

**EFFECT OF GYPSUM AND BIOCHAR AMENDMENTS ON GROUNDNUT
(*Arachis hypogaea* L.) BIOMASS YIELD AND SELECTED SOIL
PROPERTIES UNDER WATER STRESS**

BY

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the requirements for the degree of Master of Science in Integrated Soil Fertility
Management**

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DECLARATION

I, **Munsanda Ngulube**, declare that the work presented in this dissertation is my own and has never been submitted for a degree at this or any other university.

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CERTIFICATE OF APPROVAL

This dissertation of **Munsanda Ngulube** was approved as fulfilling part of the requirements for the award of the degree of **Master of Science in Integrated Soil Fertility Management** by the University of Zambia.

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ABSTRACT

Poor rainfall distribution, low soil calcium, soil acidity and low soil moisture stress contribute largely to low levels of groundnut productivity. Because the majority of groundnut farmers in Zambia are small-holder and have limited resources, they are not able to cope with these production constraints. A greenhouse pot experiment was setup at the University of Zambia during the 2016/2017 cropping season to assess the effect of gypsum and biochar soil amendments on biomass yield and soil properties under water stress. Msekera Groundnut Variety 5 (MGV 5) was planted in an acid sandy loam soil, classified in World Reference Base as a Chromic Luvisol, low in calcium. The experiment was laid out as a split-split plot experimental design with treatments consisting of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), groundnut shell biochar and plant water application rates as the main, sub-plot and sub-sub-plots, respectively. Four levels of biochar (0, 1, 2 and 4 % *w/w* of soil), two gypsum application rates (0 and 200 kg/ha) and three daily plant water application rates (100, 70 and 40 % plant water requirement (PWR)) were combined, giving a total of 24 treatment combinations. Soil reaction (pH), cation exchange capacity (CEC), leaf chlorophyll concentration index (CCI), biomass dry matter (DM), water use efficiency (WUE), crop evapotranspiration (ET_c) were determined during crop growth or at the end of the experiment. Applying biochar had a neutralizing effect on the acid soil as it significantly raised the soil pH from 5 to 7.15 and increased the CEC by 75 %. Biochar also significantly increased the CCI at vegetative (V3) and reproductive (R1 & R3) stages of groundnut growth by 42, 46 and 40 %, respectively. Biochar at 1 and 2 % increased the dry biomass and ET_c, by 28 and 13 %, respectively while at 4 % both were negatively affected. The optimum biochar application rate in this soil for biomass was at 1.42 % *w/w*. Biochar at 1 and 2 % had no effect on WUE while 4 % biochar reduced the WUE by 45 %. With a reduction in plant water application rate WUE and ET_c also reduced by 50 and 35 %, respectively while the CCI increased by 22 %. Applying 100 % PWR gave biomass yields of 2 and 3-fold greater than at 70 % and 40 % PWR. Gypsum at a rate of 200 kg/ha had no significant effect on the crop, while biochar had potential to raise the soil pH, increase moisture retention and improve crop performance.

Key words: biochar, biomass, crop evapotranspiration, groundnut, gypsum, water use efficiency

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ACRONYMS OF ABBREVIATIONS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of variance
BC	Biochar
BNF	Biological Nitrogen Fixation
CCI	Chlorophyll Concentration Index
CEC	Cation Exchange Capacity
CF	Conservation Farming
DAP	Days After Planting
DM	Dry Matter
dS	Change in storage
EC	Electrical Conductivity
E _o	Soil Surface Evaporation
EPCMU	Eastern Province Cooperative Marketing Union
ET _c	Crop Evapotranspiration
ET _o	Potential Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
K _c	Crop coefficient
LSD	Least Significant Difference
NV	Neutralizing Value
PAW	Plant Available Water
pH	-log[H ⁺]
PWR	Plant Water Requirement
SCMR	Chlorophyll Meter Readings
UNZA	University of Zambia
USA	United States of America
USDA	United States Department of Agriculture

WRB	World Reference Base
WUE	Water Use Efficiency
ASTM	American Society for Testing and Materials
SOC	Soil Organic Carbon
OM	Organic Matter
MGV	Msekera Groundnut Variety

CHAPTER 1: INTRODUCTION

1.1 Background

Groundnut (*Arachis hypogaea* L.) is among the most widely grown legume crops in the world. Cultivated in areas between 40° N to 40° S and these are tropical and semi-arid tropical countries (Ramanatha and Murty, 1994; Prasad *et al.*, 2010). Groundnut is best grown in light textured sandy loam soils with a neutral pH (6 – 6.5) (Kumar *et al.*, 2010), requires an optimum temperature range of 28 to 30 °C and crop water requirement of the range 500 - 600 mm of well distributed rainfall (Prasad *et al.*, 2010).

Groundnut is an inexpensive but highly nutritious food; rich in protein (25-36%), carbohydrate (10-15%), fibre, unsaturated fats (47-53%), a number of minerals such as phosphorus, calcium, magnesium, vitamins E, B complex and vitamin K (Savage and Keenan, 1994; Kumar *et al.*, 2010; Prasad *et al.*, 2010). The world over, it is used in different forms; as roasted nuts, boiled nuts, fresh nuts, groundnut oil, peanut paste (peanut butter) and groundnut flour (Ross and de Klerk, 2012). In agriculture, it is used as a fertilizer and animal feed (oil pressings, green material, seed and straw). The numerous uses of the groundnut make it a lucrative cash crop to grow for trade in both developing and developed countries (Kumar *et al.*, 2010; Prasad *et al.*, 2010).

Groundnut like many legumes has ecological value, as it has the ability to fixing atmospheric nitrogen (N₂) into the soil through decomposition of plant biomass that contains organic N, which improves soil fertility for cropping (Ross and de Klerk, 2012; Shah *et al.*, 2012). This process occurs through BNF, through a symbiotic relationship between the groundnut crop and *Rhizobia spp* that exist in the root nodules (Alexander, 1977; Paul, 2007). A study done on BNF in the sole and doubled-up legume cropping systems on the sandy soils of Kasungu, Central Malawi, showed that sole groundnut, sole pigeon pea and sole soybean were able to fix 55.8, 54.1 and 35.8 kg N ha⁻¹ in that season (Njira *et al.*, 2012). Groundnut can fix up to 40-80 kg N ha⁻¹ yr⁻¹, and about 86 - 92 % of N that it takes up comes from BNF (Kabir *et al.*, 2013). Groundnut can supply other crops in poor soils with substantial amounts of biologically fixed N when intercropped or rotated. This in turn can result in fertilizer

cost savings and therefore, improve incomes from crop sales, particularly in sub-Saharan Africa where fertilizer inputs are too costly for the small-holder farmers (Kanyinka, 2013).

In the 1960's, Zambia was a producer of confectionery nuts into the world market through the Eastern Province Cooperative Marketing Union (EPCMU), but because of low quality (size and shape of nut) and high aflatoxin contamination levels caused by poor drying and storage methods exports declined (Sitko *et al.*, 2011; Mukuka and Shipekesa, 2013). After the collapse of EPCMU in Zambia in the 1970's, groundnuts are predominantly sold through informal markets where farmers are faced with unpredictable markets and low prices (Sitko *et al.*, 2011). For example, during a season, prices of shelled groundnuts in Zambia can range from K 1.5 to K 6/kg (US\$ 0.5 to US\$ 0.6/kg) depending on the time of the year with the beginning of the marketing season, May as the lowest, October prices begin to pick up and February to April they are at their highest. For export to our neighboring countries, Congo DR, Angola and Tanzania the price could even go as high as K 8.5 /kg (The US \$ 0.85/kg) for shelled nuts (Mukuka and Shipekesa, 2013). Since 2000, annual trade volumes in and out of Zambia have not exceeded 2000 MT. Consequently, Zambia has experienced fluctuations as a net importer and net exporter of groundnuts (Sitko *et al.*, 2011).

Some biotic and abiotic constraints also affect the productivity of the groundnut. The leading biotic stresses are weeds, pests and diseases; with pod borers, aphids, mites and toxin-producing fungus *Aspergillus* being the major pests and leaf spots and rusts as the major diseases (Prasad *et al.*, 2010). Pests, diseases and weeds account for up to 40, 100 and 90 % groundnut yield losses, respectively (Buchanan *et al.*, 1983; Naidu *et al.*, 1999; Naab *et al.*, 2004). The main abiotic stresses of interest are extreme temperatures, low soil moisture due to drought, soil acidity, poor soil fertility and nutrient deficiencies (Prasad *et al.*, 2010).

Water stress during pod formation, an environment of low moisture in the geocarposphere zone may result in seed abortions, reduced phytoalexin production in groundnut and pod cracking. The cracking of pods predisposes kernels to infection by soil-borne aflatoxigenic fungi (Keenan and Savage, 1994). Above ground, the

groundnut leaves will tend to close or reduce the size of the stomata openings to reduce water loss through transpiration (Akhkha *et al.*, 2011). This crop water stress survival-mechanism decreases the rate of photosynthesis, resulting in low chlorophyll production (Akhkha *et al.*, 2011), WUE and kernel yield, as these factors are known to have a strong correlation (Songsri *et al.*, 2009).

Studies on crop water requirements show that additional water supplied by irrigation during prolonged drought periods at the crops' most sensitive stages of growth (flowering and pod development stages) increased the total yield of seed and individual seed weights (Salter and Goode, 1967). However, most groundnut farmers in Zambia are small-holder farmers who depend entirely on the rain fed production because they do not have the financial capacity to implement supplemental irrigation systems (Ross and de Klerk, 2012).

The continuous use of land for cultivation with the addition of minimal inputs practiced by most small-holder farmers in Zambia tends to deplete some nutrients in the soil and acidify the soil over time, thus affecting productivity (Ross and de Klerk, 2012). The nutrients that tend to be deficient in acid soils are calcium (Ca), phosphorus (P), nitrogen (N), potassium (K), magnesium (Mg) and sulphur (S) (Tisdale *et al.*, 1985). For instance, low levels of P in the soil affect nodulating legumes more than non-nodulating crops as P plays a major role in the formation of nodules and fixation of atmospheric N. Application of P has shown to improve the groundnut yield in P deficient soils (Kabir *et al.*, 2013). Although the cultural practices and soil pH affect some nutrients, the major nutrient of interest in this study is calcium.

Calcium plays a vital role in seed development, balancing levels of other nutrients within the plant, strengthening the pods and improving plant vigour (Gascho and Davis, 1994). During dry spells, groundnut shows deficiencies of Ca (Alva *et al.*, 1989) and cracks in pod shells tend to develop, increasing the occurrence of pops, and aflatoxin contamination by *Aspergillus spp.* resulting in low yields (Keenan and Savage, 1994; Nahdi, 1996; Njoroge *et al.*, 2013). There is, therefore need to broaden areas of research also to discover mitigation strategies to address low soil Ca and low soil moisture constraints faced by the farmers, which would improve the fertility of the soil and ultimately crop yield.

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is mainly used to supply plants with calcium, but it has the added benefit of supplying sulphur, an essential nutrient for the production of proteins, oil and flavour compounds (Ramdevputra *et al.*, 2010). Gypsum application rates for groundnut range from 200 to 1 000 kg/ha (Nyambok, 2011) depending on the soil but in South Africa where less than 0.25 cmol/kg Ca is present in the soil, 200 kg/ha gypsum is applied to the soil (Department of Agriculture, 2010). The efficiency of calcium will depend on the quality of the calcium source, application rate, soil type and time of application. In Zambia, there is limited information on the use of calcium amendments to improve groundnut productivity specifically.

Biochar is made from any organic material charred in the presence of limited oxygen, by a process called pyrolysis (Steinbeiss *et al.*, 2009; Lehmann *et al.*, 2011; Abel *et al.*, 2013; Cornelissen *et al.*, 2013). It is known to pose unique chemical and physical properties which give it the ability to buffer soil temperature fluctuations, neutralize acid soils, sequester carbon, improve nutrient retention and increase moisture retention in some studies (Lehmann *et al.*, 2011; Cornelissen *et al.*, 2013). Therefore, biochar can be applied to improve the productivity and fertility status of the soil making it more suitable for optimal groundnut production.

This study evaluated the individual and interactive effects of gypsum and biochar soil amendments as mitigation strategies to address low soil calcium and moisture faced by groundnut farmers.

1.2 Statement of the Problem

Currently, in Zambia groundnut production is far below demand and potential yields of the existing varieties. End of season droughts, soil acidity and low soil calcium are major factors affecting productivity. With most groundnut farmers being resource-poor and dependent entirely on rainfall, seldom apply calcium as a nutrient or lime or use certified seed and when they do, the benefits may not be realized in low calcium and acidic soils.

1.3 Main Objective

To evaluate the effect of the soil amendments gypsum and biochar on groundnut (*Arachis hypogaea* L.) biomass yield and on selected soil properties under water stress conditions.

