaves produced from the control treatments were generally lower compared with the number of leaves produced from the treatments with biochar and irrigation. This trend is in line with the report by Uzoma *et al*. (2011) who reported that biochar addition increased the maize plant height and number of leaves. It must however be explained that applying biochar alone (with no irrigation) might increase the number of leaves of maize but it will be significantly better if irrigation is applied (Alburquerque *et al.*, 2014) especially where climate change has affected precipitation. Situmeang *et al*., (2015) also reported that treatment with a dose of 10 t ha^{-1} of bamboo biochar in addition to compost and fertilizer provided the highest number of leaves when compared to the control.

It was observed that plant height increased as the amount of biochar applied was increased and also when irrigation was applied (Figure 5.1 and 5.2). Chan and Xu, (2009) attributed the increase in height to the benefits of biochar on soil including increased soil pH of acidic soils, and also though not a fertilizer, significant amounts of plant nutrients such as potassium, calcium, nitrogen and magnesium are contained in biochar. Biochar application has the ability to retain soil nitrogen and moisture (Warren *et al*., 2006; Mitchell & Tu, 2005) which have a positive effect on growth in terms of plant height. Situmeang *et al*. 2013 also reported that application of bamboo biochar at a rate of 10 t ha^{-1} showed a significant effect on the corn plant height.

Biochar and irrigation had significant effect on maize leaf area and leaf area index (Table 5.4a and 5.4b and Table 5.5a and 5.5b). Generally in both experiments, the parameters measured under the treatments with no biochar no irrigation was significantly lower than treatment with biochar and irrigation. For instance, an increase in the rate of biochar increased the leaf area and leaf area index, however, biochar rates ladened with phosphorus performed significantly better than other biochar treatment without phosphorus. This results is in line with the report from Situmeang *et al*., (2015) who stated that biochar (bamboo) at a rate of 10 and 20 t ha^{-1} provided the highest value of leaf area of maize compared to the control. Similar findings were realised when Milla *et al.*, (2013) applied rice husk biochar and observed a significant improvement of leaf area of spinach.

The results of the above and below-ground maize biomass indicates that biochar and irrigation had significant effect on its production. Report from De la Rosa *et al*. (2014) confirms that application of biochar showed a significant increase of the biomass production of perennial ryegrass grown in pots. The effect of biochar and irrigation on leaf area, total leaf area, stem girth and plant height could possibly have a positive effect on the above ground biomass. Increased application rates of biochar (20 and 40) with or without phosphorus significantly improved the above and below ground biomass. This is because the general trend throughout the seasons was that biomass produced from treatments with no biochar under irrigation was not significantly different from biomass produced from treatments with 10 t ha^{-1} under no irrigation. There has been several reports that are similar to our results, that, biochar as compared to control has a significant effect on biomass production (Baronti *et al*., 2010;

Alburquerque *et al*., 2013; Milla *et al*., 2013). These results also suggest that over reliance of rains for the production of biomass defeats the fight against food insecurity.

Reproductive organs play a key role in crop production. One of the important reproductive organ in maize is the tassel. The early exit from the whorls denotes early maturity. In this experiment, it was realised that though the first to show tassels were maize plants established on plots treated with no biochar under no irrigation, it took some more days to attain 50% of the tassels. This might be as a result of the fact that the airy environment of the maize growing on control plots were adequate but lack the required plant nutrient to promote flower production. Thus, under no irrigation and no biochar, the duration between first tassel emergence and 50% tasselling is longer than under full and deficit irrigation with biochar. This suggest that there is uniformity of tasselling under soil amendments with biochar and irrigated systems. The results is comparable to reports from Situmeang *et al*., (2015) who stated that bamboo biochar at rate 5-10 t ha^{-1}, provided fastest appearance of 50% tassels as compared to the controls.

As stated by Blackwell *et al*. (2009) biochar has the greatest ability to enhance plant growth and soil nutrient content when combined with fertiliser. The results obtained in this experiment attest to this fact. Gaskin *et al*. (2010) reported that a decrease in growth is regularly reported with biochar amendments when it is not associated with fertiliser additions. However, in this experiment a recommended amount of fertilizer was applied hence an increase in growth of maize in all seasons. Maize growth rate from treatments with no biochar under no irrigation was generally lower as compared to treatments with biochar and irrigation (Figure 5.6). This indicates that in the presence of good soil conditions and nutrient availability crop growth is vigorous (Dolan *et al.*, 2006). Our results concur to this assertion because biochar and irrigation provided a favourable growing environment for maize plants to grow.

Effect of biochar and irrigation on maize yield

Previously, maize cobs have been extensively used for things. It has been used as a source of fuel and also as part of animal feed. Recently, it has become an important commodity in crop production because of it use as a feedstock for biochar production. The results of this experiment showed that maize cob yield was significantly affected by corn cob biochar and irrigation (Figure 5.9a and 5.9b). The results show that the significantly lowest cob yield produced were from biochar treatment without irrigation compared to the treatments with biochar and irrigation. The above results coincide with the report made by Gokila and Baskar (2015) that application of biochar at 5 t ha^{-1} where recommended dose of inorganic fertilizer were applied produced the highest cobs weight compared to yields from control. Sara *et al*. (2018) also reported that maximum cobs yield of 6.881 t ha^{-1} was obtained after the application of biochar at 80 t ha^{-1}, though the report stated that it was statistically similar to treatments receiving biochar at 40 or 60 t ha^{-1}. Our results concur to this report because cob yield increased with increasing rate of biochar.

Stover yield of maize was significantly influenced by biochar and irrigation. For instance, in 2016, the biochar treatment with 20+P t ha^{-1} produced the significantly highest amount of stover, i.e. 17.94 t ha^{-1}, compared to the control, i.e. 8.22 t ha^{-1}, about 54.18% higher than the stover produced from the control plots (no biochar and no irrigation). Also in 2016, full irrigated plots produced 15.63 t ha^{-1} maize stover, about 59.50% more than the no irrigated plots. Similar results have been reported by Arif *et al.* (2012) that there was an increase in maize stover yield when 5 t ha^{-1} biochar was applied compared to the control. A recent work from Gokila and Baskar (2015) concur to this assertion. However, Sara *et al*. (2018) reported a differing results that there was no significant effect of biochar on maize stover yield compared with the control.

Several studies have indicated that biochar application has been found to increase crop yields (Lehmann *et al.*, 2006; Sohi *et al*., 2010; Major *et al*., 2010). The findings from this experiment revealed that the impact of biochar and irrigation and their interaction on maize yield concur to the above statements. Maize grain yield increased by 82% and 83% for 20 and 20+P t ha^{-1} under full irrigation respectively, compared with control under no irrigation in 2016. Similar trends were obtained in 2017 where grain yield increased 67% and 69% for 40 and 40+P t ha^{-1} respectively, compared to control under no irrigation. In 2016, the highest maize grain yield (8.06 t ha^{-1}) obtained was from plots treated with 20+P t ha^{-1}. This is about 5 times the current yield of maize (1.8 t ha^{-1} in 2016) in Ghana (FAOSTAT, 2017). It was even higher than the potential grain yield of maize (4-6 t ha^{-1}). The findings suggest that application of biochar is relevant but in the presence of climate change an application of water is necessary. Higher grain yield in this experiment could be due to high nutrient retention in the presence of biochar and nutrient availability in the presence of water for effective assimilate production. The results of Sara *et al*. (2018) conforms to ours because it was reported that the highest grain yield of 5. 10 t ha^{-1} was obtained from biochar treatments at a rate of 40 t ha^{-1} while the lowest grain yield of 3.69 t ha^{-1} was obtained in the control treatment. Njoku *et al.* (2015) also observed a remarkable yield when biochar at a rate of 15 t ha^{-1} produced grain yield of 31 t ha^{-1} of maize compared with 0.51 t ha^{-1} obtained from the control plot. Several other experiments are in support of our findings (Chen *et al.*, 2010; Solaiman *et al*., 2010; Uzoma *et al*., 2011; Antonio *et al*., 2013) that biochar improved grain yield of maize appreciably. Blackwell *et al.* (2010) (as reported in Sara *et al*. 2018) reported that application of biochar improved the yields of crops due to better supply of water to plants. It could therefore be stated that biochar works perfectly in the presence of water. Interestingly, Oguntunde *et al*. (2004) recorded an increase of 44% and 91% in biomass and grain yield respectively, in maize on soils amended with charcoal when compared with adjacent field soils in Ghana. More so, Kimetu *et al.* (2008) supported our findings where it was stated that maize yield from a degraded soils in Kenya was doubled when biochar made from Eucalyptus was applied. Though our findings did not result in any decrease in grain yield it must be stated, however, that an increase in application rate of biochar could reduce yield (Gaskin *et al.* 2010).

The impact of biochar and irrigation on the growth and yield of cowpea

Cowpea growth parameters such as number of leaves, plant height, above and below-ground biomass, days to 50% flowering, number of branches, number of nodules, stem girth, number of grains per pod and grain yield were significantly affected by biochar and irrigation. The findings from this experiment revealed that biochar treatments ladened with phosphorus significantly increased the measured growth and yield parameters confirming the results observed by Krasilnikoff *et al*. (2003), Nyoki *et al*. (2013) and

Haruna and Usman, 2013. These findings agrees with the fact that phosphorus plays significant roles in many plant processes such as energy metabolism, nitrogen fixation, synthesis of nucleic acids and membranes, photosynthesis, respiration and enzyme regulation (Nkaa *et al*., 2014). In the presence of water and biochar, the phosphorus adsorbed to the biochar is slowly released for the growth and yield of the crop. There has been reports on increased P (Zhao *et al*., 2014) and other nutrients (Novak, *et al*., 2009; Park, *et al*., 2011; Luo, *et al.*, 2014) availability after biochar application to the soil, hence an increase in growth and yield of the crop. The increase in grain yield in this experiment at 56% and 54% from treatment with 20+P t ha^{-1} and 40+P t ha^{-1} under full irrigation in 2016 and 2017 respectively, as compared to the control treatments under no irrigation agrees with the findings from Glaser *et al.* (2002) who recorded yield increase in cowpea by 100% after biochar application.

The multiple ears formed in this experiments could be due to water stress that occurred at different crop developmental stages. Asare *et al.* 2011 indicated that the extent of reduction in maize productivity does not depend solely on the severity of the water stress but also on the stage of the crop development to be able to tolerate water stress. Subsequently the grain yield from the plot under no irrigation was lower when compared to the current and potential yield of maize produced in Ghana.

Conclusion

It was discovered in the study that biochar and irrigation increased maize growth and yield. However, an optimum growth and yield were obtained when phosphorus was added to biochar before its application to the soil. Again, supplemental irrigation was found to be necessary even in the rainy season.