1.3.1 Specific Objectives

1. To determine the effects of biochar on soil pH.
2. To determine the effects of biochar on soil cation exchange capacity (CEC).
3. To determine the effects of gypsum and/or biochar on groundnut chlorophyll concentration index (CCI).
4. To determine the effects of gypsum and/or biochar on groundnut dry biomass yield.
5. To determine the effects of gypsum and/or biochar on crop evapotranspiration (ET_c).
6. To determine the effects of gypsum and/or biochar on crop water use efficiency (WUE).

1.4 Hypotheses

1. Applying biochar significantly increases the pH of soils.
2. Applying biochar significantly increases the cation exchange capacity (CEC) of soils.
3. Applying gypsum and/or biochar significantly increases groundnut leaf chlorophyll concentration index (CCI).
4. Applying gypsum and/or biochar significantly increases groundnut dry biomass yield.
5. Applying gypsum and/or biochar significantly increases crop evapotranspiration (ET_c).

6. Applying gypsum and/or biochar significantly increases crop water use efficiency (WUE).

CHAPTER 2: LITERATURE REVIEW

2.1 Botany

The *A. hypogaea* are classified botanically as Virginia and Spanish-Valencia, based on the crop branching pattern (Ramanatha and Murty, in Smart, 1994). It is a self-pollinating annual herbaceous legume (Groundnuts – production guideline, 2010). The crop undergoes several stages of growth which are described according to population-based field observations, and they consist mainly of the vegetative (V) and reproductive (R) stages. The vegetative stage begins to be visible 3 – 5 days after sowing and is described as follows; the emergence of cotyledons (VE), 1st trifoliolate appears (V1) all the way to when the nth trifoliolate appears (VN). The reproductive stage of groundnut begins about 25 - 30 days after sowing, and is described as follows: appearance of first flower (R1), pegging (R2), podding (R3), full pod (R4), starting of seeding (R5), full seed (R6), mature seed (R7) and harvest maturity (R8) (Boote, 1982; Prasad *et al.*, 2011).

2.2 Groundnut production in Zambia

There is a high demand for groundnut products; worldwide nut, oil and seed cake make up the three top international trade markets for groundnut (Florkowski, in Smart, 1994). About 75 % of groundnut produced is used for extraction of edible oils (Kumar *et al.*, 2010). From 2004 to 2014 groundnut has been cultivated on 24.2 million hectares of land of the world, with a total production of 39.3 million metric tons (Table 2. 1; FAOSTAT, 2016). China (40.1%), India (16.4%), Nigeria (8.2%), USA (5.9%) and Indonesia (4.1%) are the major groundnut producing countries, with USA as the leading exporter of groundnut grain and products (Florkowski, in Smart, 1994; Kumar *et al.*, 2010). In the 1980's, Senegal and Sudan were the two African countries among the major world traders who exported oil and seed cake to the Asian and European markets, respectively (Florkowski, in Smart, 1994). Over a period of five years before 2001, there was an improvement with developing countries having exported two-thirds of 1.2 million tons of groundnuts exported globally (Exporting groundnuts, 2001).

Table 2. 1 compares the mean area harvested, production and yield trends of groundnut in Zambia with Africa and the World from 2004 to 2014.

Table 2. 1. Comparison of mean area harvested, production and yield trends of Groundnut in Zambia with Africa and the World from 2004 to 2014

Element	Zambia	Africa	World
Area harvested (ha)*	166.1	11,014.8	24,232.4
Production (kg)*	115.5	10,477.8	39,326.8
Yield (kg/ha)	690.1	954.8	1,620.8
Seed (kg)*	18.5	668.9	1,813.4

*multiply the value by 1000.

Source: FAOSTAT, 2016

In Zambia, groundnut is the second most cultivated crops after maize. They are an important cash crop, a good and cheap source of protein which can improve the nutrition and economic status of most rural households (Sitko *et al.*, 2011). Small and medium-holder farmers mostly grow it, with the majority located in Chipata, Chadiza, Petauke, Lundazi and Katete districts of the Eastern Province (Mukuka and Shipekesa, 2013). Traditionally in Zambia, groundnut is planted on ridges at variable spacing and seed densities or just broadcast in a plowed or dug-out field. Rip lines and basins are also being used by the farmers who practice conservation farming. Groundnut is sometimes intercropped with cereals such as maize but usually grown as a monocrop in rotation with cereals (Ross and de Klerk, 2012). Table 2. 2 shows the common groundnut varieties grown in Zambia and their potential yields.

The seed distributors in Zambia are out-growers, seed companies such as ZAMSEED, PANNAR, and Seed Co, with local large-scale agro-dealers as major dealers. The large-scale agro-dealers sell both improved seed varieties and recycled seed (Mofya-mukuka and Shipekesa, 2013). Despite many high yielding varieties available in Zambia, the adoption rate is still very low (20 %) (Ross and Klerk, 2012). Some factors contributing to this are limited access to information, lack of credit facilities and cost of certified seed (Chirwa *et al.*, 2015). Large-scale agro-dealers mostly sell recycled seed which is a 10th of the cost of certified seed because aside from out-grower schemes the demand for seed is low therefore, they focus more on other agro-

inputs such as maize seed. Among all the varieties, MGV 4, Chalimbana, and Makulu Red are the most commonly distributed with Chalimbana commonly sold as recycled seed, because farmers believe it remains high yielding even after several years (Mofya-mukuka and Shipekesa, 2013).

Table 2. 2. Groundnut Varieties, Yields, and Days to Maturity in Zambia

Variety	Year Released	Days to Maturity	Seed Size	Oil Content (%)	Yield (MT/ha)
Makulu Red	1964	130-145	Medium	48-50	2.0-2.5
Champion	1998	130-140	Large	48-50	1.5-3.0
Chalimbana	1966	150-160	Large	48-50	0.5-1.0
MGS-2	1988	130-140	Medium	45-48	1.0-2.0
MGV-4	1992	120-130	Medium	48-50	1.5-3.0
MGV-5	2008	130-140	Large	45-48	1.5-4.0
Luena	1998	90-100	Small	48-50	1.0-2.0
Chishango	2007	130-140	Medium	48	1.5-4.0
Natal Common	1976	90-100	Small	45-48	0.5-1.0
Chipego	1995	100-110	Small	45-48	1.0-1.5
Comet	1970	90-100	Small	45-48	0.5-1.5
Katete	2008	90-100	Small	43	1.0-2.0

Source: Mukuka and Shipekesa, 2013.

The area cultivated and yields produced in Zambia were at its peak from 2010 to 2011 (Ross and de Klerk, 2012; FAOSTAT, 2016). In spite of the gradual increase in area harvested, production and groundnut yields in recent years (Figure 1.1), Zambia's production is still very low with an average of less than 2,000 MT of shelled nuts per year in the last decade when compared to other countries in the region, such as Malawi, which traded around 8,900 MT in 2010 alone (FAO, 2012). Zambia is currently producing yields of 690.1 kg kernels/ha (FAOSTAT, 2016), which is approximately only 50 – 70 % of the potential yield of the varieties grown in the country (Table 2. 2). With the estimated mean population increase of 2.7 % locally which demands an estimated 69,964 MT, Zambia is currently not able to meet the groundnut demand of the growing population (Sitko *et al.*, 2011; Kanyika, 2013). Meeting this requirement would be of significant nutritional and economic benefit for

the rural households and the country. The annual area harvested, production and yield trends of groundnut in Zambia over a period of 10 years from 2004 can be seen in Figure 2. 1.

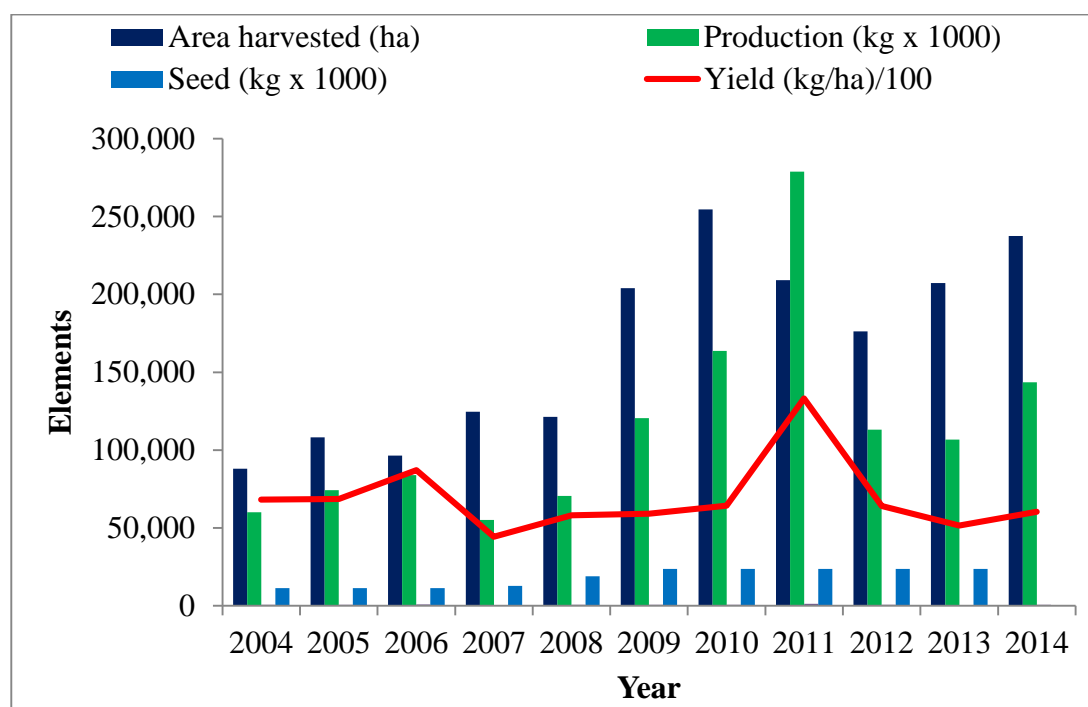


Figure 2. 1 Annual area harvested, production and yield trends of Groundnut from 2004 to 2014. Source: FAOSTAT, 2016

The groundnut value chain in Zambia is faced with some production and market constraints. The critical factor is that most small-holder farmers resort to recycling Open Pollinated Varieties (OPV) seed as opposed to buying certified seed (Mofyamukuka and Shipekesa, 2013). In addition, groundnut production is labour intensive regarding weeding, harvesting and shelling since it is done manually mostly by the women and children (Mukuka and Shipekesa, 2013).

2.3 Climate

Zambia has good tropical weather and vast land suitable for agriculture, which should allow the country to produce higher groundnut yields for local consumption and export (Mukuka and Shipekesa, 2013). However, the changing climate poses a significant threat to productivity in agriculture due to extremes of temperature, floods and droughts, alkalinity, acidity and nutrient deficiencies (Leu *et al.*, 2007; Xu *et al.*, 2015). Most farmers are largely dependent on rainfall so, climate variability may endanger the nation’s food and nutrition security (Kumar *et al.*, 2012; Xu *et al.*, 2015).

To achieve economic gains and to meet the country's groundnut demand, new and improved agricultural practices are needed to counteract the adverse effects of the changing climate (Leu *et al.*, 2007; Xu *et al.*, 2015).

The groundnut crop does not perform well under high soil temperatures and during end-of-season drought, especially in the last 40 days of its growth cycle, as it may result in low yields and poor quality (Nahdi *et al.*, 1996). These conditions tend to occur because of long dry spells, uneven rainfall distribution or short rain seasons. Planning and management by farmers also play a role because at the start of the season, farmers tend to focus on planting cotton and maize first, therefore delaying groundnut planting, which increases the possibility of the crop being exposed to end-of-season drought (Njoroge *et al.*, 2013).

Studies have shown that the groundnut plant is not very sensitive to drought stress at the seedling stage, but is highly sensitive at flowering and pegging stages which are the period for fruit setting (Thiyagarajan *et al.*, 2009; Salter and Goode, 1967). The low moisture in the geocarposphere zone may result in seed abortions and reduces phytoalexin production in the groundnut and causes pods to crack, thus predisposes kernels to infection by soil-borne aflatoxigenic fungi (Keenan and Savage, 1994).

During low or uneven rainfall periods, photorespiration increases in groundnut crops as C3 plant species (Marschner, 2012). To reduce water loss through transpiration, the groundnut closes or minimizes the size of its leaf stomata openings (Mohale, Belane and Dakora, 2014). This crop water stress survival mechanism decreases the rate of photosynthesis, resulting in low chlorophyll production (Akhkha *et al.*, 2011) and WUE. Chlorophyll content and WUE are known to have a strong correlation (Songsri *et al.*, 2009).

2.4 Soil Fertility

There has been a decline in soil fertility of agricultural land around the world as farmers try to meet the food demands of a fast-growing population. Poor management of land has led to nutrient mining and a decline in SOC. Most commercial groundnut farmers solely practice conventional farming which involves the use of mineral fertilizers and clearing of crop residues, which has resulted in a decline in land

productivity (Grace *et al.*, 1995). While most small-holder farmers practice conservation farming involving, crop rotations and fallow systems to promote soil nutrient recycling and nutrient use efficiency.

Areas that experience high rainfall and free drainage favour nutrient leaching and organic acid production, creating acidic soils (Singer & Munns, 1987). Calcium (Ca), phosphorus (P), nitrogen (N), potassium (K), magnesium (Mg) and sulphur (S) tend to be deficient in acidic soils (Tisdale *et al.*, 1985). When cultivating groundnut on acidic soils, Ca is the major nutrient which should be of concern. Both small-holder and commercial farmers tend to apply lime just to neutralise the soil acidity to a level suitable for crop growth. However, Ca is an essential element most commonly deficient in many soils when growing groundnut (Gascho and Davis, 1994). When sufficient Ca is present in the geocarposphere it has been shown to result in increased yield, oil content and protein content of the kernel in Virginia large seed types (Gashti, Vishekaei and Hosseinzadeh, 2012). Calcium deficiency results in blackened plumules, empty pods ('pops'), high frequencies of pod rot, poor grade and weak pods which increase the production potential of aflatoxins in soils that favour the growth of fungus (*Aspergillus spp*). At times in highly deficient soils, it may also result in poor germination (Gashti *et al.*, 2012).

Calcium, applied at the base of the plant 45 to 60 days after planting has been shown to strengthen the pod shell thus protecting the nut and allowing it to mature fully (Gascho and Davis, 1994). Some studies carried out to evaluate the effect of using different calcium materials such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), limestone (CaCO_3) and dolomite on the groundnut crop yield have shown that calcium chloride (CaCl_2) is the most soluble and effective source of calcium, however it is the most costly (Gascho and Hodges, 1991 in Gascho and Davis, 1994).

The use of calcium amendments has shown to increase the pod yield significantly in research done in different soil types. However, most small-holder farmers will only apply calcium in the form of lime to neutralize soil acidity for maize if they had grown it before growing groundnut and not as a nutrient fertilizer for groundnut. This has shown to supply inadequate calcium to significantly increase the yield for the larger seeded Virginia type groundnut (Gascho and Davis, 1994). On the other hand,

commercial farmers resort to application of fertilizers and lime as possible solutions to counteracting nutrient deficiencies and soil acidity (Prasad *et al.*, 2010), but most groundnut farmers in Zambia are small-holder farmers who cannot afford these inputs and may not have sufficient knowledge on what inputs groundnut requires, as they traditionally do not add any inputs (Ross and de Klerk, 2012).

2.5 Uses of Biochar as an amendment

Historically, soils containing charcoal can be traced to the *Terra Preta* soils of the Amazon in Brazil and some soils in Japan. In both countries incorporating charcoal into their soils were ancient traditional agricultural practices (Ernsting, and Smolker, 2009; International Biochar Initiative, 2009). As a result of these soils being known to be highly fertile, biochar is now being produced commercially as a soil amendment being used to replenish degraded soils in many parts of the world. Lehmann *et al.* (2008) estimated the mean residence time for naturally occurring biochar carbons at about 1,300 – 2,600 years based on a study in Australia, which shows biochar has a long-lasting effect on the soil over the years. It should be noted that not all biochar is the same. The chemical and physical properties greatly depend on the organic material used and the conditions during the pyrolysis process (Chan *et al.*, 2008). For example, biochar from groundnut shell and paddy straw had higher total nitrogen content as compared to *Prosopis juliflora* wood chips according to a study by Shenbagavalli and Mahimairaja (2012) on production and characterization of biochar from different biological wastes.

There is growing interest in the use of biochar as a soil amendment to counteract some effects of the changing climate on the soil productivity. Studies have shown that it has unique properties such as a large surface area, high CEC, alkalinity and high carbon content (Lehmann *et al.*, 2011). These properties contribute to its potential to improve fertilizer efficiency, raise soil pH, increase soil CEC, increase base saturation (BS), increase organic matter, increase moisture holding capacity, create an improved habitat for beneficial soil microbes, buffer soil temperature fluctuations and sequester carbon (Steinbeiss *et al.*, 2009; Lehmann *et al.*, 2011; Abel *et al.*, 2013; Cornelissen *et al.*, 2013).

Several studies have shown that use of biochar can increase and improve crop yields years after application on low nutrient soils and in drought-prone areas. Maize yields were seen to have improved from the 2nd to the 4th growing season when biochar was applied to the soil, which was attributed to the availability of Ca and Mg and the effect of biochar on reducing the soil's exchangeable acidity (Major *et al.*, 2010). Cornelissen *et al.* (2013) carried out a study on a combination of biochar and conservation farming (CF) on maize yield in Zambia, on the sandy acidic soil in farmed field pilots where they observed a significant increase in plant available water and nutrient retention. Martinsen *et al.* (2014) carried out a CF study with biochar in three locations in Zambia (Mongu: sandy soils; Kaoma: sandy or loamy sand soils; Mkushi: sandy loam or loamy soils) on maize and groundnut. They observed that addition of biochar resulted in increases in plant available water (PAW), CEC, available K⁺, pH, in these acidic tropical soils, which resulted in an increase in yield of fertilized maize (increases of 232 ± 60% in Mongu, 289 ± 216% in Kaoma, and 110 ± 16% in Mkushi) but not in unfertilized groundnut. They suggested that biochar is most effective in combination with fertilizer as the increase in CEC and pH help nutrient retention.

Currently, not much research has been done on the effect of biochar on groundnut calcium requirements, susceptibility to water stress and soil acidity both locally and internationally, though a few studies show biochar has great potential regarding improvement in yields because of it improving soil properties. A study in Queensland, Australia carried out on two soils (red ferrosol and redoxi-hydrosol) by Xu *et al.* (2015) studying the effect of biochar on yield and photosynthesis of peanuts showed that biochar improved soil available N, BNF and photosynthesis. It also increased the groundnut biomass and pod yields 2- and 3- times on the red ferrosol and redoxi-hydrosol respectively.

A water use efficiency study carried out on maize in Indonesia on a sandy soil by Sukartoon and Utomo (2012), compared the effect of biochar and cattle dung on the WUE. They found that biochar and cow dung had a significant (16.83 % and 23.39 % respectively) positive effect on the WUE, but unlike biochar which has a residual effect, cattle manure would have to be applied at every planting time to attain this continuous positive effect, which would be costly in the long run.

2.6 Crop Coefficient

The crop coefficient (K_c) is defined as an estimate of consumptive water use by crops based on evapotranspiration values (ratio of ET_c to ET_o) (Stannard *et al.*, 2013). The K_c changes during the growing season as it is affected by the relationship between the atmosphere, crop physiology and agricultural practices. Each crop has a characteristic K_c curve according to the different crop development and growth stages (initial, middle and late. Therefore, it has $K_{c\text{ in}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$) (Lazzara and Rana, 2009). The K_c value of a groundnut crop in a subhumid climate ($RH_{\text{min}} = 45\%$) climate at initial development is about 0.4, the mid-season increases to 1.15 and late season it drops to 0.6 (Allen *et al.*, 2000). During the groundnut growing period, dekads are selected to represent the initial (25 - 35 days), mid (35 - 70 days) and late (105 - 130 days) crop development stages (Boote, 1982; Allen *et al.*, 2000; Prasad *et al.*, 2011).

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area description

The soil used in this study was collected from the Agricultural Technology Development Centre (ATDC) at the UNZA Farm located in Chongwe district of Zambia (at latitude 15° 21' 25" South and longitude 28° 27' 25" East, 1 260 m above mean sea level). This site falls in Agroecological region IIa of Zambia, which receives an average annual rainfall of 800 – 1, 000 mm during the cropping season that runs from November to March. The soil at this site is a sandy loam, classified in the World Reference Base (WRB) as Chromic Luvisol (IUSS Working Group WRB, 2015). The site was used to grow maize in the previous cropping season.

3.2 Soil Sampling and preparation

The soil used in the study was collected from the top 20 cm of the field using a hand hoe, in a random sampling pattern from different points. The bulk soil samples were collected from the random points within the field and were uniformly mixed to form a composite soil sample for laboratory analysis. The composite soil sample was sieved through a 2 mm sieve and was replicated four (4) times for characterization of selected chemical and physical properties; texture, pH, electrical conductivity (EC), CEC, exchangeable acids, exchangeable bases, total nitrogen, available phosphorus and organic matter. Undisturbed soil samples were collected for bulk density.

3.3 Analysis of selected Soil Chemical and Physical Properties

3.3.1 Soil reaction (pH)

Soil reaction (pH) was measured with a glass electrode pH meter in 1: 2.5 soil to solution ratio of calcium chloride (0.01 M CaCl₂) solution. The pH meter (Hanna, HI2210-01 Benchtop pH/mV Meter) was calibrated before use with buffer pH 7.0 and then buffer pH 4.0 (Van Reeuwijk, 1992).

3.3.2 Electrical Conductivity

The EC was measured in a soil-water extract of a 1: 5 ratio (Richards, 1954). The conductivity meter was calibrated before use with potassium chloride (0.01 M KCl) to give a conductivity of 1.412 mS/cm at 25°C.

3.3.3 Exchangeable Bases and Cation exchange capacity (CEC)

The leaching method (Rowell, 1994) was used to determine the exchangeable bases (K^+ , Mg^{2+} and Ca^{2+}) and CEC.

Exchangeable bases (K^+ , Mg^{2+} and Ca^{2+})

Ten grams (10 g) of air dried soil placed on filter paper in a funnel was leached with 100 ml of ammonium acetate (1 N NH_4OAc at pH 7.0). The K^+ and Na^+ were read directly from the filtrate by flame emission. For the Ca^{2+} and Mg^{2+} , an aliquot of the filtrate (1 ml) and 5 ml strontium chloride (500 mg/L $SrCl_2$) were added to a 25 ml volumetric flask, made to the mark with 1 N NH_4OAc . The Ca^{2+} and Mg^{2+} concentration were then read by atomic absorption spectrometry.

Prior to taking each cation reading the AAS was calibrated using the following stock solutions;

Na^+ : 0 mg/L, 100 mg/L

K^+ : 0 mg/L, 100 mg/L

Ca^{2+} : 0 mg/L, 5 mg/L, 15 mg/L, 30 mg/L

Mg^{2+} : 0 mg/L, 0.5 mg/L, 1.5 mg/L, 3 mg/L

The concentration reading of each cation from the AAS was in mg/L and was converted to cmol (+)/ kg soil using equation 1;

$$\text{Cation cmol (+)/ kg soil} = \frac{\text{mg/L} \times \text{Volume of Extractant(L)}}{\text{Eq. Wt.of Cation} \left(\frac{\text{mg}}{\text{cmol}}\right) \times \text{Wt.of sample (kg)}} \times \text{DF} \quad (1)$$

Cation Exchange Capacity (CEC)

The CEC was determined from the exchangeable bases leachate. Ten millilitres (10 ml) of the leachate and 1 g MgO catalyst were distilled for 5 minutes into 20 ml Boric acid. The NH_4-N in the Boric acid was then titrated with 0.1 M HCl. The CEC was calculated using equation 2;

$$\text{CEC meq/100g} = \frac{[(\text{vol titrated (L)}) \times \text{conc Acid (M)} \times \text{DF} \times 100\text{g}]}{\text{mass of sample (g)}} \quad (2)$$

3.3.4 Exchangeable acidity

Exchangeable acidity (Al^{3+} and H^+) were determined by the titration method (McLean, 1965). To extract Al^{3+} and H^+ , 100 ml of 1 M KCl extracting solution was added to ten grams (10 g) of air dried soil. The mixture was shaken for 1 hour and then filtered.

The Al^{3+} and H^+ concentrations were determined by titration: to twenty-five millilitres (25 ml) of the filtrate, 100 ml of distilled water and 5 drops of phenolphthalein indicator were added. The solution was titrated with standard 0.01 M sodium hydroxide (NaOH) till the solution reached a permanent pink colour. The amount of base used was equivalent to the exchangeable acidity.

To the same pink solution, 10 ml of NaF solution was added. The pink solution was titrated with standard 0.01 M hydrochloric acid (HCl) till the pink colour in the solution disappeared. The amount of acid used was equivalent to the exchangeable Al^{3+} .

The exchangeable acidity was calculated using equations 3;

$$\text{Exch acidity meq/100g} = \text{Vol. NaOH (ml)} \times \frac{100}{25} \times \frac{100}{25} \times 0.01 \quad (3)$$

3.3.5 Available Phosphorus

The Bray 1 method was used to determine available plant phosphorus (Bray and Kurtz, 1945).

Preparation of Reagents;

Bray-1 Extracting Solution

The extracting solution was made by adding 15 ml of 1 M NH_4F and 25 ml of 0.5 M HCl to 460 ml of distilled water.

Reagent A

To prepare reagent A, twelve grams (12 g) of ammonium molybdate ($(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$) was dissolved in 250 ml of distilled water to make solution 1. Then 0.2908 g of Potassium Antimony Tartrate ($\text{KsbOC}_4\text{H}_4\text{O}_6$) was dissolved in 100 ml of distilled water to prepare solution 2, and then 1000 ml of 2.5 M H_2SO_4 was used to make

solution 3. The solutions 1, 2 and 3 were mixed in a 2 L volumetric flask and made up to the volume mark with distilled water.