CHAPTER SIX

IMPACT OF CORN COB BIOCHAR AMENDED SOIL ON ROOT SYSTEM ARCHITECTURE OF MAIZE AND COWPEA UNDER DRIP IRRIGATION SCHEMES IN THE COASTAL SAVANNAH ZONE OF GHANA

Introduction

Plant root systems are key drivers of plant function, growth and yield. Therefore understanding the characteristics of root morphology such as root surface area, root length, root diameter and root distribution in the soil are imperative for water/nutrient-uptake, crop growth, and water/nutrient management (Asseng *et al*., 1997; Coelho & Or, 1999). This has led to several studies of root system architecture (RSA). Root system architecture which is the topological arrangement of component root types and their geometrical characteristics (Lynch, 1995; Danjon & Reubens, 2008). Root system architecture and development patterns vary greatly, as they are affected by plant species, soil factors, and particularly by water and nutrient availability in the soil environment (Ruiz-Sanchez *et al*., 2005; Malamy, 2005) and has high plasticity responding to soil environmental change (Hodge, 2004; Nibau *et al*., 2008; Gruber *et al*., 2013). Conversely, the subterranean nature of roots has made studies of root in the field very challenging, though there has been some root system architecture studies in the lab with (Armengaud *et al*., 2009; Fang *et al*., 2009; Iyer-Pascuzzi *et al*., 2010; Clark *et al*., 2011, 2013). For instance, Zhu *et al*. (2011) reviewed some laboratory studies which included an artificial, high-throughput setups and pot experiments. Generally, plant root studies have been limited to root biomass measurements (Lehmann *et al.*, 2003; Noguera *et al.*, 2010; Prendergast-Miller *et al.*, 2011) ignoring the importance of other parts of the root system. Field studies are time consuming and pose unique technical challenges associated to mature root system imaging under realistic conditions (Bucksch *et al*., 2014; Zhu *et al*., 2011).

Recently, a new approach, namely shovelomics, has been proposed to produce high throughput data from field studies (Trachsel *et al*., 2011). This technique consists of the excavation of maize root system using a shovel, cleaning of the root system followed by visual scoring and assessing counting of root characteristics on a scoreboard. Shovelomics has been used widely and mainly to detect differences between genotypes of maize plants (Grift *et al*., 2011; Trachsel *et al*., 2011). It has also been used to investigate the effect of nitrogen fertilisation on root architecture (Trachsel *et al*., 2013). The shovelomics method is increasingly combined with image-based phenotyping techniques to enable reproducible results (Grift *et al*., 2011). Several softwares have been used to analyse images taken under shovelomics, e.g. Root Estimator for Shovelomics Traits (REST), ImageJ, General Image Analysis of Roots (GiA Roots), Root System Analyzer (RSA), RootSnap, RootView, SmartRoot and many others.

In this study, it was hypothesised that biochar and irrigation have effect on root system architecture of maize and cowpea.

Material and methods

Experimental design and field layout

The experiment was laid out in a split-plot design with four replications with irrigation regimes as the main plots and biochar levels as subplots. The net experimental plot size was 864 m^2 made up of 48 plots each measuring 3 m × 6 m (18 m^2).

Experimental treatment

The experiment was conducted in June 16, 2016 to September 20, 2016 and repeated in July 5, 2017 to October 10, 2017. All treatments were made up of a combination of biochar and irrigation. There were four levels of biochar and three levels of irrigation for the two experiments. In 2016, biochar was applied at 0 (control), 10, 20 and 20+P t ha^{-1} (biochar mixed with phosphorus before application). In 2017, there were four (4) levels of biochar, control, 20, 40 and 40+P t ha^{-1}. There were three levels of irrigation regime, that is, full (FI), deficit (DI) and no irrigation (NI) in both 2016 and 2017. However, the results presented in this chapter is for the experiment in 2016.

Agronomic practices

All the necessary agronomic practices in maize and cowpea production like irrigation, fertilizer application, weeding and pest and disease control was done as described in chapter five.

Root sampling

The roots were sampled using the shovelomics method of measuring root traits (Trachsel *et al.*, 2011). At anthesis, maize plants tagged for root system analysis were excavated. Before excavation, a sharp knife was used to cut off the shoot. With the aid of a sharp standard shovel, two whole roots system were excavated from each plot by removing a cylinder of soil approximately 40 cm diameter and 25 cm depth, with the plant stem in the middle of the cylinder. Eight plants were sampled per treatment i.e. two from each plot, each from the middle row of each treatment, similar to Martinsen *et al*. (2014). After the excavation, all root crowns were soaked in water for 3 hours followed by rinsing under a mild flow of water for 15 to 30 minutes, making sure there were no soil attached to the roots (Figure 6.1). After blotting the surface of the roots, it was placed on a black background and a photograph was taken with a digital camera (TECNO® Camon 8) with a resolution of 13 megapixel (Figure 6.2). Root excavation, washing and photography were carried out by the same researcher to avoid bias from slight variations in the sampling strategy.

After the image of the root crown was taken, they were visually scored on a shovelomics scoreboard (Figure 6.3) for the following cowpea and maize root traits. Cowpea root traits scored were: Adventitious root (AR) diameter, AR root angle (°), AR length (cm), AR number, AR branching density, basal root (BR) diameter (mm), BR length (cm), BR number, BR angle (°), tap root density and cowpea shoot diameter (mm). Maize root traits scored were: brace root (BR) diameter, BR angle (°), BR root length (cm), BR number, BR branching, crown root (CR) diameter, CR angle (°), CR length (cm), CR number and CR branching density.

Brace and crown root angles were measured by vertically placing the root on the shovelomics scoreboard with the stem on the 90° line of the protractor on the board as shown in Figure 6.4. To obtain the branching density of maize, the brace and crown roots were removed from the main root axis and the number of lateral roots were counted within 3 cm on the root segment starting from 5 cm below the soil surface. Branching density was then calculated as the number of lateral roots per 1 cm, with the score chart showing in Figure 6.5 from the maize Shovelomics scoreboard (Figure 6.3). It indicate that, for example, if the CR has 2 lateral roots per 1 cm then it was scored 1 as the lowest but if it has 24 lateral roots per cm then it was scored 9 as the highest (Score: 1=2 LR/cm, 2=4, 3=6, 4=8, 5=10, 6=12, 7=16, 8=20, 9=24). Diameter of root traits were measure using a digital Veneer callipers.

Figure 6.1: Cleaning and washing procedure of maize roots. It passed through a succession of stages before the final washing.

Figure 6.2: Maize root after washing placed on a black background for image taken.

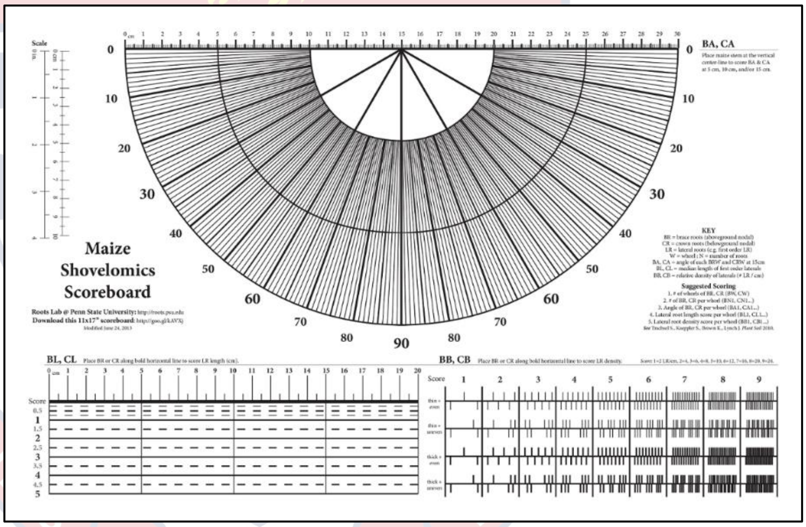

Figure 6.3: Maize Shovelomics scoreboard (Source: Roots Lab at Penn State University, http://roots.psu.edu and http://goo.gl/kAVXj)

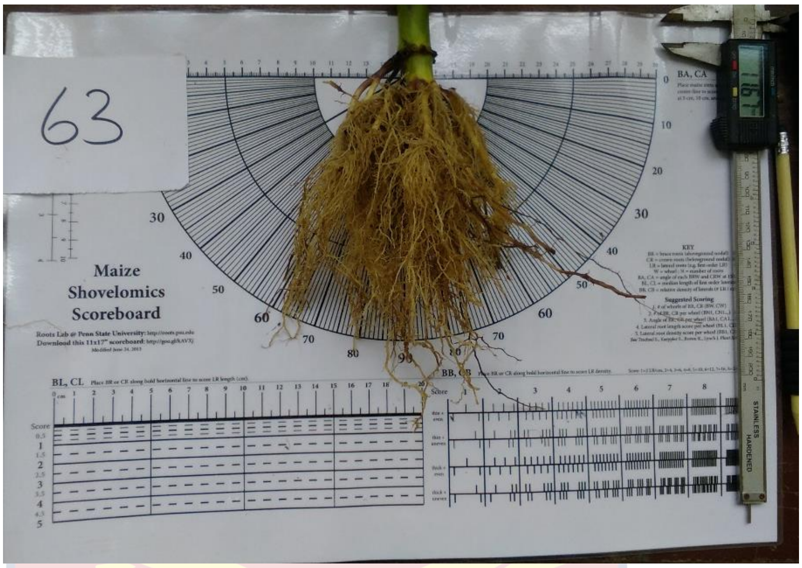

Figure 6.4: Maize root on shovelomics scoreboard to measure BR and CR angles

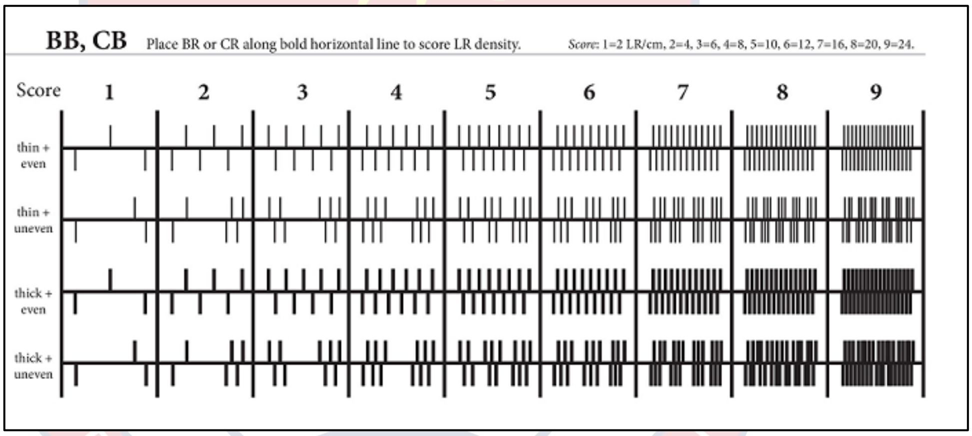

Figure 6.5: Score chart for Brace and crown root branching density (Source: http://goo.gl/kAVXj)
Score: 1=2 LR/cm, 2=4, 3=6, 4=8, 5=10, 6=12, 7=16, 8=20, 9=24.

Statistical analysis

Data obtained on maize and cowpea root traits were subjected to analysis of variance (ANOVA) using the GenStat statistical package (GenStat, 2007). Tukey test for means separations was used when significant differences occurred among experimental plots. The test for statistical differences between means was done at 5% level of probability. Correlation analyses were carried out to determine the nature and magnitude of relationships between and among principal maize and cowpea parameters.