Reagent B

A 1.056 g of ascorbic acid was dissolved in 200 ml of reagent A. Reagent B must be freshly made from Reagent A each time before use.

Extraction of available P

A 1:7 soil to Bray-1 extracting solution ratio was used. The solution was put on the mechanical shaker, shaken for one minute and the solution was filtered. Five millilitres (5 ml) of filtrate and 4 ml of reagent B were added to a 25 ml volumetric flask, then made up to the mark with distilled water. The samples stood for 10 minutes to allow for colour development before the absorbance of P was read on the spectrophotometer at a wavelength of 882 nm. The spectrophotometer was calibrated using the 0 ppm and 1 ppm standards before reading the samples. The formulas used to determine available P concentration were equations 4 and 5;

$$\text{Concentration of sample (mg/L)} = \frac{\text{absorbance sample}}{\text{absorbance 1 ppm std}} \quad (4)$$

$$\text{Available P (mg/kg)} = \frac{\text{Conc. sample (mg/L)} \times \text{Vol. extractant (L)}}{\text{the weight of the sample (kg)}} \times \text{DF} \quad (5)$$

3.3.6 Total Nitrogen

Total nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney, 1982). A 1 g soil sample was weighed into a 500 ml Kjeldahl flask, to which 0.03 g starch and 10 ml concentrated sulphuric acid (H₂SO₄) were added. The mixture was then swirled thoroughly.

For the digestion, 3 g of the catalyst mixture (10 g K₂SO₄, 10 g CuSO₄.5H₂O and 1 g Selenium) was added to the flask which was then placed on the Kjeldahl digestion stand. The flask was heated cautiously until the water was removed and the frothing had ceased. The heat was then increased and regulated so that the H₂SO₄ condensed about one-third of the way up the neck of the flask. After the digest had cleared, gentle boiling was continued for 5 hours. During this time, the flask was rotated in the stand

at intervals and then allowed to cool. The digest was transferred to a 100 ml bottle and made up to 100 ml with distilled water.

For the distillation, 10 ml of the digest solution and 10 ml of 10 M NaOH were poured into the distillation apparatus and distilled the sample for 5 minutes while the distillate collected in 20 ml of boric acid (H_3BO_3) for titration.

The distillate was titrated with 0.01 M standard HCl until the colour changed from green to pink. The result was corrected by subtracting the titration value of an equally treated blank using 0.03 g of pure starch. The total N was calculated using equation 6;

$$\% N = \frac{\text{Molarity (mol/L)} \times (\text{Vol. sample} - \text{Vol. Blank}) \text{ml}}{\text{the weight of the sample (kg)}} \times 1.4 \times \text{DF} \quad (6)$$

3.3.7 Organic Carbon

Walkley and Black (1934) chromate reduction method was used to determine soil organic carbon. To one gram (1 g) of air dry soil, 10 ml of 1 N potassium dichromate ($K_2Cr_2O_7$) and 20 ml of concentrated sulphuric acid (H_2SO_4) were added to the flask under the fume hood. The flask was swirled gently until the soil and solution were mixed for about 1 minute. The suspension stood for 30 minutes, after which 150 ml of distilled water and 10 ml concentrated phosphoric acid (H_3PO_4) were added.

Ten drops (1 ml) of diphenylamine indicator was added to the suspension before titrating with 1 N iron (II) sulphate solution ($Fe(II)SO_4 \cdot 7H_2O$). The colour changed from an initial yellow-brown to blue and then to green marking the end point of the titration. The organic carbon and organic matter (OM) were calculated using equations 7 and 8;

$$\% \text{ Org C} = \frac{0.4 \times [\text{Normality of titrant (Volume of blank} - \text{Volume sample (ml))}]}{\text{mass of soil (g)}} \quad (7)$$

Assuming organic matter consists of 50 % C;

$$\% \text{ OM} = \% \text{ Org C} \times 2 \quad (8)$$

3.3.8 Particle Size Distribution

The Hydrometer method according to Day (1965) was used to determine the soil texture. Fifty grams (50 g) of air dry soil and 50 ml of a dispersing agent, 5 % Calgon solution (sodium metaphosphate, NaPO_3) were put in a dispersing cup. The cup was then half filled with distilled water and stirred for 5 minutes continuously. The suspension was transferred to the sedimentation cylinder made to the 1 L mark. The temperature of the suspension was measured using a thermometer. A plunger was inserted and moved up and down to stir the suspension thoroughly. After 20 seconds, a hydrometer was lowered into the soil suspension and a density reading was taken after 40 seconds to determine the silt and clay content. This was repeated 3 times to obtain an average value. The suspension was then left for 2 hours and then the density reading was taken for estimating the clay content. The percent sand, silt and clay were calculated using equations 8, 9, 10 and 11:

$$\% (\text{Silt} + \text{Clay}) = (40 \text{ second reading} - C1 \pm C2) \times 100/50 \quad (8)$$

$$\% \text{ Sand} = 100 \% - \% (\text{Silt} + \text{Clay}) \quad (9)$$

$$\% \text{ Clay} = (2 \text{ hour reading} - C1 \pm C3) \times 100/50 \quad (10)$$

$$\% \text{ Silt} = 100 \% - \% \text{ Sand} - \% \text{ Clay} \quad (11)$$

Where, C1 is the correction factor due to dispersing agent reading, the C2 hydrometer reading at 40 seconds, and C3 hydrometer reading at 2 hours.

Based on the sand, silt and clay %, the soil textural classification was determined using the USDA textural triangle.

3.3.9 Bulk Density

The core ring method was used to determine the bulk density of the soil (Blake, 1965). The core ring mass, height and diameter were measured before sample collection. Crop residues and vegetation were scraped off from the sample site and a core ring sample was collected from the top 0 – 20 cm vertical soil layer and weighed its mass while in the core ring. The undisturbed soil core ring sample was then oven dried at 105 °C for 24 hours and weighed after attaining equilibrium. The bulk density was then calculated with equation 12:

$$\text{Bulk density} = \frac{\text{Mass of oven dry soil (g)}}{\text{Volume of sample (cm}^3\text{)}} \quad (12)$$

3.4 Production of Biochar

The biochar was prepared from dry groundnut shells collected from groundnut shellers in Soweto market in Lusaka. The groundnut shells were placed in a homemade kiln at UNZA (Figures 3.1) and underwent pyrolysis to produce biochar, which was then ground and sieved through a 1 mm sieve;

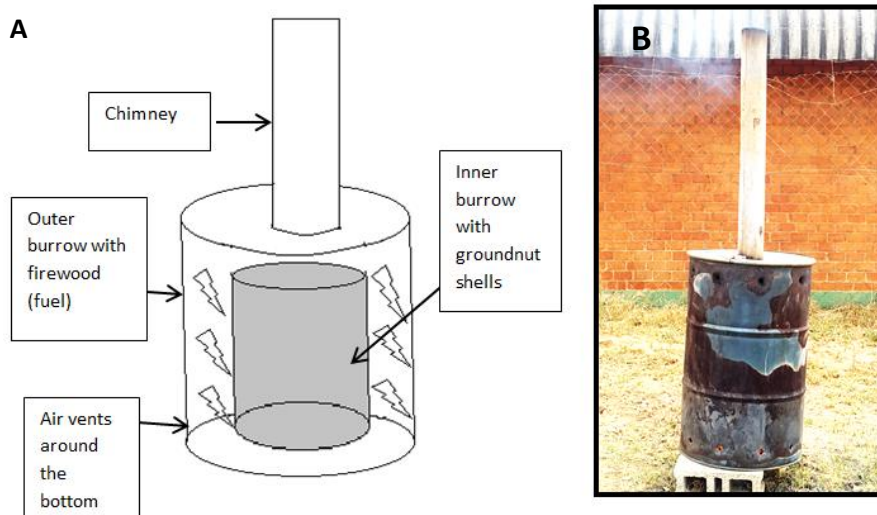


Figure 3. 1 Schematic diagram of the kiln (A) and a picture of the kiln (B).

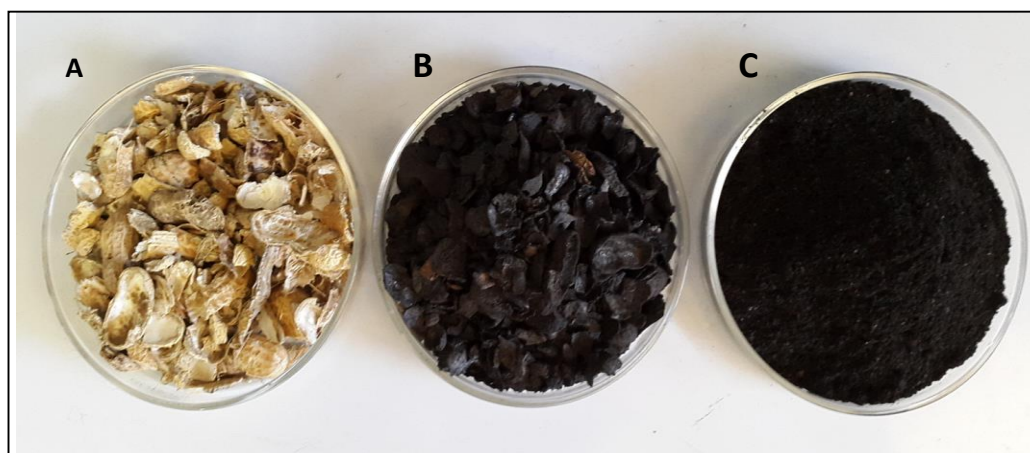


Figure 3. 2 Groundnut shells (A), uncrushed biochar (B) and ground biochar (C).

3.5 Characterization of Biochar

The biochar was characterized for selected properties chemical and physical properties; pH, CEC, organic carbon, total nitrogen, total calcium, total magnesium,

total potassium, total sodium, total phosphorus, neutralizing value (NV) and ash content.

3.5.1 Biochar pH

Biochar pH was determined according to the American Society for Testing and Materials (ASTM) D4972 – 01 (2007). The biochar pH was measured with a glass electrode pH meter in 1: 10 sample to distilled water ratio. The pH meter was calibrated before use with buffer pH 7.0 and then buffer pH 4.0.

3.5.2 Cation Exchange Capacity (CEC)

The CEC was determined using the leaching method (Rowell, 1994). Ten grams (10 g) of air dried biochar placed on filter paper in a funnel was leached with 100 ml of ammonium acetate (1 N NH₄OAc at pH 7.0). Ten millilitres (10 ml) of the leachate and 1 g MgO catalyst were distilled for 5 minutes into 20 ml Boric acid. The NH₄-N in the Boric acid was then titrated with 0.1 M HCl. The CEC was calculated using equation 13;

$$\text{CEC meq/100g} = \frac{[(\text{vol titrated (L)}) \times \text{conc Acid (M)} \times \text{DF} \times 100\text{g}]}{\text{mass of sample (g)}} \quad (13)$$

3.5.3 Organic Carbon

Walkley and Black (1934) chromate reduction method was used to determine organic carbon content in biochar. To zero point one gram (0.1 g) of air biochar, 10 ml of 1 N potassium dichromate (K₂Cr₂O₇) and 20 ml of concentrated sulphuric acid (H₂SO₄) were added to the flask under the fume hood. The flask was swirled gently until the soil and solution were mixed for about 1 minute. The suspension stood for 30 minutes, after which 150 ml of distilled water and 10 ml concentrated phosphoric acid (H₃PO₄) were added.

Ten drops (1 ml) of diphenylamine indicator was added to the suspension before titrating with 1 N iron (II) sulphate solution (Fe(II)SO₄.7H₂O). The colour changed from an initial yellow-brown to blue and then to green marking the endpoint of the titration. The organic carbon and organic matter (OM) were calculated using equation 14;

$$\% \text{ Org C} = \frac{0.4 \times [\text{Normality of titrant (Volume of blank} - \text{Volume sample (ml))}]}{\text{mass of biochar (g)}} \quad (14)$$

3.5.4 Total Nitrogen

Total nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney, 1982). A one gram (1 g) biochar sample was weighed into a 500 ml Kjeldahl flask, to which 0.03 g starch and 10 ml concentrated sulphuric acid (H₂SO₄) were added. The mixture was then swirled thoroughly.

For the digestion, 3 g of the catalyst mixture (10 g K₂SO₄, 10 g CuSO₄.5H₂O and 1 g Selenium) was added to the flask which was then placed on the Kjeldahl digestion stand. The flask was heated cautiously until the water was removed and the frothing had ceased. The heat was then increased and regulated so that the H₂SO₄ condensed about one-third of the way up the neck of the flask. After the digest had cleared, gentle boiling was continued for 5 hours. During this time, the flask was rotated in the stand at intervals and then allowed to cool. The digest was transferred to a 100 ml bottle and made up to 100 ml with distilled water.