Results

Influence of biochar and irrigation on cowpea root traits

The result of the effect of biochar and irrigation on cowpea root traits is shown in Table 6.1. Out of the 14 cowpea root traits measured 12 were significantly affected by biochar additions. Adventitious root number and tap root length were the only 2 traits that were not significantly (P = 0.933 and P= 0.151, respectively) affected by biochar additions. Biochar additions reduced the adventitious and basal root angles, especially on plots treated with 20+P t ha^{-1}. An increase in biochar application rate reduced the number of basal roots and tap root diameter significantly.

Irrigation regimes did not significantly affect adventitious root diameter (P = 0.057), adventitious root length (P = 0.652), adventitious root number (P = 0.128), basal root angle (P = 0.138), basal root number (P = 0.478) and shoot diameter (P = 0.414). Adventitious root angle was significantly (P <0.001) affected by irrigation. An increase in the amount of water applied reduced the adventitious root angle significantly, with DI (50.00°) as the lowest compared to the FI (51.33°) and NI (53.75°). An increase in irrigation also increased the basal root diameter significantly, where FI (2.35 mm) compared to the NI (1.40 mm). The number of lateral roots recorded on the basal roots (basal root branching density) were significantly affected by irrigation regimes. The number was high on the NI plots (4.92) compared the FI (4.33) which was similar but significantly different from the DI (3.75) (Table 6.1).

Seven (adventitious root diameter, adventitious root angle, adventitious root branching density, basal root diameter, basal root length, basal root branching density and tap root branching density) out of 14 cowpea root traits measured were significantly affected by biochar and irrigation interaction (Table 6.1). Figure 6.6 shows the biochar and irrigation interactive effect on the cowpea root system architecture.

Table 6. 1: Effect of biochar and irrigation on cowpea root traits

Treatment	AR dia. (cm)	AR angle	AR length (cm)	AR number	AR branch. density	BR angle	BR dia. (mm)	BR length (cm)	BR number	BR branch. density	TR branch. density	Shoot dia. (mm)	Tap root dia. (mm)	Tap root length (cm)
Biochar														
0	1.09ab*	57.22a	10.83ab	5.78	3.22c	60.83a	1.45b	15.78b	8.67a	3.22b	6.33ab	7.68ab	2.78ab	11.73
10	0.77b	45.00c	5.53b	5.56	5.67b	53.94a	1.52b	20.11a	6.78ab	6.67a	7.22ab	7.63b	2.55b	11.62
20	1.39a	56.67a	15.67a	6.33	7.33a	56.94a	2.46a	22.78a	5.67b	4.33b	5.33b	9.42a	3.28a	13.63
20+P	1.03ab	47.89b	9.72ab	6.00	4.67b	42.44b	1.79b	14.56b	4.94b	3.11b	8.44a	8.96ab	3.29a	10.1
P-value	0.006	<0.001	0.002	0.933	<0.001	0.001	<0.001	<0.001	0.013	<0.001	0.006	0.02	0.017	0.151
S.E.D	0.15	0.904	2.214	1.239	0.484	3.85	0.148	1.358	1.046	0.437	0.776	0.623	0.25	1.45
Irrigation regime														
DI	1.093	50.00c	10.25	5.33	3.25	50.6	1.67b	17.33ab	7.08	3.75b	9.75a	8.27	3.52a	13.97a
FI	1.321	51.33b	11.19	5.25	5.92	58.1	2.35a	21.83a	5.75	4.33ab	6.67ab	8.59	3.24a	11.38ab
NI	0.803	53.75a	9.88	7.17	6.5	51.8	1.40c	15.75b	6.71	4.92a	4.08b	8.41	2.17b	9.97b
P-value	0.057	<0.001	0.652	0.128	0.001	0.138	<0.001	0.025	0.478	0.02	0.008	0.414	0.001	0.02
S.E.D	0.146	0.297	1.388	0.808	0.34	3.1	0.071	1.368	1.03	0.236	0.874	0.211	0.1394	0.823
B*I (*P*-value)	0.004	<0.001	0.14	0.176	<0.001	0.061	<0.001	0.003	0.153	0.004	<0.001	0.692	0.21	0.814
S.E.D	0.268	1.388	3.599	2.026	0.802	6.55	0.232	2.454	1.877	0.697	1.456	0.958	0.4	2.326

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. AR: adventitious root, BR: basal root, TR: tap root and dia.: diameter. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

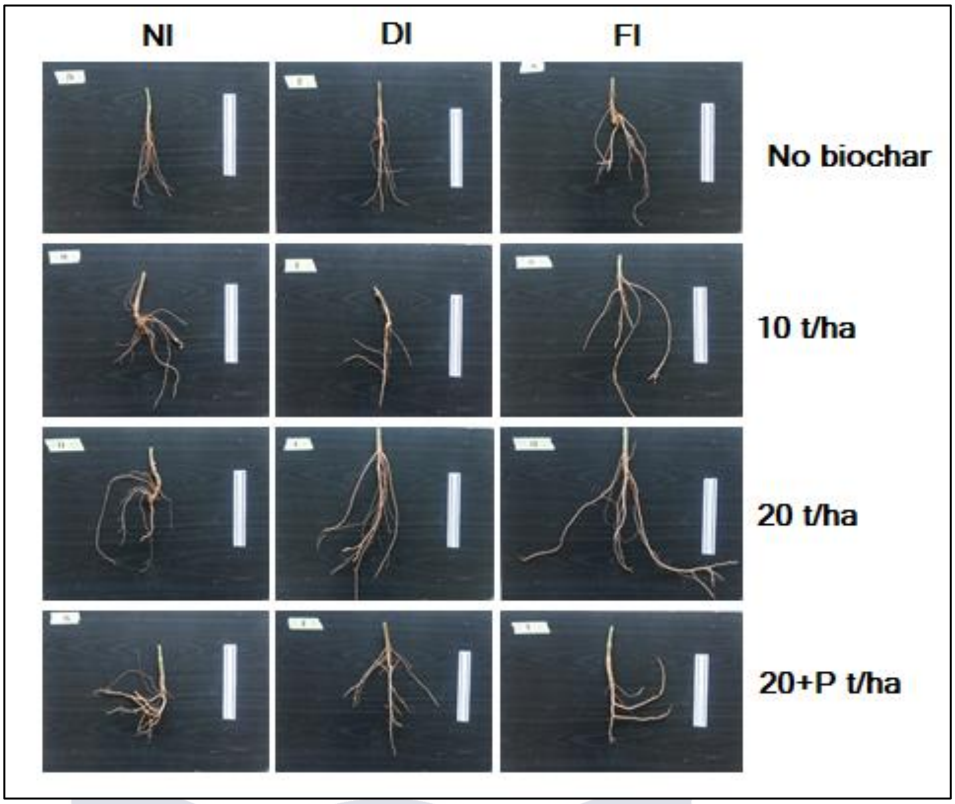

Figure 6.6: Cowpea root images showing the root system architecture as affected by biochar and irrigation in a maize cowpea intercrop.

Results of the correlation between cowpea root traits and cowpea grain yield is shown in Table 6.2. The relationship between cowpea yield and shoot diameter, adventitious root diameter, adventitious root number, adventitious root angle, adventitious root branching density, brace root number, brace root angle and brace root branching density were weak and not significant. However, the correlation between and brace root diameter, tap root diameter and tap root branching density was significant with a correlation coefficients, r = 0.499, r = 0.707 and r =0.519, respectively.

Table 6.2: Relationship between cowpea root traits and cowpea grain yield

	Shoot diameter (mm)	AR number	AR diameter (mm)	AR angle (°)	AR branching	BR number	BR diameter (mm)	BR angle (°)	BR branching	TR diameter (mm)	TR branching
AR number	-0.167										
AR diameter (mm)	0.265	-0.342*									
AR angle (°)	0.050	-0.115	0.468**								
AR branching	0.110	0.264	0.207	0.180							
BR number	-0.173	-0.077	-0.067	0.217	-0.464**						
BR diameter (mm)	0.285	-0.211	0.671**	0.225	0.269	-0.379*					
BR angle (°)	-0.221	0.061	0.099	0.308	0.047	0.091	0.251				
BR branching	-0.235	-0.191	-0.280	-0.196	0.244	-0.058	-0.020	0.116			
TR diameter (mm)	0.402*	-0.353*	0.432**	-0.035	-0.234	-0.210	0.393*	-0.254	-0.302		
TR branching	-0.255	-0.121	0.086	-0.149	-0.246	0.145	-0.032	-0.309	-0.250	0.375*	
Cowpea grain yield (t ha^{-1})	0.161	-0.284	0.378*	-0.266	-0.216	-0.231	0.499**	-0.006	-0.251	0.707**	0.519**

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. AR: adventitious root, BR: basal root, TR: tap root and dia.: diameter. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Influence of biochar and irrigation on maize root system architecture

The results of the effect of biochar application rates on maize root traits is presented in Table 6.3. All maize root traits measured were significantly (P <0.001) affected by biochar, except for brace root length (P = 0.389) and crown root length (P = 0.186) which were not significantly affected by biochar. An increase in biochar application rate significantly reduced the brace and crown root angles (Table 6.3). For instance, plots amended with 20+P and 20 t ha^{-1} biochar recorded significantly lower (41.11° and 39.72°, respectively) brace root angles compared to that of plots treated with 10 t ha^{-1} biochar (52.00°) and no biochar (39.72°). Crown root angles recorded from plots amended with biochar at a rate of 20+P, 20 and 10 t ha^{-1} (52.56°, 54.00° and 51.67°, respectively) were significantly lower compared to the no biochar plots (67.67°). Biochar additions significantly (P <0.001) increased the number of brace and crown roots compared to the number recorded on the control plots. There were significantly high crown root diameter recorded on the biochar amended plots compared to the crown root diameter recorded on control plots (Table 6.3).

The effect of irrigation regimes on maize root traits is shown in Table 6.3. Generally, an increase in the amount of water significantly altered maize root traits measured. Brace root branching density, brace root number, crown root angle and crown root branching density were not significantly affected by irrigation regimes. Plots where water was applied fully or reduced improved the maize root traits measured compared plots which were not irrigated.

The biochar and irrigation interactive effect were highly significant (P <0.001) on brace root branching density, brace root diameter, brace root length, brace root number, crown root branching density and crown root number. However, crown root angle and crown root length were not significantly (P = 0.165 and P = 0.897, respectively) affected by biochar and irrigation interaction. Figure 6.7 shows the effect of biochar and irrigation interaction on maize root system architecture. It was observed in the figure that root system architecture improved with increasing amount of water and biochar.