For the distillation, 10 ml of the digest solution and 10 ml of 10 M NaOH were poured into the distillation apparatus and distilled the sample for 5 minutes while the distillate collected in 20 ml of boric acid (H₃BO₃) for titration.

The distillate was titrated with 0.01 M standard HCl until the colour changed from green to pink. The result was corrected by subtracting the titration value of an equally treated blank using 0.03 g of pure starch. The total N was calculated using equation 15;

$$\% \text{ N} = \frac{\text{Molarity (mol/L)} \times (\text{Vol. sample} - \text{Vol. blank}) \text{ml}}{\text{weight of sample (kg)}} \times 1.4 \times \text{DF} \quad (15)$$

3.5.5 Total Calcium, Magnesium, Potassium, Sodium and Phosphorus

Extraction: Half a gram (0.5 g) of biochar was weighed into a crucible and placed in a furnace at 550 °C for 2 hours (Campbell and Plank, 1998). Na⁺, K⁺, Mg²⁺, Ca²⁺ and P were extracted with 30 ml of 1 M HNO₃, then filtered into a volumetric flask and made it up to 250 ml with distilled water.

Total Potassium and Sodium in Biochar

For K and Na, the samples were read directly from the filtrate on the ASS.

Total Calcium and Magnesium in Biochar

For Ca and Mg, 1 ml of the filtrate was pipetted into a 50 ml volumetric flask and 10 ml of strontium chloride (SrCl) was added and the solution was made up to the mark with distilled water. The sample was then read for Mg and Ca on the AAS.

Prior to taking each cation reading the AAS was calibrated using the following stock solutions:

Na⁺ : 0 mg/L, 100 mg/L

K⁺ : 0 mg/L, 100 mg/L

Ca²⁺: 0 mg/L, 5 mg/L, 15 mg/L, 30 mg/L

Mg²⁺: 0 mg/L, 0.5 mg/L, 1.5 mg/L, 3 mg/L

The total Na⁺, K⁺, Mg²⁺ and Ca²⁺ in biochar were calculated using equation 16;

$$\text{Cation mg/ kg soil} = \frac{\text{mg/L} \times \text{Volume of Extractant(L)}}{\text{Weight of sample (kg)}} \times \text{DF} \quad (16)$$

Total Phosphorus in Biochar

Preparation of Reagents for P;

Reagent A: Twelve grams (12 g) of ammonium molybdate (NH₄)₆Mo₇O₂₄) were dissolved in 250 ml of distilled water to make solution 1. Then 0.2908 g of Potassium Antimony Tartrate (KsbOC₄H₄O₆) was dissolved in 100 ml of distilled water to prepare solution 2, and then 1000 ml of 2.5 M H₂SO₄ was prepared to make solution 3. The Solutions 1, 2 and 3 were mixed in a 2 L volumetric flask and made up to the volume mark with distilled water.

Reagent B: Dissolved 1.056 g of ascorbic acid in 200 ml of reagent A.

For determination of total phosphorus, 1 ml of the extracted biochar stock solution was pipetted into a 25 ml volumetric flask to which 4 ml of reagent B was added and made to the mark with distilled water. The mixture was shaken and left for 15 minutes to allow for colour development and then the absorbance was read on the

spectrophotometer at a wavelength of 882 nm. The formulas used to determine available P concentration were equations 17 and 18;

$$\text{Concentration of sample (mg/L)} = \frac{\text{absorbance sample}}{\text{absorbance 1 ppm std}} \quad (17)$$

$$\text{Available P (mg/kg)} = \frac{\text{Conc. sample (mg/L)} \times \text{Vol. extractant (L)}}{\text{weight of sample (kg)}} \times \text{DF} \quad (18)$$

3.5.6 Neutralizing Value

The NV was determined using the titrimetric method (Faithfull, 2002). To 0.5 g mass of biochar 25 mls 1 N HCl acid was added and the solution was heated on a hot plate for 2 minutes. One hundred millilitres (100 ml) distilled water was added to the solution, which was reheated for another 2 minutes and then cooled. Five (5) drops of phenolphthalein indicator was added and then the solution was titrated with 1N NaOH till the solution reached a permanent pink colour. The NV was calculated using equation 19;

$$\text{NV \%} = \frac{(\text{Volume of Blank} - \text{Volume of Sample}) \times \text{Conc. of Acid} \times 0.05 \times 100}{\text{weight of the lime sample}} \quad (19)$$

3.5.7 Ash Content

The ash content was determined according to the ASTM D1752-84 (2007) at 750 °C.

Weighed 1 g of oven dry biochar into a crucible and placed it in the muffle furnace at 750 °C for 2 hours, at which point the specimen was burned to ashes. Cooled the crucible in a desiccator, and determine the mass. The ash content was calculated using equation 20;

$$\text{Ash Content (\%)} = \frac{\text{Weight of ashed biochar (g)}}{\text{Weight of Oven dry biochar (g)}} \times 100 \quad (20)$$

3.6 Characterization of gypsum

Commercially available gypsum was used as a source of calcium in this study. The gypsum was characterized for total calcium (Ca %) and sulphur content (% S) which were determined according to the ASTM C 471M – 01(2002).

3.7 Groundnut crop trials

3.7.1 Greenhouse study area

The study was a pot experiment set up in the greenhouse at UNZA in the School of Agricultural Sciences located at 15° 23' 24" S and 28° 19'48" E, at an altitude of 1,260 m above mean sea level. A groundnut crop was grown to full maturity on soil treated with biochar and gypsum under water stress conditions.

3.7.2 Treatments and Experimental design

The crop trial was laid out in a split-split plot experimental design with gypsum as the main plot, biochar as the sub-plot and daily PWR as the sub-sub plot. The treatments for this experiment consisted: (i) two (2) gypsum application rates (0 and 200 kg/ha), (ii) four biochar application rates (0, 1, 2 and 4 % by mass of a 5 kg soil), and (iii) three irrigation regimes (100, 70 and 40 % PWR. The rain water was used for irrigation was harvested from the building roof during the 2015/2016 rain season. The daily PWR was calculated using the CROPWAT version 8.0 (FAO, 2009). Each of the treatment combinations were applied in four replications and are described in the schematic diagram in Figure 3.3.

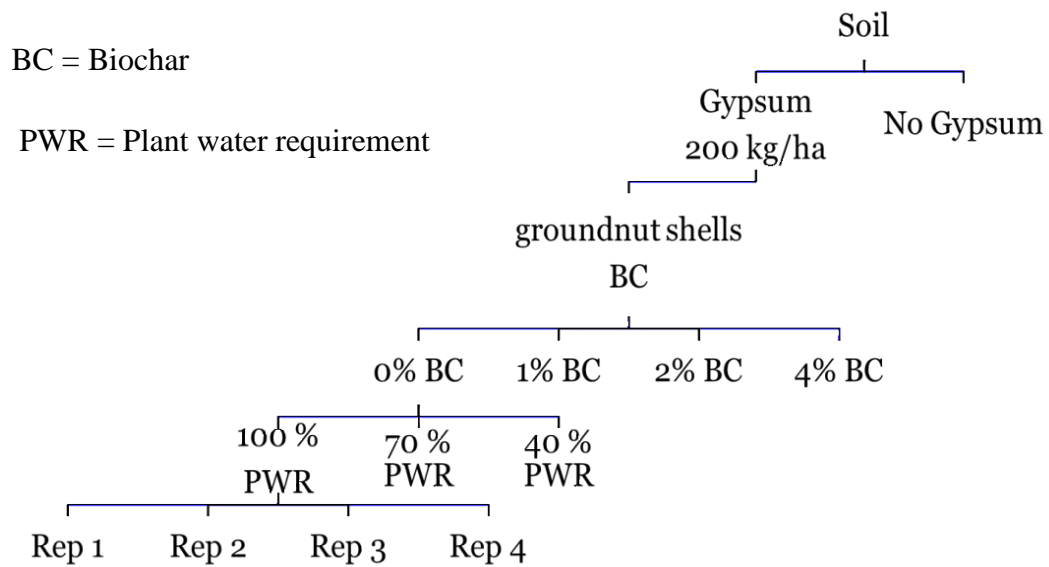


Figure 3. 3 Treatment combinations in pot experiments

Table 3. 1 Biochar treatments in soil moisture and temperature trials.

Treatment	Application rate			
	Pot Experiment	Field Experiment		
% Biochar (w/w)	Per 5 kg pot (g)	Broadcast (ton /ha)	Basin (ton /ha)	Ridges (ton/ha)
0	0	0	0	0
1	50	28	2	9.4
2	100	56	4	18.8
4	200	112	8	37.6

Assumptions; Basin dimensions: width = 0.15 m, length = 0.3 m, depth = 0.2 m, approximately 16,000 basins/ha

Ridge dimensions: width = 0.5 m, height = 0.2 m, inter row spacing = 0.75 m

3.7.3 Pre-germination of seed and Planting

The groundnut seed, Msekera Groundnut Variety 5 (MGV 5) used in this study is large seeded, bunch type, chestnut in colour, late maturing (130 – 140 days) and has an oil content of 45 – 48 % and a potential yield of 1.5 – 4.0 MT/ha. Before planting, the groundnut seeds were sterilized in 1.5 % sodium hypochlorite for 1 minute, rinsed three (3) times with sterile distilled water and placed on moist filter paper in a petri dish. The seeds were then incubated at 25 °C for seven (7) days ready for planting. Before planting, the biochar was applied at rates of 0 (control), 1, 2 and 4 by mass of a 5 kg soil were incorporated into the soil by uniformly mixing it in each pot. Four (4) pre-germinated groundnut seeds were planted in 5 kg of moist soil and later thinned to one plant per pot 10 days after emergence.

3.7.4 Crop Management

The groundnut crop was irrigated every 2 days with rainwater at the optimum PWR (100 %) rate until flowering (59 DAP) was initiated. At fifty-nine (59) DAP, moisture stress was induced by changing the irrigation schedule by exerting daily irrigation at rates of 100, 70 and 40 % PWR. The change in the amount of water applied simulated moisture stress similar to end-of-season drought.

Gypsum was applied at 200 kg/ha at 40 DAP as a source of calcium for the treatments that required it. The gypsum was placed around the groundnut plant at 1 - 2 cm depth and was covered with soil.

Routine management practices such as weeding, spraying with insecticides and fungicides were done when needed during the growing period. The groundnut crop was grown to maturity.

3.8 Data collection and Analysis

3.8.1 Weather parameters

The daily soil surface evaporation (E_o) was measured as the depth of water loss from four open buckets filled with water (evaporation buckets), located within the greenhouse.

To get the ambient temperature and evaporation loss in the greenhouse environment, readings of these two parameters were recorded each day at 9 hours throughout the growing season. The maximum (T_{\max}) and minimum temperatures (T_{\min}) were measured (using a maximum-minimum thermometer). The potential evapotranspiration (ET_o) was calculated using FAO ET_o Calculator version 3.2 (FAO, 2012) based on the Hargreaves-Samani method (1982, 1985). The daily T_{\min} and T_{\max} readings were used in this program to calculate the ET_o .

3.8.2 Water balance components

The amount of water applied to each pot was recorded as irrigation (I). The weight of pot was recorded every day after irrigating and amount of drainage (D) water was also recorded. The change in soil moisture storage (ΔS) was calculated as the difference in pot weight of consecutive days. The actual crop evapotranspiration (ET_c) was calculated using equation 21:

$$ET_c = I - (D + \Delta S) \quad (21)$$

Where; I = irrigation (mm), D = drainage (mm) and ΔS = change in storage (mm).

3.8.3 Soil reaction (pH)

Soil pH was taken at 35 DAP, which was read by inserting an in situ pH electrode (SCT-pH-PEN-5) 5 cm into the soil.

3.8.4 Leaf Chlorophyll Concentration

The leaf CCI of each plant was determined by a non-distractive technique using a portable SPAD Chlorophyll Meter (CCM-2000 plus). The SPAD Chlorophyll Meter Readings (SCMR) were taken at the vegetative stage (V3), 1st reproductive stage (R1) and 3rd reproductive stages (R3) which were at 41, 54 and 99 DAP respectively, read from midway leaves between the youngest and oldest leaves (as the rate of photosynthesis differs with leaf age). The leaf chlorophyll concentrations were recorded between 10 - 11 am each time.

3.8.5 Biomass and kernel yield

At maturity (182 DAP), the above and below ground biomass and mature pods were harvested. The roots, shoots and pods were separated from each plant and were sun-dried for 4 days. The root, shoot, pod dry weights and pod count were recorded.