Table 6.3: Effect of biochar and irrigation on maize root traits

Treatment	Brace root angle	Brace root branching density	Brace root diameter (mm)	Brace root length (cm)	Brace root number	Crown root angle	Crown root branching density	Crown root diameter (mm)	Crown root length (cm)	Crown root number
Biochar										
0	50.72a	20.9c	3.63a	17.67	9b	67.67a	12.78b	2.64b	18.51	24.06c
10	52.00a	30.6ab	3.03b	17.04	17a	51.67b	26.44a	3.46a	16.97	20.33d
20	39.72b	27.2bc	3.79a	17.04	15a	54.00b	25.50a	3.53a	19.95	28.61b
20+P	41.11b	39.3a	3.52a	15.53	16a	52.56b	21.94a	3.71a	18.27	31.72a
P-value	<0.001	<0.001	<0.001	0.389	<0.001	<0.001	<0.001	<0.001	0.186	<0.001
S.E.D	2.313	3.29	0.124	1.246	1.136	2.43	2.05	0.125	1.292	0.501
Irrigation regime										
DI	43.83b	26.2	3.62ab	15.95ab	12	56.75	21.2	3.76a	18.93ab	27.00b
FI	42.62b	29.9	3.69a	19.88a	17	52.67	25.5	3.58a	20.07a	29.88a
NI	51.21a	32.5	3.17b	14.64b	14	60	18.3	2.67b	16.28b	21.67c
P-value	0.009	0.419	0.033	0.031	0.422	0.096	0.246	0.007	0.041	<0.001
S.E.D	1.5	4.29	0.134	1.26	2.892	2.46	3.62	0.1732	0.98	0.43
B*I (*P*-value)	0.001	<0.001	<0.001	<0.001	<0.001	0.165	<0.001	0.003	0.897	<0.001
S.E.D	3.779	6.53	0.23	2.254	3.356	4.397	4.75	0.255	2.171	0.866

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. AR: adventitious root, BR: basal root, TR: tap root and dia.: diameter. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

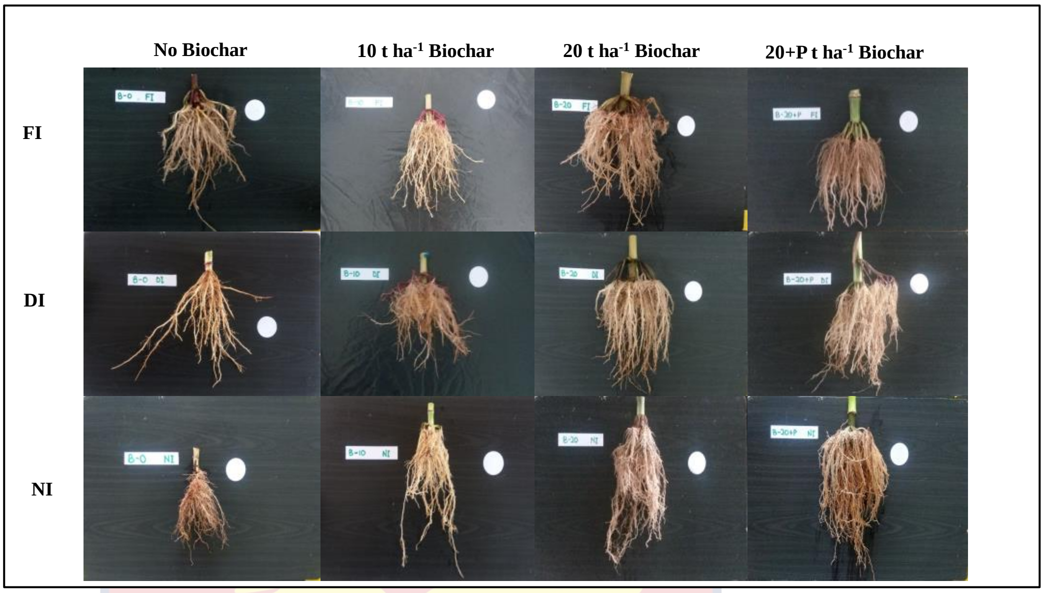

Figure 6.7: Effect of biochar and irrigation on maize root system architecture:

Results of the correlation analysis among some selected maize root traits and grain yield is presented in Table 6.4. The correlation showed a significant but negative and moderate correlation (r = -0.462) between maize grain yield and brace root angle. There was a significant positive correlation (r = 0.329) between brace root diameter and maize grain yield. A strong and positive correlation (r = 0.681) was observed between crown root diameter and maize grain yield. The analysis showed a strong relationship between maize grain yield and crown root number with r = 0.574. The relationship between crown root angle and grain yield was weak and negatively (r = -0.369).

Table 6.4: Correlation of some maize root traits and grain yield

	BR angle (°)	BR number	BR diameter (mm)	BR branching density	CR angle (°)	CR number	CR diameter (mm)	CR branching density
BR number	0.038							
BR diameter (mm)	-0.070	-0.015						
BR branching density	-0.151	0.084	0.183					
CR angle (°)	0.375**	-0.261*	-0.008	-0.169				
CR number	-0.320**	-0.012	0.162	-0.123	-0.136			
CR diameter (mm)	-0.345**	0.127	0.425**	0.233*	-0.471**	0.322**		
CR branching density	-0.309**	0.145	0.015	0.146	-0.447**	-0.012	0.322**	
Maize grain yield	-0.462**	0.104	0.329**	0.004	-0.369**	0.574**	0.681**	0.257*

BR: brace root, CR: crown root, *, ** indicates: significance at 0.05, 0.01 respectively.

Discussion

Root are important plants parts because of its valuable responsibility to absorb soils available water and plant nutrients for growth and development. The growth of plant roots is dependent on the availability of plant nutrients and water and also in the soil physical and chemical conditions (Soethe *et al*., 2006). To be able to survive, plants usually extend their root (Eissenstat & Yanai, 1997; Prendergast-Miller *et al*., 2014) to be able to obtain enough nutrients and water. In this experiment, biochar did not significantly influence maize brace and crown root length. It could be due to the fact that when biochar improves the soil fertility plant roots do not grow deeper in search of nutrients (Hodge, 2004; Peng *et al*., 2010). On the other hand, plots without biochar often lacks water and plant nutrients in the root zone, hence, the roots grows deeper in search of water and nutrients in the deeper soil substratum (Wasson *et al*., 2012). Deficit and full irrigation significantly increased maize brace and crown roots lengths compared to the no irrigation. This is in agreement with the report by Bengough *et al*. (2011) who reported that if plant nutrients are mobile, it induces an elongation of the root system. The cowpea basal and tap root length in this experiment was however influenced by biochar (Figure 6.6) where plots treated with biochar at 20+P t ha^{-1} were significantly shorter than those from the control plots. However, the 20 t ha^{-1} treatments produced the longest cowpea tap and basal roots, which were similar to reports from Prendergast-Miller *et al.* (2014) and Bruun *et al.* (2014). Their report suggested that biochar amendments to agricultural soils is advantageous for because it enlarges the plant rhizosphere for water and nutrient absorption by roots. The general trend that root length produced under 20+P t ha^{-1} treatment was shorter in our experiment indicate that when P is loaded with biochar before application it makes P available within the 0-20 cm depth of the soil for easy uptake by maize roots.

Biochar and irrigation increased the diameter of cowpea adventitious, basal and tap roots. Diameter of maize brace and crown roots were generally increased by biochar application rates and irrigation regimes. This result is relevant because Fitter (1996) reported that root diameter determines the length of root that the plant can produce for a unit input of resources to the system. However, reports from Gill *et al*. (2000) and Kucbel *et al*. 2011 suggest that as diameter increased, the root turnover decreased. Another advantage of increased diameter is its ability to penetrate soil pores that are smaller than the root diameter (Wiersum, 1957) to be able to access water and nutrients.

Plant root angles are determinants of the region of the soil that is explored. In this experiment, biochar, especially treatments loaded with P (20+P t ha^{-1}) significantly decreased the adventitious and basal root angles of cowpea. It also reduced the brace and crown (seminal) roots of maize. For example, the basal roots of cowpea produced from the 20+P t ha^{-1} biochar treatments had 42.4° as compared to the control (60.8°). Brace and crown root angles of maize were also influenced by biochar. For instance, 20 t ha^{-1} and 20+P t ha^{-1} produced shallow angles of 39.72° and 41.11° respectively, compared to the control which produced 50.72°. The brace root angles from the control plot under no irrigation was increased to over 70°, described as steep roots. This is in agreement with the report by Cornelissen *et al.* (2013) and Martinsen *et al.* 2014 who reported that root angle of maize was decreased from soil without biochar and fertilizer but root angles were increased when soils were amended with biochar and fertilizer. Singh *et al*. (2010b) and Lynch and Brown, (2001) reported that steep angles primarily explore deeper soil layers but roots with shallow angles primarily explore the topsoil. Similar observations were made where biochar influenced cowpea basal root angles, especially, from biochar loaded with P. Lynch & Brown, 2001 reported that there is a better P acquisition of common bean when the basal roots are shallow. Also, the brace and crown roots at a shallower angle are more efficient in N use (Den Herder *et al*., 2010; Miguel *et al*., 2015; York, 2015).

An important component of the root system architecture is the lateral roots which are considered to be the most active portion of the root system for water uptake. It represent the majority of the length and surface area of root systems in various types of plants (Rewald, *et al*., 2011). In this study, biochar and irrigation increased the number of lateral root produced on maize brace and crown roots, hence improving the branching density. This is in agreement with the report by Malamy (2005) who confirmed that in the presence of biochar plant roots can increase the branching density by increasing the number of lateral roots produced. This is relevant because it could aid in the overall root absorption ability leading to a sustainable crop growth and yield. The low root branching densities obtained from the control plots (no biochar and no irrigation) could be due to low N availability (Eghball *et al*., 1993). Finally it has been reported that increased lateral root density is associated with increased nutrient and water uptake (Tian, *et al*., 2014; Sun, *et al*., 2015), hence, the improved root growth and yield from plots treated with biochar and under irrigation.

Biochar and irrigation significantly increased the number of maize brace and crown root to about (7)42% and (9)27% compared to the control. This is in line with the statement by Lynch (2014) and Saengwilai (2014) that low number of crown roots is related to a greater rooting depth, for nitrogen uptake in low nitrogen soils. López-Bucio *et al.* (2003) also reported that primary root growth is reduced when P is limited. This experiment supported this report because in the presence of biochar, P might have increased, improving the growth and the number of brace and crown roots of maize and other root traits.

Another important observation made in this experiment was the relationship between maize yield and root traits (Table 6.4). The findings of this experiment revealed that there were positive and negative relationship between maize root traits and maize grain yield. For instance, the relationship between brace root and crown root angles (r = -0.462 and r = -0.369, respectively) and maize grain yield were negative and weak. Crown root number (r = 0.574) had a positive and moderate relationship with maize grain yield. This is an indication that biochar and irrigation could be used to increase the crown root number, hence the yield of maize. There was a strong and positive correlation between crown root diameter and maize grain yield. It was clear that this relationship was as a result of biochar and irrigation which improved the soil condition for growth and yield of maize (Yamato *et al.*, 2006; Martinsen *et al.*, 2014).

Conclusion

The root system architecture of maize and cowpea was influenced by the irrigation and biochar in this study. Biochar and irrigation improved maize and cowpea root traits, hence, improved their yields. Biochar should however, not to be used as a fertilizer, although it contains some amount of plant nutrients.

CHAPTER SEVEN

EFFECT OF CORN COB BIOCHAR ON GROWTH, YIELD, QUALITY AND SHELF LIFE OF TOMATO (*Solanum lycopersicum*) UNDER DRIP IRRIGATION STRATEGIES IN THE COASTAL SAVANNAH ZONE OF GHANA

Introduction

Tomato (*Solanum lycopersicum*), one of the most widely grown vegetables in the world (Srinivasan, 2010). Tomato was not eaten until the Nineteenth Century, because Mattiolus had called it *mala insane* (unhealthy flower) (Kybal, 1993). Tomato is now one of the most nutritious vegetable in the world (Paran & van der Knaap, 2011). It is the third economically most important crop family, exceeded only by grasses and legumes and the most valuable in terms of vegetable crops (van der Hoeven *et al*., 2002). The fruit of tomato, classified as a vegetable in trade, is a prominent "protective food" (Alam *et al*., 2007). It is also considered one of the best healthy foods in the American diet (Bradley, 2003).

Tomato abound in essential nutrients such as vitamins and minerals (Norman, 1992). One cup of cherry tomatoes, for example, contains approximately 31 calories, 7 g of carbohydrates, and only 0.5 g of fat (Bradley, 2003). Lycopene is the pigment responsible for the characteristic deep red colour of ripe tomatoes and their products (Ibitoye *et al.*, 2009).

Tomato forms a very important component ingredient of almost every dish consumed in Ghana (Tambo & Gbemu, 2010). Production of tomato is highly seasonal and mostly rainfed in Ghana. Potential yield of tomatoes has not been achieved in Ghana (Robinson & Kolavalli, 2010) due low soil fertility and high cost of inputs such irrigation, fertilizer, seeds and labour. This has put Ghana in a position of continually importing several tonnes of tomato and tomato products into the country (Robinson & Kolavalli, 2010). According to Aryeetey (2006), Ghana is second to Germany as the largest importer of tomato paste. The European Union reportedly exported 27, 000 tonnes of preserved tomatoes to Ghana in 2003. Although figures of the subsequent years were not given, the trend suggests that in each year Ghana's import volume of tomato paste increased by an average of 23%. Robinson and Kolavalli (2010) reported that tomato paste imports into Ghana amounted to over 78,000 tons of paste per year of which 12,000 tons are exported after being repackaged, suggesting a domestic tomato paste consumption of around 66,000 tons in 2007.

There has been efforts by farmers, government and researchers to intensify the production of tomatoes to meet the demands of the local market. In this study, the interactive effect of biochar and irrigation on growth and yield of tomato was assessed.

Biochar also known as 'black gold' for agriculture, is being used increasingly in agriculture with an intention to mitigate climate change by sequestering carbon (C), improving soil properties and functions and enhancing crop yield (Lehmann, 2007; Sohi *et al.*, 2010). Streubel *et al.* (2011) reported that biochar enhance water holding capacity of soil and this indicate that soil amendment with biochar may improve crop productivity by retaining more water from rainfall and reduce the frequency or amount of irrigation water. What makes the use of biochar in crop production sustainable is that crop residues that will eventually be damped off, are used to produce biochar (Sohi *et al.*, 2010) as a way of recycling organics.

Climate change is leading to erratic rainfall and increased duration of drought. It is therefore important to improve irrigation to reduce the amount of water used in crop production. As drip irrigation is capable of applying small amounts of water and fertilizer precisely where it is needed and with a high degree of uniformity and frequency, it represents a potentially much more efficient method for increased water- and fertilizer-use efficiency than other irrigation methods (Hanson *et al.*, 1997). In addition, excess or deficit soil water content limits crop root growth and development, which reduces root absorbing area and capacity (Kang & Zhang 2004; Ehdaie *et al.*, 2010). Also deficit drip irrigation involves less water than potential evapotranspiration (English *et al.*, 1990) and has received increased attention.

The overall objective of this study was to determine the effect of corn cob biochar and drip irrigation on the growth, yield, quality and shelf life of tomato in the coastal savannah zone of Ghana.

Materials and methods

Experimental details

The experiment was conducted in the major growing seasons in June to October, 2016 and repeated in July to October, 2017. Pectomech tomato variety was used in this experiment. Details of the experimental plot sizes and treatments are described in chapter three of this thesis.

Nursery and transplanting

The tomato seeds (Pectomech) purchased from an agricultural input shop in Cape Coast was primed by putting it in fridge for two days before sowing. Plant nursery was established and synchronized with the planting date. The seeds were nursed on nursery beds for a period of one month after which the healthy seedlings were transplanted to the experimental plots when they had attain about 4-6 leaves. All necessary nursery management was undertaken for a good quality seedlings.

Data collection

An area of 5.4 m^2 from each plot of 18 m^2 was demarcated for yield data and the rest was demarcated for the measurement of crop growth parameters. Details of the data collected in these experiments are described as follows.

Tomato morphological parameters

Six (6) tomato plants were randomly tagged for the measurement of non-destructive morphological parameters.

Plant height

The height of the tomato plant was determined by using a meter ruler to measure from soil surface level to the tip of the plant shoot starting from 14 days after transplanting (DAT) and continued till 42 DAT and the average height (cm) was calculated.

Number of branches and leaves per plant

Number of primary branches and leaves on the main stem was counted from 14 to 42 DAT.

Stem girth

The girth of the main stem at 5 cm above the soil level was measured using Vernier callipers at 14 to 42 DAT and the average girth was determined and expressed in centimetres.

Above and below ground biomass weight

Four (4) were randomly selected from each treatment. These plants were uprooted and divided into below and above-ground biomass. These parts were weighed for their fresh weight and then dried in an oven at 80 $^{\circ}$C until a constant weight was obtained and their dry weights was recorded. The fresh and dry weights of tomato biomass was measured every 14 days till the 42nd day after transplanting. The mean weight was expressed as fresh and dry weights in g plant^{-1}.

Crop growth rate (CGR)

This is the rate of dry matter production per unit ground area per unit time. It was determined by using the formulae given by Watson (1952) and expressed as gm^{-2}day^{-1}. Crop growth rate was measured at 14, 28 and 42 DAT.

$$CGR = \frac{W2 - W1}{P(T2 - T1)}$$

Where,

W1 and W2 is dry weight of the plant (g/m^2) at time T1 and T2 (time interval in days) respectively. P is the unit land area.

Chlorophyll content

Chlorophyll content meter (CCM-200 plus) was used to measure the amount of chlorophyll present (CCI). Measurements were taken on 14, 28 and 42 DAT.

Tomato fruit yield and quality parameters

Number of fruits per plant

Matured fruits were harvested at the yellow ripe stage from the 5.4 m^2 demarcated area and counted and the total number of fruits per plant was determined.

Average fruit weight (g)

At each harvest day the total number of marketable fruits from the marked (5.4 m^2) area from each plot were weighed and the mean fruit weight was calculated. The mean fruit weight was initially taken in kg per plot and converted to t ha^{-1}.

Equatorial and polar diameter of the tomato fruit

The polar diameter of the tomato fruit was measured from the stalk end to blossom end of the fruit whereas the equatorial diameter of the fruit was measured from the fruit breadth at the maximum bulged portion using Vernier callipers. An average of 3 fruits from each plot was used to determine these two fruit parameters and the averages were expressed in millimetres.

Fruit quality and shelf life

Tomato fruit shelf life

After harvest five (5) marketable fruits were selected from each plot making a total of 20 fruit sampled from each treatment. The fruits were harvested at near riped stage and stored under ambient temperature and relative humidity conditions of 26 to 27°C and 85 to 95%, respectively. The shelf life was then determined by counting the number of days taken for all fruits to deteriorate. Rotten fruits were taken away from the rest to prevent any cross contamination of microbes to healthy fruits.

Fruit quality analyses

The total soluble solids (°Brix) and pH were examined on 10 representative fruit sampled from each treatment. An extract was obtained by squeezing each fruit into a pulp. The total soluble solids was then determined using a portable, digital refractometer (Atago DR-A1) and the pH of the fruits was determined using a digital pH meter.

Statistical analysis

All data on tomato growth, yield and quality traits measured were subjected to analysis of variance (ANOVA) using the GenStat statistical package (GenStat, 2007). When significant differences occurred among the experimental plots, the Tukey's HSD test was used to differentiate between the means at 5 % level of probability.

Results

Influence of biochar and irrigation on tomato growth parameters

Significant differences among biochar treatments were observed in tomato for biweekly number of leaves in the 2016 growing season. Biochar at a rate of 20 t ha^{-1}, 10 t ha^{-1} and the control had similar effect and produced the low number of leaves compared to biochar at a rate of 20+P t ha^{-1} which was significantly (P <0.001) high in the first two week. It was generally observed that an increased in biochar increased the number of leaves. In all weeks the control plots had the least influence on the number of leaves of tomato. There were no significant differences among irrigation regimes for tomato number of leaves in all weeks. Again, there were no significant biochar and irrigation interaction effect on tomato number of leaves (Table 7.1a).

In the 2017 growing season similar trend was followed where an increase in biochar increased the number of leaves. Plots treated with 20+P t ha^{-1} produced significantly (*P* <0.001) high number of leaves compared to the control plots. Irrigation also did not significantly affect number of leaves in the 2017 growing season. However, a significant biochar and irrigation interaction effect on number of leaves at 28 and 42 DAP was observed (Table 7.1b).

Table 7.1a: Impact of irrigation and biochar on tomato leaf number in 2016

	Number of leaves		
Treatment	14	28	42
Biochar rate			
Control	6b*	11c	15c
10	6b	12c	17bc
20	6b	15b	19b
20+P	8a	17a	22a
P-value	<0.001	<0.001	<0.001
S.E.D	0.479	0.688	0.644
Irrigation regime			
DI	7	14	18
FI	7	14	18
P-value	0.532	0.714	0.39
S.E.D	0.434	0.602	0.351
B × I (*P*-value)	0.313	0.75	0.871
S.E.D	0.73	1.036	0.864

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.1b: Impact of irrigation and biochar on tomato leaf number in 2017

	Number of leaves		
Treatment	14	28	42
Biochar rate			
Control	8c*	17d	22d
20	10b	20c	26c
40	11ab	26b	32b
40+P	12a	32a	39a
P-value	<0.001	<0.001	<0.001
S.E.D	0.5	0.954	0.905
Irrigation regime			
DI	10	24	29
FI	11	24	30
P-value	0.387	0.678	0.202
S.E.D	0.500	0.908	0.871
B × I (*P*-value)	0.481	0.039	0.028
S.E.D	0.8	1.48	1.41

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

The results of the main and interactive effects of biochar and irrigation on tomato stem branches is shown in Table 7.2a. An increase in biochar rate significantly (P <0.001) increased the number of branches. Plots amended with biochar at the rate of 20+P t ha^{-1}, 20 t ha^{-1} and 10 t ha^{-1} produced significantly high number of stem branches compared with the number of branches produced on the control plots. However, biochar at the rate of 20+P t ha^{-1} produced significantly high number of stem branches compared to the other biochar treatments. There was no significant (P = 0.772) irrigation effect on number of branches of tomato. There was also no significant biochar and irrigation interactive effect on number of stem branches in the 2016 growing season (Table 7.2a).

In 2017, biochar effect on number of tomato stem branches was similar to the stem branches obtained in 2016 where biochar rates significantly ($P < 0.001$) increased the number of stem branches. Similar in 2016, irrigation had no significant ($P = 0.934$) effect on number of tomato stem branches. However, there was significant ($P = 0.01$) biochar and irrigation interactive effect on the stem branches (Table 7.2b).