3.8.6 Water use efficiency

To understand how well the groundnut crop was using the water supplied, the WUE was calculated. The WUE of the total biomass (WUE_T) was calculated and was also split into root biomass (WUE_R) and shoot biomass (WUE_S) calculations using equations 22, 23 and 24:

$$WUE_T = \frac{\text{Total biomass (g)}}{ETc \text{ (mm)}} \quad (22)$$

$$WUE_S = \frac{\text{Shoot biomass (g)}}{ETc \text{ (mm)}} \quad (23)$$

$$WUE_R = \frac{\text{Root biomass (g)}}{ETc \text{ (mm)}} \quad (24)$$

3.8.7 Crop coefficient

The groundnut crop coefficient (K_c) was calculated in dekadal periods throughout the growing season. The dekads selected to represent the initial (25 - 35 days), mid (35 - 70 days) and late (105 - 130 days) crop development stages (Boote, 1982; Allen *et al.*, 2000; Prasad *et al.*, 2011) were at the 2nd dekad of April, 1st dekad of June and 2nd dekad of August, respectively to obtain representative values for the $K_{c \text{ in}}$, $K_{c \text{ mid}}$ and $K_{c \text{ end}}$. The K_c values were calculated using equation 25:

$$K_c = \frac{ETc \text{ (mm)}}{ETo \text{ (mm)}} \quad (25)$$

3.8.8 Statistical Analysis

All data collected were analyzed as a split-split plot design using R statistical package (Version 3.3.2). Analysis of variance (ANOVA) was used to compare the effect of biochar on the soil pH, exchangeable bases and cation CEC of the soil treatment characteristics. A 3-way ANOVA was used to determine the effect of biochar, gypsum and water on the leaf chlorophyll concentration, biomass yield, water balance components, WUE and crop coefficient (K_c) of the groundnut crop under water stress. Fisher's Least Significant Difference (LSD) was used to separate treatment means.

Simple correlations between biochar, gypsum and water levels were also done where the ANOVAs showed significant differences.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Selected chemical and physical soil characteristics

Tables 4.1 shows selected characteristics of the soils used in the study. The soil used in this experiment was a sandy loam textured soil, suitable for growing groundnut because it is well-drained and loose and allows for pegging and unimpeded growth of the pods (Prasad *et al.*, 2010). This soil is classified in WRB classification system as Chromic Luvisol (IUSS Working Group WRB, 2015).

4.1.1 Soil reaction

The soil reaction was pH 4.02 in 0.01 M CaCl₂, which is classified as extremely acidic (Hazelton and Murphy, 2007). The ideal soil pH for groundnut ranges from pH 5.5 (slightly acidic) to 7.0 (neutral) (Nyambok, 2011). The extremely acidic soil conditions are not favourable for groundnut because the crop is likely to suffer from deficiencies of exchangeable bases (K, Ca, and Mg), P and molybdenum. The sub-optimal levels of P and molybdenum inhibit early root development in legumes, which reduces nodulation and nitrogen fixation (Muhati *et al.*, 2011). Phosphorus, aside from playing a major role in energy transfer, it also promotes cell division and elongation. The low soil pH can also create imbalances in trace elements such as aluminium and manganese (Tisdale *et al.*, 1985; Nyambok, 2011) which may result in poor crop development. This soil was selected for this experiment because of its low pH, suitable to test the effect of biochar on soil pH and its subsequent application to acid soils.

4.1.2 Total Nitrogen

The soil used in this study contained 0.048 % total N, which was far below the recommended critical limit of 0.2 % total N for most crops (Muhati *et al.*, 2011). The groundnut crop required starter nitrogen to be applied to this soil for the early stages of growth. As the crop began to develop nodules, soil N was less of a factor because groundnut can fix atmospheric nitrogen (N₂), when in a symbiotic relationship with effective strains of *Rhizobia* (Mweetwa *et al.*, 2014).

Table 4. 1 Selected soil characteristics

USDA Textural Class	Sand (%)	Silt (%)	Clay (%)	Soil reaction (pH) in 0.01M CaCl ₂ (1:2.5)	Exch acidity (cmol/kg)	EC (mS/cm)	Total Nitrogen (%)	Available Nitrogen (mg/kg)		Plant available P (mg/kg)	Organic Matter (%)	C:N ratio
								NH ₄ ⁺	NO ₃ ⁻			
Sandy loam	71.3	20.7	8	4.02	0.26	0.13	0.05			12.26	0.98	10:1
Critical levels				6.5		≤ 3.2	0.2			10.0	2.0	20:1

4.1.3 Available Phosphorus

Groundnut, unlike most crops often requires lower levels of available soil phosphorus (P), with the critical level at approximately 10 mg P/kg (Gascho and Davis, 1994). The available P content of 12.3 mg/kg was considered adequate for growing groundnut despite the soil being extremely acidic. The phosphorus present in the soil may have been residual P from the previous growing season when fertilizers were applied to the maize which had been grown on the land, where the soil was collected.

4.1.4 Organic Matter

The soil contained 0.98 % organic matter. According to Landon (1991), it is classified as being very low in organic matter as it was below the critical limit of 2 %. This was expected because of the previous continuous cultivation practiced on the land, where the soil was collected. Continuous cultivation tends to deplete the organic materials through clearing plant residues before planting the next crop (Yakubu, 2001). It had a low C/N ratio of 10:1, which favours nitrogen mineralization if all other factors for mineralization are favourable (Singer and Munns, 1987).

4.2 Calcium and Sulphur content in Gypsum

The gypsum used in the study contained 28 % calcium (Ca) and 11 % sulphur (S). Refined gypsum in the anhydrite form (CaSO_4) is 29.4 percent calcium (Ca) and 23.5 percent sulphur (S). However, it usually has water associated in the molecular structure ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and is approximately 23.3 percent Ca and 18.5 percent S (Sawyer and Banker, 2003). The gypsum had a low S content and was quite enriched in Ca content when compared to both pure anhydrite gypsum (CaSO_4) and hydrated gypsum.

4.3 Selected Biochar Characteristics

The characteristics of biochar are presented in Table 4.2. The biochar is strongly alkaline as it had a pH of 10.34 (Hazelton and Murphy, 2007). The total nitrogen and organic carbon content were 1.24 and 18.7 %, respectively, giving a C: N ratio of 15:1. Biochar C/N ratios fall between 7 and 500 (Herbert *et al.*, 2012). The low C/N ratio indicates that application of this biochar may lead to a supply of nitrogen to the groundnut crop because it is favourable for nitrogen mineralization (Singer and Munns, 1987). The total phosphorus content was 5.32 mg/kg and total sodium,

potassium, calcium and magnesium were 0.63, 1.10, 1.19 and 2.00 g/kg, respectively. The biochar was notably higher in calcium, potassium and magnesium than sodium. The low sodium is preferable because Na⁺ is not a plant nutrient. The ash content was relatively high at 24.5 %, indicating that the biochar had a high mineral content. The biochar contained most of the minerals that make up the groundnut shells, which are released slowly into the soil (Sukartono *et al.*, 2011). Major *et al.* (2010) had shown that the slow release of nutrients improved maize yields from the 2nd to the 4th growing season on low nutrient soils. Therefore, biochar supplied the groundnut crop with nutrients and would be of benefit to enhance the development of future crops grown in the same soil in seasons to come.

Table 4. 2 Selected Biochar Characteristics

pH in H ₂ O (1:10)	Total N (%)	Total P (mg/kg)	Total cations (g/kg)				CEC (cmol(+) /kg)	Organic Carbon (%)	C:N ratio	Ash (%)
			Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺				
10.34	1.24	5.32	0.63	1.10	1.19	2.00	11.25	18.7	15 :1	24.5

4.4 Effects of biochar on selected soil characteristics

Table 4.3 shows the effect of treating the soil with biochar at 1, 2 and 4% (w/w) on the bulk density, exchangeable bases and CEC. Incorporating biochar at the three levels had no significant effect statistically on the bulk density, which ranged from 1.31 g/cm³ to 1.4 g/cm³ across biochar treatments. The bulk density shows that the soil was not compacted, which was ideal for root growth and pod development.

The exchangeable bases from the soil were very low at planting particularly in the very low soil reaction range. The exchangeable potassium, calcium and magnesium were at 0.004, 0.51 and 0.24 cmol (+)/ kg soil, respectively. For groundnut, the critical level of exchangeable Ca²⁺ in soil is 1.0 cmol (+)/ kg in the root zone and 3.0 cmol (+)/kg in the pod zone (5 cm of topsoil), and exchangeable Mg²⁺ is also at 1.0 cmol (+)/ kg (Pradeep *et al.*, 2006). Exchangeable K⁺ required by most crops is 0.2 cmol (+)/ kg soil (Tisdale *et al.*, 1985). Groundnut requires a higher Ca level than what was available in this soil; it is essential especially for pod development. Gascho and Hodges (1991 in Gascho and Davis, 1994) recommend the supplemental application

of Ca when soils have less than 1.25 cmol (+)/kg. Therefore, application of gypsum as a source of calcium was required for the studied soil.

Incorporation of biochar had a significant ($P = 0.04$) effect on the soil CEC (Table 4.3). The CEC increased from 2.0 cmol (+)/kg in the soil to 3.2, 3.25, 3.5 cmol (+)/kg in soils with 1, 2 and 4% biochar, respectively. This CEC increase is characteristic of biochar as it is known to have the ability to increase CEC, attributed to its high CEC because it contains high levels of exchangeable bases (Lehmann *et al.*, 2011). Biochar application had a highly significant ($P < 0.001$) effect on both the exchangeable K^+ and Mg^{2+} content in the soil. Exchangeable K^+ increased from 0.04 to 0.08, 0.10 and 0.16 cmol (+)/kg in soils with 1, 2 and 4% biochar application, respectively.

Exchangeable Mg^{2+} also increased, from 0.24 to 0.26, 0.30 and 0.32 cmol (+)/kg in soils with 1, 2 and 4% biochar application, respectively. However, there were no significant differences in exchangeable Ca^{2+} among any of the biochar treatments as it ranged from 0.45 to 0.51 cmol (+)/kg (Table 4.3).

Table 4. 3 Effect of biochar application on bulk density, exchangeable bases and cation exchange capacity (CEC) of soil

Treatment	Bulk density (g/cm ³)	Exchangeable Bases (cmol(+)/kg)			CEC (cmol(+)/kg)
		K^+	Ca^{2+}	Mg^{2+}	
0 % BC (soil)	1.31	0.04	0.51	0.24	2.00
1 % BC	1.40	0.08	0.45	0.26	3.20
2 % BC	1.36	0.10	0.48	0.30	3.25
4 % BC	1.35	0.16	0.48	0.32	3.50
CV (%)	2.26	2.16	2.16	2.16	2.18
<i>P- value</i>	0.84	<0.001***	0.71	<0.001***	0.04*

Levels of Significance: 0 '****' 0.001 '***' 0.01 '**' 0.05 '.' 0.1 ' ' 1

4.5 Effect of Biochar application rates on soil reaction (pH) and cation exchange capacity (CEC)

Figure 4.1 shows the effect of biochar on soil reaction (pH). Biochar application significantly increased soil pH indicating a neutralizing effect on the soil. Biochar significantly ($P < 0.001$) raised the *in-situ* soil reaction from pH 5.00 to 6.03, 6.38 and 7.15 with 1, 2 and 4 % w/w of biochar application, respectively (Appendix A). However, biochar had a low NV, so the rise in pH may not be attributed to its NV. The rise in soil pH may be attributed to biochar's reactive surface; it has a large specific surface area with some charged functional groups which strongly attract cations from the soil solution to accumulate and increase the soil pH (Herbert *et al.*, 2012).

Incorporation of biochar at increasing levels showed a 75 % increase in the CEC of the soil, ranging from 2.0 - 3.5 cmol/kg as the application rose from 0 to 4 % w/w biochar as presented in Table 4.3. There was a strong relationship ($R^2 = 0.8698$) between CEC and soil reaction (pH) at different rates of biochar applied (Figure 4.2). This relationship exists because both CEC and pH depend on the large negatively charged specific surface area of biochar. The linear increase in pH and CEC and their positive relationship in the soil agree with findings from a field study on biochar-treated sandy loam soils in Mkushi by Martinsen *et al.* (2014).