Table 7.2a: Effect of biochar and irrigation on tomato number of branches in 2016

Treatment	Number of stem branches
Biochar rate	
Control	2d*
10	3c
20	4b
20+P	5a
P-value	<0.001
S.E.D	0.3
Irrigation regime	
DI	3
FI	4
P-value	0.772
S.E.D	0.2
B × I (*P*-value)	0.262
S.E.D	0.4

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.2b: Effect of biochar and irrigation on tomato number of branches in 2017

Treatment	Number of Branches
Biochar rate	
Control	2c*
20	2c
40	4b
40+P	7a
P-value	<0.001
S.E.D	0.26
Irrigation regime	
DI	4
FI	4
P-value	0.934
S.E.D	0.231
B × I (*P*-value)	0.01
S.E.D	0.393

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

The effect of biochar and irrigation on tomato plant height in the 2016 growing season is shown in Table 7.3a. There was a significant (P <0.001) effect of biochar on tomato plant height. It was observed that an increase in biochar rate increases the amount of the height of the tomato plants. The highest plant height (60 cm) was recorded at 42 DAP on the plots amended with 20+P t ha^{-1}. The lowest plant height was recorded on the 10 t ha^{-1} and the control plots. There was a significant (P = 0.018) effect of irrigation on tomato plant in the first 2 weeks after planting where FI significantly influenced plant height compared to DI. Irrigation did not significantly affect tomato plant height in the 14th and 42nd DAP. There was no significant biochar and irrigation interaction effect on tomato plant height.

In the 2017 growing season, the effect of biochar on tomato plant height was similar to what was recorded in 2016. An increase in biochar significantly (P <0.001) increased plant height. The highest plant height (70.21 cm) recorded was from the plots treated with 40+P t ha^{-1}. Irrigation regimes, however, did not significantly affected tomato plant height in the 2017 growing season. Significant (P = 0.02) biochar and irrigation interactive effect on plant height was only observed at 28 DAP (Table 7.3b).

Table 7.3a: Biochar and irrigation effect on tomato plant height in 2016

	Plant height (cm) over DAP		
Treatment	14	28	42
Biochar rate			
Control	26b*	35c	48b
10	27b	35c	49b
20	28ab	38b	52b
20+P	30a	43a	60a
P-value	<0.001	<0.001	<0.001
S.E.D	0.851	0.916	1.804
Irrigation regime			
DI	27b	36.58	50
FI	29a	38.85	55
P-value	0.018	0.154	0.113
S.E.D	0.315	1.198	1.928
B × I (*P*-value)	0.334	0.69	0.814
S.E.D	1.089	1.641	2.932

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.3b: Biochar and irrigation on tomato plant height in 2017

	Plant height (cm)		
Treatment	14	28	42
Biochar rate			
Control	29.85b*	52.12b	62.79c
20	30.06b	54.02b	64.3c
40	31.03b	62.25a	69.02b
40+P	32.8a	64.06a	73.21a
P-value	<0.001	<0.001	<0.001
S.E.D	0.515	0.998	1.059
Irrigation			
DI	30.97	57.99b	66.95
FI	30.9	58.24a	67.71
P-value	0.86	0.82	0.35
S.E.D	0.379	1.014	0.693
B × I (*P*-value)	0.64	0.02	0.785
S.E.D	0.736	1.588	1.47

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.4a shows the effect of biochar and irrigation on tomato leaf chlorophyll content index (CCI) measured in the 2016 growing season. There was significant (P <0.001) effect of biochar on tomato leaf CCI. Generally, an increase in biochar rate increased the amount of CCI in the leaves, where plots amended with 20+P t ha^{-1} recorded the highest CCI in all weeks. At 14 DAP and 42 DAP irrigation regimes influenced CCI significantly (P = 0.002 and P = 0.019, respectively). In each case DI significantly increased CCI compared to FI. There were no significant biochar and irrigation interaction effect on tomato leaf CCI.

The effect of biochar on CCI recorded in the 2017 growing season was similar to that recorded in the 2016 growing season. The trend changed in 2017 where there was no significant effect of irrigation on tomato CCI, however, a similar trend was that DI plots recorded high CCI compared to FI plots. Again, there were significant biochar and irrigation interaction effect on tomato leaf CCI (Table 7.4b).

Table 7.4a: Effect of biochar and irrigation on chlorophyll content of tomato leaves in 2016

	Chlorophyll content index		
Treatment	14	28	42
Biochar rate			
Control	13.19c*	25.26c	26.51c
10	15.53b	28.05bc	31.22b
20	16.61ab	29.87b	32.86ab
20+P	18.11a	32.95c	35.79a
P-value	<0.001	<0.001	<0.001
S.E.D	0.784	1.053	1.205
Irrigation			
DI	16.93a	30.43	33.54a
FI	14.78b	27.63	29.65b
P-value	0.002	0.14	0.019
S.E.D	0.200	1.405	0.839
B × I (*P*-value)	0.546	0.333	0.572
S.E.D	0.981	1.907	1.698

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.4b: Effect of biochar and irrigation on chlorophyll content of tomato leaves in 2017

	Chlorophyll content index		
Treatment	14	28	42
Biochar rate			
Control	14.20c*	26.58c	28.82c
20	15.36bc	29.36b	32.61b
40	16.85ab	30.43b	33.14b
40+P	17.75a	33.32a	36.61a
P-value	<0.001	<0.001	<0.001
S.E.D	0.543	0.964	1.184
Irrigation			
DI	17.11	32.09	35.06
FI	14.96	27.76	30.53
P-value	0.045	0.029	0.025
S.E.D	0.65	1.101	1.092
B × I (*P*-value)	0.082	0.682	0.866
S.E.D	0.93	1.614	1.815

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

In the 2016 growing season, biochar significantly (P <0.001) influenced the number of days to 50 percent flowering. It took significantly less number of days (37) for plants on the 20+P t ha^{-1} amended plots to produced 50% flowers compared to the control plots (40 days). It was observed generally that an increase in the amount of biochar applied reduced the number of days for the tomato plants to attain 50% flowering stage. Irrigation regime did not significantly (P = 0.312) affect the number of days the plants reach 50% flowering. There was also no significant (P = 0.227) biochar and irrigation interaction effect on days to 50% flowering of tomato plants (Table 7.5a).

In the 2017, the effect of biochar on days to 50% flowering was similar to that of 2016. However, plots with 40+P t ha^{-1} significantly had less number of days to 50% flowering compared to the control, 20 t ha^{-1} and 40 t ha^{-1} plots which recorded high number of days to 50% flowering. There was no significant (P = 1.000) effect of irrigation on days to 50% flowering of tomato plants. The 2017 growing season also recorded a no significant (P = 0.286) biochar and irrigation interaction effect on days to 50% flowering (Table 7.5b).

7.5a: effect of biochar and irrigation on days to 50% flowering of tomato in 2016

Treatment	Days to 50% flowering
Biochar rate	
Control	40a*
10	39ab
20	38b
20+P	37c
P-value	<0.001
S.E.D	0.504
Irrigation regime	
DI	38
FI	39
P-value	0.312
S.E.D	0.258
B × I (*P*-value)	0.227
S.E.D	0.669

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.5b: Effect of biochar and irrigation on days to 50% flowering of tomato in 2017

Treatment	Days to 50% flowering
Biochar rate	
Control	39.38a*
20	38.75a
40	38.75a
40+P	36.62b
P-value	<0.001
S.E.D	0.479
Irrigation regime	
DI	38.38
FI	38.38
P-value	1.000
S.E.D	0.306
B × I (*P*-value)	0.286
S.E.D	0.661

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Biochar rate significantly (P <0.001) affected the dry above-ground biomass of the tomato plants in the 2016 growing season. Plots treated with 10 and 20 t ha^{-1} recorded similar above-ground biomass but was significantly different from that of the control plots. However, the general trend was that the 20+P t ha^{-1} biochar amended plots recorded significantly high amount above-ground biomass compared to the control and other biochar amended plots. The first 2 weeks after transplanting recorded a significant (P = 0.042) effect of irrigation on tomato above-ground biomass. There were no significant irrigation effect on above-ground biomass at 28 and 42 days after transplanting but the first 2 weeks after transplanting showed a significant (P = 0.026) biochar and irrigation interaction effect (Table 7.6a).

In 2017, the effect of biochar on above-ground biomass was similar to that of 2016. An increase in biochar rate increased the amount of biomass produced. The highest above-ground biomass was recorded on the 40+P t ha^{-1} biochar amended plots compared to the control plots. There was no significant irrigation and biochar and irrigation interactive effect on the tomato above-ground biomass (Table 7.6b).

Table 7.6a: Tomato above-ground biomass as affected by biochar and irrigation in 2016

	Above-ground biomass (g plant^{-1})		
Treatment	14	28	42
Biochar rate			
Control	18.28c*	29.12c	36.40c
10	26.14b	37.92bc	47.37b
20	30.98b	44.19b	55.22b
20+P	42.21a	60.89a	72.76a
P-value	<0.001	<0.001	<0.001
S.E.D	2.246	4.22	3.58
Irrigation			
DI	31.11a	44.1	53.9
FI	27.69b	41.9	52
P-value	0.042	0.423	0.424
S.E.D	0.998	2.35	2.06
B × I (*P*-value)	0.026	0.94	0.951
S.E.D	2.927	5.68	4.85

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.6b: Tomato above-ground biomass as affected by biochar and irrigation in 2017

Treatment	Above-ground biomass (g plant^{-1})		
	14	28	42
Biochar rate			
Control	19.2c	34.9c	57.5d
20	27.4bc	45.4bc	74.8c
40	33.4b	52.9b	85.7b
40+P	49.5a	71.9a	98.0a
S.E.D	4.1	4.8	3.27
P-value	<0.001	<0.001	<0.001
Irrigation			
DI	33.5	52.3	79.9
FI	31.3	50.2	78
S.E.D	2.24	2.6	2.04
P-value	0.392	0.474	0.423
B × I (*P*-value)	0.949	0.972	0.971
S.E.D	5.5	6.43	4.49

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Biochar rates significantly (P <0.001) affected below-ground biomass of tomato. It was observed that as biochar rates increased below-ground biomass also increased. However, the increase was highly significant on the 20+P t ha^{-1} biochar treated plots compared to the control, 10 and 20 t ha^{-1} biochar treated plots. Irrigation had no significant (P = 0.222) effect on tomato root weight. However, there was a significant (P = 0.003) biochar and irrigation interactive effect on tomato root weight (Table 7.7a).

In 2017, biochar effect of root weight was similar. However, there was a significant (P = 0.041) effect of irrigation on root weight in 2017. There was also a significant (P = 0.004) biochar and irrigation interaction effect on tomato root weight (Table 7.7b).