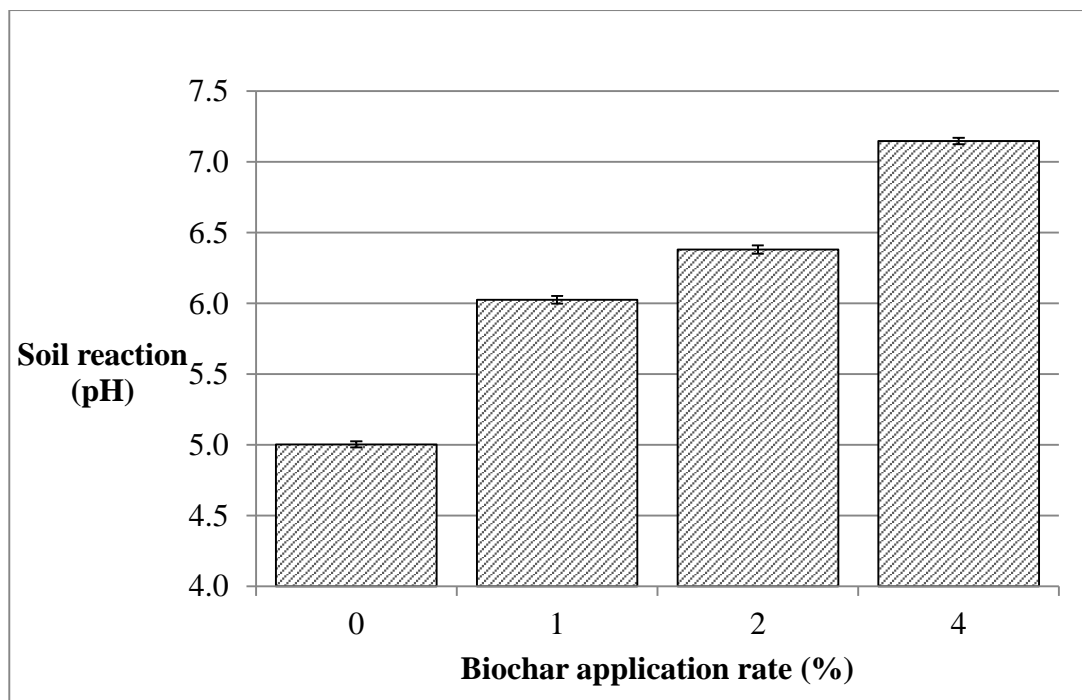


Figure 4. 1 Effect of biochar application rates on soil reaction (pH)

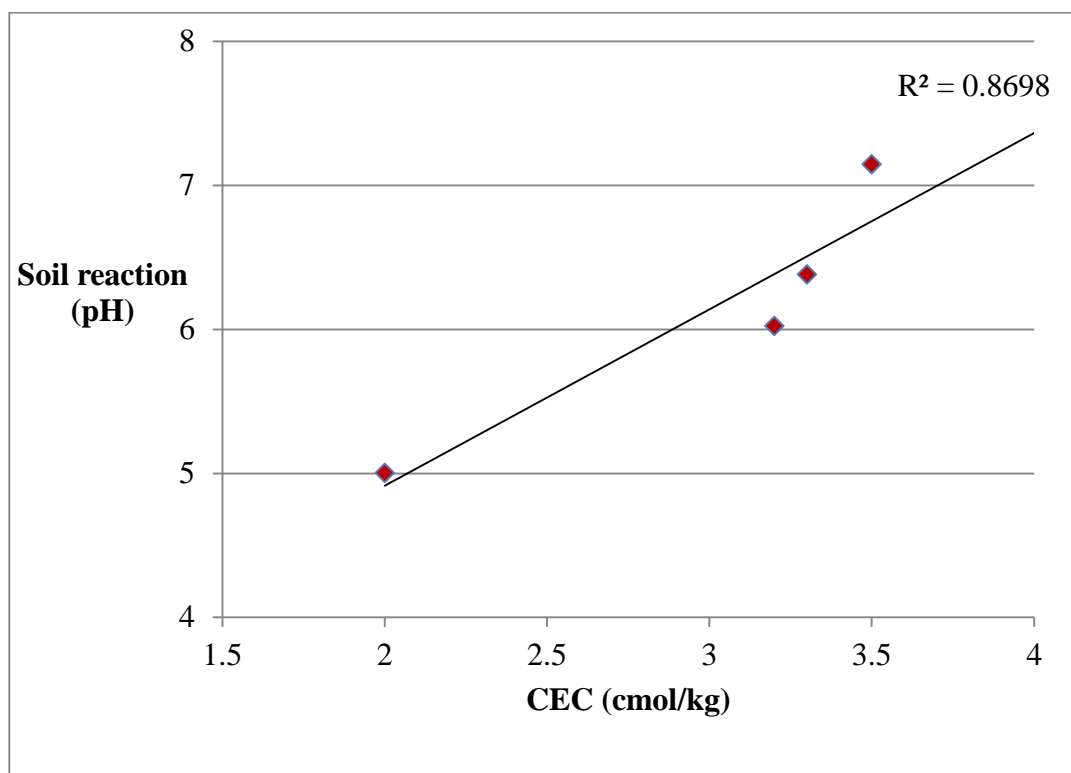


Figure 4. 2 Relationship between CEC and soil reaction (pH) at different rates of biochar application

4.6 Effect of water, biochar and gypsum application rates on leaf chlorophyll concentration

Chlorophyll is an important crop biophysical characteristic, which is the only pigment that assimilates light. It correlates well with plant physiological processes (i.e., photosynthesis, transpiration and stomatal conductance) and therefore can be related to crop productivity and growth stages (Wood *et al.*, 1993; Ciganda *et al.*, 2008; Papasavvas *et al.*, 2008). The leaf chlorophyll concentration was measured at 3 stages of growth (vegetative (V3), first flowering (R1) and podding (R3)). Phenology plays a significant role in the leaf chlorophyll, which increases or reduces depending on whether the leaves are just emerging or are at senescence (Ciganda *et al.*, 2008). The graphs in Figure 4.3 present the effect of the water, gypsum and biochar application rates on the leaf CCI at three stages of growth; V3 (41 DAP), R1 (54 DAP) and R3 (99 DAP).

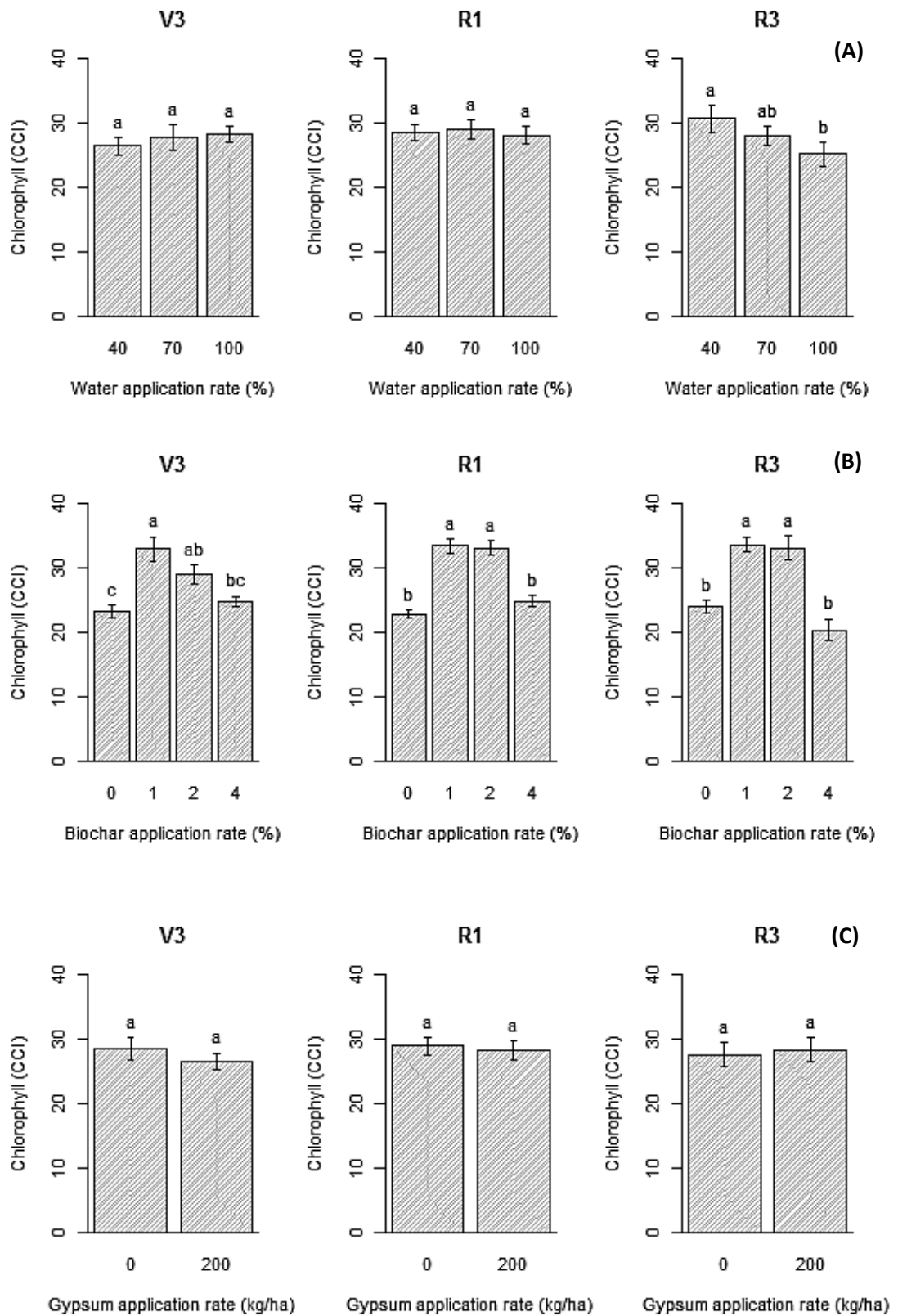


Figure 4.3 (A.) Effect of water application rates on chlorophyll concentration at V3, R1 and R3. (B.) Effect of biochar application rates on chlorophyll concentration at V3, R1 and R3. (C.) Effect of gypsum on chlorophyll concentration at V3, R1 and R3

The results show that the water application at 100, 70 and 40 % PWR had no significant effect on the chlorophyll concentration at V3 and R1 (Figure 4.3A) since the water treatments had not yet been initiated. At R3 water application rates had a significant ($P = 0.016$) effect on the chlorophyll concentration, with 30.71, 28.10, and 25.22 CCI for 40, 70 and 100 % PWR, respectively. The 40 % PWR had a 22 % increase in CCI at R3 as compared to the 100 % PWR. Moisture stress is a critical abiotic stress that impairs plant processes such as chloroplast development which impedes biosynthesis of chlorophyll precursors and reduce chlorophyll production (Prakash and Ramachandra, 2000; Dalal and Tripathy, 2012). Other studies have shown that moisture stress reduced chlorophyll concentration in maize (Homayoun *et al.*, 2011; Khayatnezhad and Gholamin, 2012), turfgrass (Mathowa *et al.*, 2012), wheat (Akhkha *et al.*, 2011), *Avena* species and many other plants (Pandey *et al.*, 2012). However, these findings are not in agreement with the results found in this study, where the highest leaf chlorophyll reading was observed at the lowest water application rate (40 % PWR). In addition, groundnut is a C3 plant species therefore, low soil moisture increases photorespiration which reduces the efficiency of photosynthesis (Marschner, 2012). The MGV 5 variety response may be attributed to a drought-resistant trait that increases leaf chlorophyll under drought stress, evident in studies on maize (Homayoun *et al.*, 2011; Mathowa *et al.*, 2012) and turf grass (Khayatnezhad and Gholamin, 2012). However, little is known about this variety about this trait. The decrease in chlorophyll content with increase in water application rate may have been as a result of leaching of nutrients (Marschner, 2012). On the other hand, excessive irrigation and water logging also decrease the leaf chlorophyll content. Excess irrigation, especially in sandy soils induces leaching of nutrients such as N, S, exchangeable K^+ and Mg^{2+} as they are not tightly bound (Mathowa *et al.*, 2012). These nutrients are essential for chlorophyll formation and therefore, the deficiency will inhibit chlorophyll production (Marschner, 2012). Figure 4.9 shows that 100 % PWR had the highest drainage among the water application treatments; therefore, nutrient leaching was highly likely.

Figure 4.3 (B) show that biochar application had a significant effect on the chlorophyll concentration at all three stages of crop growth (V3, R1 and R3). Due to its effect of raising soil pH, the increase in chlorophyll content could be attributed to increased availability of key nutrients for crop growth. The chlorophyll concentration readings ranged from 23.3 to 32.99, 22.9 to 33.47 and 20.4 to 33.7 CCI at V3, R1 and R3,

respectively. The CCI increased by 42, 46 and 40 % at V3, R1 and R3, respectively. The general trend at V3, R1 and R3 was that the lowest chlorophyll concentrations were at 0 and 4 % biochar application and the highest concentrations were at 1 and 2 %. The low chlorophyll concentration in the 0 % biochar soil was because of the low soil pH which affected nutrient availability, thus inhibiting plant growth and chlorophyll production. Macronutrients tend to be affected the most in acid soil (Tisdale *et al.*, 1985), therefore nutrients such as N, P and Mg that are directly involved in chlorophyll production would be limited (Marschner, 2012). At 1 and 2 % biochar, the rate of photosynthesis improved because it increased the soil pH, making nutrients more available, agreeing with the findings of Xu *et al.* (2015) who also observed this effect in groundnut. At 4 % biochar, the low chlorophyll concentration may have been as a result of this soil treatment having a higher nutrient retention capacity than the other treatments. Biochar is highly porous, giving it a large surface area for water and nutrient adsorption (Foereid, 2015). Nutrients in the soil may have been strongly adsorbed to biochar at the highest biochar concentration making plant uptake difficult. On the other hand, the maximum biochar rate in combination with the 100 % PWR resulted in saturation and high drainage and possibly leaching, resulting in a nutrient deficiency that slows crop growth and chlorophyll production.