Table 7.7a: Below-ground biomass of tomato as affected by biochar and irrigation in 2016

Treatment	Below-ground biomass (g plant^{-1})
Biochar rate	
Control	2.38c*
10	2.99b
20	2.99b
20+P	3.66a
P-value	<0.001
S.E.D	0.183
Irrigation regime	
DI	2.985
FI	3.025
P-value	0.222
S.E.D	0.026
B × I (*P*-value)	0.003
S.E.D	0.225

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.7b: Below-ground biomass of tomato as affected by biochar and irrigation in 2017

Treatment	Below-ground biomass (g plant^{-1})
Biochar rate	
Control	2.04c*
20	2.83b
40	3.10b
40+P	3.94a
P-value	<0.001
S.E.D	0.199
Irrigation regime	
DI	2.85b
FI	3.11a
P-value	0.041
S.E.D	0.075
B × I (*P*-value)	0.004
S.E.D	0.255

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

The rate of tomato crop growth was significantly affected by biochar only at the first 14 days after transplanting (DAT). It was realised at this stage that as biochar rate increased crop growth rate (CGR) also increased. Tomato CGR declines from 14 DAT to 42 DAT. There was no significant effect of biochar rate on CGR at 28 DAT (P = 0.24) and 42 DAT (P = 0.239) (Table 7.8a). Figure 7.1 shows the effect of biochar on growth of tomato plants on plots under irrigation. The figure indicates that biochar have an influence on the growth of tomato plants. With the exception 14 DAT, irrigation did not significantly affect CGR of tomato plants. There was significant (P = 0.026) effect of biochar and irrigation interaction on CGR at 14 DAT. There were no significant biochar and irrigation interaction effect on CGR at 28 DAT (P = 0.57) and at 42 DAT (P = 0.933).

In 2017, tomato CGR declined from 14 DAT to 28 DAT but rose from 28 DAT to 42 DAT. Biochar significantly (P <0.001) influenced CGR at 14 DAT and 28 DAT. Biochar did not influence tomato CGR at 42 DAT. Irrigation did not significantly affected tomato CGR at all the sampling periods. There was also no significant biochar and irrigation interaction effect on to tomato CGR (Table 7.8b).

Table 7.8a: Effect of biochar and irrigation on the rate of growth of tomato plant in 2016

	Crop growth rate (g m^{-2} day^{-1})		
Treatment	14	28	42
Biochar rate			
Control	2.18c	1.29	0.87
10	3.11b	1.4	1.13
20	3.69b	1.57	1.31
20+P	5.03a	2.22	1.41
P-value	<0.001	0.24	0.239
S.E.D	0.27	0.474	0.275
Irrigation regime			
DI	3.7	1.55	1.164
FI	3.3	1.7	1.196
P-value	0.042	0.7	0.893
S.E.D	0.12	0.351	0.219
B × I (*P*-value)	0.026	0.57	0.933
S.E.D	0.35	0.678	0.401

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.8b: Effect of biochar and irrigation on the rate of growth of tomato plant in 2017

	Crop growth rate (g m^{-2} day^{-1})		
Treatment	14	28	42
Biochar rate			
Control	2.29c	1.862c	2.69
20	3.26bc	2.137bc	3.5
40	3.98b	2.313b	3.9
40+P	5.89a	2.663a	3.11
P-value	<0.001	<0.001	0.163
S.E.D	0.488	0.1127	0.531
Irrigation regime			
DI	3.99	2.237	3.29
FI	3.72	2.25	3.32
P-value	0.392	0.851	0.85
S.E.D	0.267	0.0631	0.136
B × I (*P*-value)	0.949	0.856	0.998
S.E.D	0.654	0.152	0.664

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Figure 7.1: Effect of biochar on growth of tomato plants 31 days after transplanting. *Left*: tomato plants on plot with no biochar amendment. *Right*: tomato plants on plot amended with biochar.

Effect of biochar and irrigation on tomato fruit yield and yield parameters

Table 7.9a and 7.9b shows the effect of biochar and irrigation on tomato yield parameters such as weight of fruit per hectare, number of fruits per plant and size of fruit. Biochar significantly (P <0.001) influenced all the yield parameters measured. Tomato fruit yield obtained indicates that weight of fruits increased with increased rate of biochar applied. Again the plots amended with biochar at the rate of 20+P t ha^{-1} recorded significantly the highest fruit weight, number of fruits and size of tomato fruit compared to that of the control plots. Irrigation significantly affected all yield parameters measured. Generally, yield parameters recorded on the FI plots performed significantly better than those from the DI plots. Number of fruit per plant, equatorial and polar diameter of tomato fruit were significantly (P <0.001) affected by biochar and irrigation interaction. Tomato fruit yield was also influenced significantly (P = 0.028) affected by biochar and irrigation interaction (Table 7.9a).

In the 2017 growing season, biochar significantly (P <0.001) affected number of fruit per plant and fruit weight. Plots treated with 40 and 40+P t ha^{-1} significantly performed better than the control plots. However, biochar did not significantly affected tomato fruit polar and equatorial dimeter (*P* = 0.881 and 0.312, respectively). Irrigation significantly affected the number of fruit per plant (*P* = 0.001), fruit equatorial diameter (*P* = 0.021) and fruit weight (*P* <0.001). There was no significant (*P* = 0.752) effect of irrigation on fruit polar diameter. Biochar and irrigation interaction effect did not influence all the yield parameters measured (Table 7.9b).

Table 7.9a: Effect of biochar and irrigation on tomato fruit yield and yield parameters in 2016

Treatment	Number of fruit per plant	Fruit equatorial diameter (mm)	Fruit polar diameter (cm)	Fruit weight (t ha^{-1})
Biochar rate				
Control	6c*	44.62a	47.85b	10.21c
10	6c	41.16c	46.49c	11.53c
20	8b	42.16b	47.90b	13.82b
20+P	9a	41.99b	50.17a	16.14a
P-value	<0.001	<0.001	<0.001	<0.001
S.E.D	0.4	0.111	0.053	0.801
Irrigation regime				
DI	6b	41.06b	45.96b	11.89b
FI	7a	43.90a	50.25a	13.82a
P-value	0.01	0.001	<0.001	0.007
S.E.D	0.2	0.104	0.02	0.318
B × I (*P*-value)	<0.001	<0.001	<0.001	0.028
S.E.D	0.50	0.171	0.067	1.031

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.9b: Effect of biochar and irrigation on tomato fruit yield and yield parameters in 2017

Treatment	Number of fruits per plant	Fruit equatorial diameter (cm)	Fruit polar diameter (cm)	Fruit yield (t ha^{-1})
Biochar rate				
Control	16.16b*	4.30	5.06	25.24b
20	18.51b	4.36	4.97	27.38b
40	20.24ab	4.51	4.97	30.72ab
40+P	23.62a	4.40	5.03	35.18a
P-value	<0.001	0.312	0.881	<0.001
S.E.D	1.468	0.109	0.131	2.018
Irrigation regime				
DI	18.33b	4.28b	4.98a	27.81b
FI	20.94a	4.51a	5.04a	31.45a
P-value	0.001	0.021	0.752	<0.001
S.E.D	0.213	0.051	0.19	0.193
B × I (*P*-value)	0.156	0.819	0.177	0.243
S.E.D	1.81	0.143	0.249	2.479

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Effect of biochar and irrigation on tomato fruit quality and shelf life in 2016

The results of the effect of biochar on tomato fruit pH, total soluble solids (Brix^{o}) and shelf life measured in the 2016 growing season is presented in Table 7.10a. Biochar had no significant (P = 0.072) effect on pH. Biochar rate significantly (P = 0.03) total soluble solids. Plots treated with 20+P t ha^{-1} significantly influence the brix content of tomato fruit compared to the brix content obtained from the control plots. Brix content from the plots treated with 10 and 20 t ha^{-1} was similar. The shelf life of tomato fruits were significantly (P <0.001) affected by biochar rate. Plots treated with 20+P and 20 t ha^{-1} biochar stored for about 16 days, significantly more than the shelf life of fruits from the control and the 10 t ha^{-1} biochar treated plots. There was no significant (P =

0.424, *P* = 0.312 and *P* = 0.27) effect of irrigation on tomato fruit pH, brix content and fruit shelf life, respectively. There were also no significant biochar and irrigation interaction effect on all quality parameters measured.

In the 2017 growing season biochar did not significantly affect tomato fruit pH and brix content. However, biochar rate significantly (*P* = 0.036) affected tomato fruit shelf life. Irrigation did not significantly affected tomato fruit pH, brix content and shelf life. Biochar and irrigation interaction significantly (*P* = 0.045) affected tomato shelf life but not pH and brix content (Table 7.10b).

Table 7.10a: Effect of biochar and irrigation on tomato fruit quality in 2016

Treatment	pH	Total soluble solids (Brix^o)	Tomato fruit shelf life (days)
Biochar rate			
Control	4.14	3.85b*	15.00b
10	4.04	4.03ab	14.00c
20	4.17	4.09ab	16.00ab
20+P	4.17	4.32a	16.00a
P-value	0.072	0.03	<0.001
S.E.D	0.052	0.14	0.32
Irrigation regime			
DI	4.10	4.15	15.00
FI	4.16	3.996	16.00
P-value	0.424	0.312	0.27
S.E.D	0.067	0.127	0.22
B × I (*P*-value)	0.287	0.788	0.785
S.E.D	0.092	0.214	0.45

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Table 7.10b: Effect of biochar and irrigation on tomato fruit quality in 2017

Treatment	pH of tomato fruit	Total soluble solids (Brix°)	Tomato fruit shelf life (days)
Biochar rate			
Control	4.118	4.13	20ab*
20	4.039	4.21	20b
40	4.149	4.2	21ab
40+P	4.125	4.36	21a
P-value	0.329	0.326	0.036
S.E.D	0.061	0.126	0.514
Irrigation regime			
DI	4.081	4.28	20
FI	4.135	4.17	21
P-value	0.481	0.437	0.302
S.E.D	0.068	0.125	0.282
B × I (*P*-value)	0.321	0.2	0.045
S.E.D	0.101	0.199	0.69

P: phosphorus, B: biochar application rate, I: irrigation regime, FI: full irrigation, DI: deficit irrigation and NI: no irrigation. *Figures without letters in a column indicate no significant differences between them while those with different letters indicate significant differences between the means.

Discussion

Effect of biochar and irrigation on tomato growth

One of the important plant growth parameters which aid in improving tomato growth and yield is the chlorophyll content because of its key role in assimilate production. In this experiment, biochar significantly influenced the content of chlorophyll in tomato leaves in both seasons. The chlorophyll content index in these experiments increased with increasing biochar rates. This result is in agreement with the results of Agegnehu *et al.* (2015) who indicated that biochar at a high rate improves higher leaf chlorophyll content especially as the plant ages. However, some researchers reported the reverse of our results that there was a decrease in the chlorophyll content after biochar application (Asai *et al.*, 2009; Ventura *et al.*, 2013). Chlorophyll content is not only dependent on soil fertility. It also depend on environmental conditions like temperature, humidity and sunlight. Despite the fact that biochar improves soil fertility does not guarantee the ultimate increase in chlorophyll content of plants.

Although there was no significant effect of irrigation on below and above-ground biomass, biochar had a significant impact on biomass yield. This could be due to the fact that biochar promotes growth by adsorbing available plant nutrients and gradually release to the plants when needed. This is in line with Schiefeibein and Benfey (1991) who detected an increase in root length and biomass related to high concentrations of biochar. As biochar adsorb and release plant nutrients, the rate at which plants grow was also affected, an observation made in this experiment, that, increased biochar rate influenced the growth rate of tomato. This is in agreement with Hansen *et al.* (2016) who indicated that biochar amendments improve plant growth. Biochar also significantly affected the height of tomato plants and this was similar to the findings of Graber *et al.* (2010) who reported an increase in the height of tomato plants after the application of biochar. The number of branches increased as a result of increased biochar rate, hence, an increase in the number of leaves. This affected the overall growth of tomato plants because there was more leaves to receive the phosynthetically active radiation available for plant growth. This has been confirmed by Law-Ogbomo & Remison, (2008) who indicated that increased number of leaves boosted the exploitation of solar radiation.

The general trend of the number of days taken for tomato plants to achieve 50% flowering was that tomato grown under treatments with high biochar rate, especially treatments loaded with P achieved 50% flowering earlier than those without P and the control. This is an indication that biochar works perfectly when fertilizer is added to it. Findings of Zotarelli *et al.* (2009) agree to this results, that, fertilizer application speeds up the vegetative and reproductive stages of the tomato growth.

Effect of biochar and irrigation on tomato fruit size and yield

Tomato fruit yield in terms of weight in this experiment was highly influenced by biochar which was in line with reports from Hammer *et al*. (2015) who stated that an increase in biochar increased tomato fruit yield. It was observed from the study that tomato fruits obtained from plots treated with biochar at the rate of 20 and 40 t ha^{-1} in 2016 and 2017 was significantly higher than those from the control, 10 and 20 t ha^{-1} plots respectively. However, the significantly highest amount of tomato fruits produced was from biochar treatments loaded with P, thus, 20+P and 40+P t ha^{-1} in 2016 and 2017 respectively. This finding is in agreement with Makinde *et al.* (2001) who stated that a judicious combination of organic and inorganic (NPK) fertilizers is critical for tomato growth and yield. Our finding implies that to improve growth and yield of tomato and other crops through the use of biochar, it is necessary to supplement the biochar with some amount of organic or inorganic nutrients. Dumas *et al*. (2003) and Zottarelli *et al*. (2009) also support this assertion. The high number of branches and leaves in this experiment affected tomato yield significantly. One of the reasons why Burkina Faso achieve higher yields of tomato than Ghana is because of cultivation on dam catchment areas to receive additional source of water to supplement the rain water (Robinson & Kolavalli, 2010). Since biochar could retain water and nutrients Ghana, could achieve high yields of tomato to alleviate the imports of tomato when biochar and irrigation are applied.

The size of tomato fruit is generally variety dependent. However, biochar significantly affected the size of tomato variety (Pectomech) fruits obtained in this experiment. It was generally observed that fruit size and number had a significant effect on yield. In this experiment, fruits obtained from the control treatments were relatively bigger compared to the fruits from biochar treatments. However the number of fruits from the control plots were significantly lower than those from biochar treated plots, hence influenced yield significantly. Patanè and Cosentino (2010) reported a decrease in fruit size due to water deficit, however, our findings suggested that there was no effect of irrigation on tomato fruit size.

Though most consumers prefer bigger sized tomatoes, an important indicator of fruit quality (pH) and TSS are preferred by tomato processing companies because they have influence on good flavour and taste (Malundo *et al*., 1995) of tomato fruit. In this experiment the quality parameters measured was pH and TSS. Biochar did not have a significant effect of pH and TSS. However, the pH and TSS (Brix^{o}) was relatively higher in tomato cultivated from biochar treatments with 20+P and 40+P t ha^{-1} under full irrigation than in deficit irrigation, an indication that biochar and irrigation improved the quality of tomato in this experiment. The high pH and TSS obtained in this experiment was around 4.2 and 4.3 respectively. This result is in line with Anthon *et al*. (2011) who stated that the optimum pH value for riped tomatoes is around 4.25. The general effect of irrigation and biochar on tomato fruit quality is in agreement with the findings of Akhtar *et al*. (2014). Petruccelli *et al*. (2015) also established that tomato yield and quality was improved when straw and olive residue biochar was applied.

Although the reduced shelf life of tomato in most African countries is mostly due to lack of storage facilities (Kitinoja & Gorny, 2009), it could be also due to the quality of fruits produced. This experiment revealed that there was significant influence of biochar on tomato shelf life. In this experiment, tomato fruits produced on plots treated with 20+P and 40+P t ha^{-1} stored better. The effect of biochar and the storage condition (27°C and 85-95% relative humidity, respectively) of tomato fruits in this experiments agree with Dumas *et al*. (2003) who stated that quality of tomato fruits depends on the temperature between 12°C and below 30°C.

Conclusion

The study revealed that biochar increased growth and yield of tomato. However, biochar loaded with phosphorus before application to the soil significantly increased growth and yield of tomato. This could be a basis for more research to be conducted on other vegetable crops to ascertain the importance of biochar on the growth and yield of high-value horticultural crops.

CHAPTER EIGHT

SUMMARY, GENERAL CONCLUSIONS AND RECOMMENDATIONS

Summary

The pot and field experiments were conducted to determine effects of corn cob biochar and irrigation on the growth and yield of maize, cowpea and tomato. These experiments were set out generally to sustainably improve and intensify high value crop production strategies in Ghana. It is relevant because currently the methods of crop production in Ghana is slash-and-burn (deforestation) and shifting cultivation and it is also highly rainfall dependent even though the menace of climate change was faced. These methods of cropping have however not showed an increase in crop productivity per unit of land. The application of biochar to agricultural fields in an ecological manner increases soil fertility, growth and yield of crops, sequest atmospheric carbon into the soil and also reduce deforestation and improve on sanitation when crop residues are used for biochar.

The results of the experiments have indicated that biochar and irrigation can improve crop growth and yield. It has also shown that an agricultural country like Ghana should not only depend entirely on rains for crop production but to support it with a form irrigation, especially, drip irrigation. The long term effect is enormous as it will improve the livelihood of farmers and their dependants and all stakeholders by reducing cost of production and creating employments. Again, the agenda to feed the ever increasing population in Ghana and other parts of the world will be achieved.

Conclusions

Soil fertility management and crop yield has been on the decline over the past four decades in Ghana. The main objective of this study was to determine the integrated impact of corn cob biochar and drip irrigation on growth, yield and quality of maize, cowpea and tomato in the coastal savanna zone of Ghana. The main findings of the research are summarised below:

1. Corn cob biochar at rate of 20-80 t ha^{-1} used in the pot experiments improved maize growth parameter measured. There was no adverse effect of biochar on maize even at the highest level of biochar applied. Biochar of particle size <2 mm generally increased leaf number, leaf area, leaf chlorophyll content, plant height and above-ground biomass significantly. Generally, there was no significant difference between full and deficit irrigation on plant height, leaf area and fresh and dry above-ground biomass. Again, the effect of phosphorus on maize growth was prominent when phosphorus was loaded with biochar before its application to the soil compared with when NPK was applied after planting. The hypothesis that biochar rate, biochar particle size, fertilizer and irrigation do not affect the growth of maize is therefore rejected.
2. Biochar treatment of 20 + P and 40+P t ha^{-1} gave the highest grain yield in all the irrigation treatments but it was not significantly different from grain yields from biochar applied at 20 and 40 t ha^{-1}. The superior performance of maize under the biochar and irrigation treatments

provides great opportunities to improve maize grain yield on smallholder farmers' fields in Ghana. The maize grain yield (8.06 t ha^{-1}) obtained in this experiment was five times more than the average yields (1.2-1.8 t ha^{-1}) achieved in Ghana. The current maize grain yield in is even below the potential yield (4-6 t ha^{-1}). Generally, biochar treatment without irrigation reduced growth and produced poor grain and cob yields compared to biochar treatment with irrigation. However, there was a clear tendency of a positive interaction between irrigation and biochar for grain yield. This was positively due to the positive synergistic effect of biochar and irrigation to make nutrients available to crops. Intercropping with cowpea reduced the number of times weeding was done during the growing season of maize from 3 to 2 on the 20 and 20+P t ha^{-1} biochar treated plots. Biochar loaded with phosphorus may have made soil nutrients, especially, phosphorus available to the plants, hence improved growth and yield of maize. The hypothesis that biochar and irrigation do not affect growth and yield of maize was rejected.

3. Biochar generally improved all the cowpea growth and yield parameters measured. The higher the rate of biochar the higher the performance of cowpea growth and yield parameters. However, biochar treatments loaded with phosphorus significantly improved cowpea growth and yield. On other hand, irrigation also improved all the measured growth and yield parameters with exception of stem girth. There was significantly higher interactive effect of biochar and irrigation on all measured cowpea growth and yield parameters.

Therefore, the hypothesis that biochar and irrigation does not influence the growth and yield of cowpea in maize-cowpea intercrop is rejected.

4. Roots of cowpea and maize were significantly affected by biochar and irrigation, possibly because biochar improved the soil fertility and also made water available. Biochar positively improved all the cowpea growth and yield parameters measured with exception of adventitious root number and tap root length. Irrigation did not increase cowpea adventitious root number and length, basal root angle, basal root number and shoot diameter. Generally, the interactive effect of biochar and irrigation increased all the measured cowpea root traits. There was a positive and strong correlation between cowpea grain yield and tap root diameter. Biochar increased maize brace root angle and diameter. Brace root number and branching density and crown root angle was also increased. Irrigation also increased brace root angle and diameter, also crown root number and diameter. Biochar and irrigation had a positive relationship between maize grain yield and crown root number and diameter. In most cases, plots treated with biochar loaded with phosphorus seemed to increase maize and cowpea root traits compared to plots without biochar. It is therefore, concluded that biochar amendments, especially, those loaded with P will improve maize and cowpea root system architecture, hence increase yield.

5. Based on the results obtained from the objective 4, the hypothesis that biochar and irrigation does not improves the growth, yield and quality of tomato was rejected. This is because with the exception of pH and TSS, biochar significantly improved growth, yield and shelf life of

tomato. Irrigation did not improve dry above ground biomass yield, number of leaves and stem girth. Biochar treatment ladened with P generally improved the growth rate of tomato. The influence of biochar and irrigation on yield was highly positive with high biochar rates especially those loaded with P obtaining high yields. Deficit irrigation did not affect total soluble solids (Brix°), indicating how water is an important factor in the quality of tomato. Again biochar at the rate of 20+P and 40+P t ha^{-1} increased the shelf life of tomato.

Recommendations

1. Though corn biochar had a positive effect on the high value crops selected for this experiment, it would not be prudent to generalise it that all types of biochar will have a positive effect on all crops. It is therefore recommended that further experiment should be carried out to investigate the effect of other types of biochar on different crops, especially root crops, on different soils, and at different agro ecological zones in Ghana.
2. Because of the recalcitrant nature of biochar, it is recommended that more research should be established to confirm or disprove the effect of age of applied biochar on crop. Also the effect of biochar could be evaluated under different crop rotation patterns and intercropping schemes, typical in Ghana to understand how biochar interact with these systems.
3. It was established that biochar loaded with P before application to agricultural soils improved growth, yield and quality of the high-value crops used in this research. It is however recommended that further

research be conducted to load other plant nutrients like N and K to biochar before its application to confirm the relationship between biochar and the loaded nutrients and hence on the crop growth and yield.

4. It has been clear in this experiment and also in support of other research that biochar is not a fertilizer and therefore when farmers want to apply it, especially to poor soils, they should apply fertilizer as biochar will adsorb the applied nutrients for gradual release to plants.

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