Figure 4.3 (C) shows that gypsum had no significant effect on the chlorophyll concentration at all growth stages. The chlorophyll concentration at all three growth stages ranged from 26.5 to 28.5 CCI. Gypsum mainly supplies calcium and sulphur to the crop. Even though calcium is an essential and major plant nutrient, it is not a component of chlorophyll, therefore may not affect chlorophyll production directly. Calcium is involved in regulating numerous plant functions and processes; cell elongation and division, membrane fluidity and permeability, ion fluxes, cellular pH, source-sink translocation of carbohydrates, N-metabolism, reproductive development, stress responses and apoptosis (Jain *et al.*, 2011) that influence chlorophyll production. Sulphur, on the other hand aside from being involved in protein synthesis and nitrogen uptake, it is essential for chlorophyll production as it is a constituent of essential amino acids (methionine and cysteine) involved in chlorophyll production (Kumar and Sharma, 2013). The quantity of sulphur gypsum supplied may not have been sufficient to affect chlorophyll production.

Overall, the water, biochar and gypsum interaction had a non-significant interactive effect on the groundnut plant chlorophyll concentration at all the three stages of growth (Appendix B).

4.7 Effect of biochar, gypsum and water application rates on groundnut dry matter and kernel yield

At maturity (182 DAP) there was poor kernel yield across treatments, ranging from 0 – 3 kernels/plant. The poor kernel yield was because the crop entered the cold season when the temperatures were low and low radiation. Therefore, only biomass was used as an indicator of the economic index as opposed to the kernel yield.

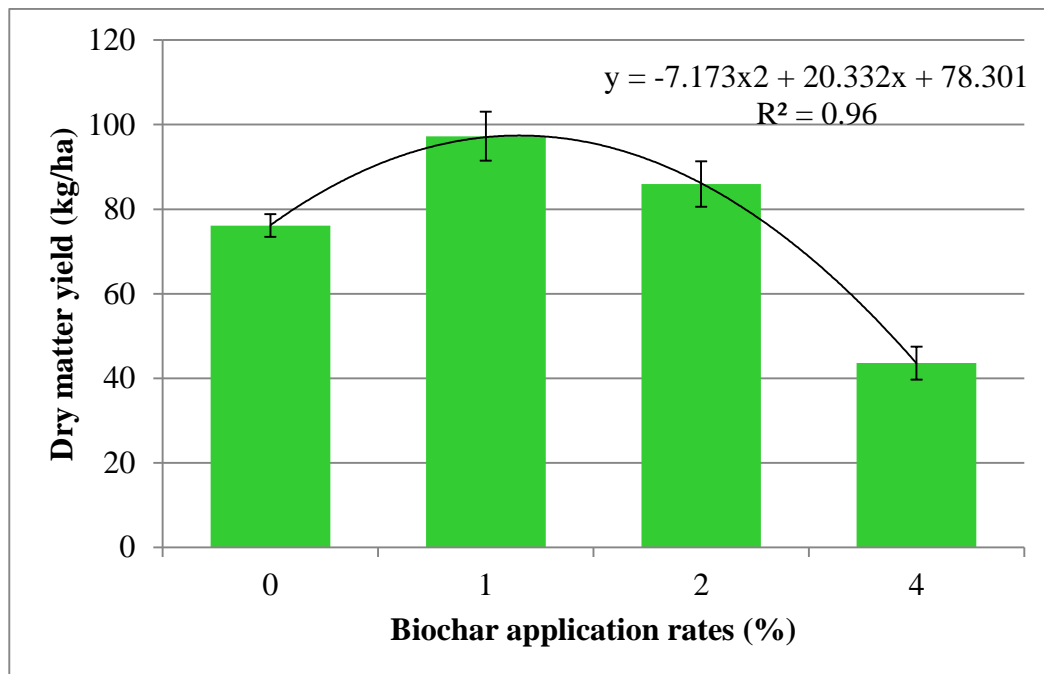


Figure 4. 4 Effect of biochar application rate on the groundnut dry matter yield at maturity (182 days)

The effect of incorporating biochar into the soil at increasing levels on the groundnut DM yield is presented in Figure 4.4. The groundnut DM yield increased with the addition of biochar and was highest at 1 % (97.25 kg/ha) and lowest 4 % (43.58 kg/ha). Applying biochar at 1 % increased DM by 28 % while 4 % reduced the DM by 43 %. Biochar can supply soil nutrients directly or indirectly to the crop, with the latter having more of an impact on the crop because it usually is a larger pool (Harris, 2011). Though biochar could neutralize the acid soil (Figure 4.2) and is known to have a high nutrient retention capacity attributed to its sorption properties, this soil was poor and

low in some nutrients (Tables 4.1). The DM yield decline may also to a large extent have been attributed to waterlogging at 4 % biochar as it retained excess moisture. The water logging created an anaerobic environment for the roots which may have had negative impacts on the root growth and limited water and nutrient uptake by inhibiting processes such as respiration (Allen *et al.*, 2000; Akhtar and Nazir, 2013) thus inhibiting crop growth. Flooding also induces stomatal closing especially in C3 plant species which retard metabolic processes such as photosynthesis (Akhtar and Nazir, 2013). Wilting and eventual death of three plants was observed during the study because of root rot, of which two plants were under a combination effect of 4 % biochar and 70 % PWR. The 4 % biochar also had the highest drainage (Figure 4.6 (B)), so the soil may have lost some essential nutrients through leaching, retarded crop growth and resulting in the lowest DM yield (Marschner, 2012; Mathowa *et al.*, 2012). The DM at 0, 1, 2 and 4 % biochar were significantly ($P = 0.0151$) different. From the equation of the line in Figure 4.4, the optimum DM yield for groundnut was achieved at a biochar application rate of 1.42 % w/w. Application of biochar at 1 and 2 % was beneficial to the plant as it increased the DM yield. This agrees with a study by Xu *et al.* (2015) where biochar at 0.375 – 6.00 % w/w increased groundnut biomass and pod yields by 2- and 3- times on the red ferrosol and redoxi-hydrosol, respectively. Martinsen *et al.* (2014) also observed a similar effect addition of biochar resulting in an increase in plant available water (PAW), CEC, available K^+ , pH, in these acidic tropical soils, which increased yield of maize but not on groundnut.

Figure 4.5 shows a line graph of the pooled effect of biochar, gypsum and water on the DM yield of the groundnut at maturity (182 days). At 40 % PWR, the application of gypsum to the soil had no significant effect on the DM regardless of the level of biochar incorporated into the soil. Moisture is a key factor for crop development and it also affects the availability of nutrients in the soil solution for uptake (Gascho and Hodges, 1991 in Gascho and Davis, 1994). At 70 % PWR, the application of gypsum had a positive effect on the DM at 0 and 1 % biochar. At 2 and 4 %, the 70 % PWR with or without gypsum had no significant effect on the DM either. The 100 % PWR had a significant ($P < 0.001$) effect on the DM, where it positively increased from 0 % to 2 % biochar and began to decline, with 4 % biochar having the lowest value. The DM decline is linked with excess drainage and leaching of nutrients at 4 % biochar and 100 % water (Figure 4.6 (B)) which is similar to what was earlier alluded to in

the description of Figure 4.4. At 100 % PWR the DM was about 2 – and 3-fold greater than at 70 and 40 %, respectively.

Overall, only biochar and water had a significant effect on the development hence, on the DM (Appendix C).

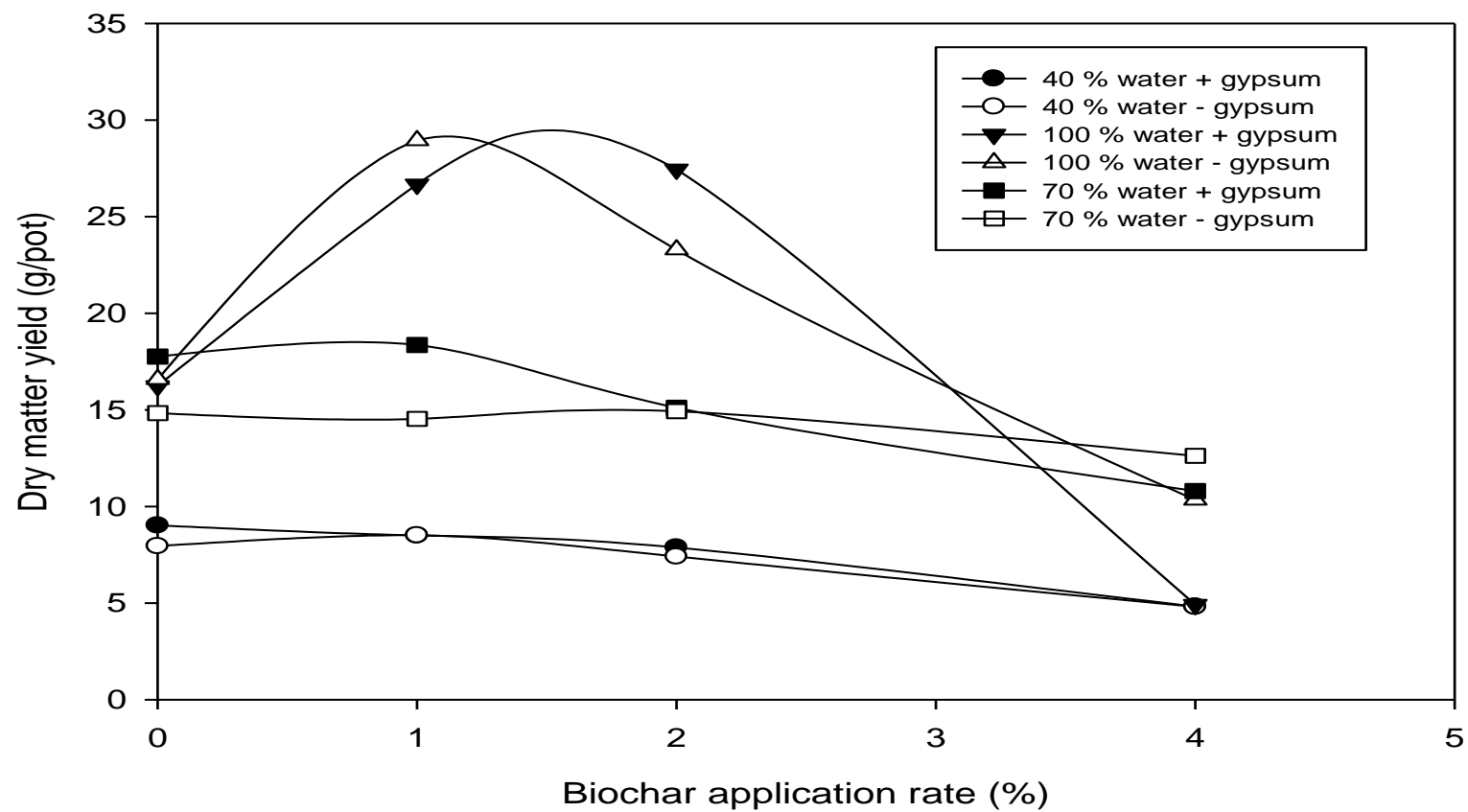


Figure 4. 5 Effect of biochar, gypsum and water application rates on groundnut dry matter yield at maturity (182 days)

4.8 Effect of gypsum, biochar and water application rates on soil water balance components

The soil water balance was monitored to help estimate the actual daily soil water uptake, to get a better understanding of the crop's growth response to water stress. Water balance is based on the "law of conservation of mass" and is defined as an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a specified period (Hillel, 2004). The water balance in the root-zone is usually expressed as follows:

Change in storage = Gains – Losses

$$(\Delta S + \Delta V) = (P + I + U) - (R + D + E + T)$$

Where; ΔS is the change in soil-moisture storage in the root-zone, ΔV is the increment of water incorporated in vegetative biomass, P is precipitation, I is irrigation, U is upward capillary flow into the root zone, R is runoff, D is downward drainage out of the root zone, E is evaporation from the soil surface, and T is transpiration by plants.

For this study, the equation was further simplified to:

$$dS = I - (D + E + T)$$

The effect of the application of gypsum on the change in soil water storage (dS), drainage (D), crop evapotranspiration (ETc), are displayed in Figure 4.7. Application of 200 kg/ha gypsum had no significant effect on the change in storage, drainage or evapotranspiration with P values at 0.636, 0.463 and 0.753, respectively. Change in soil water storage (dS), D and ETc ranged from -6.79 to -6.17 mm, 29.99 to 38.92 mm, and 429.48 to 423.11 mm, respectively. Although gypsum applied, supplied the soil with calcium and sulphur that are involved in plant cell elongation and protein synthesis, respectively (Jain *et al.*, 2011; Kumar and Sharma, 2013) it was not sufficient to enhance crop growth or affect the dS, D and ETc components.

The effect of biochar application rates on the change in soil water storage (dS), drainage (D), crop evapotranspiration (ETc), are displayed in Figure 4.8. Application of biochar had no significant effect on dS and ETc (P = 0.896 and 0.563, respectively) but significantly affected the D (P = 0.076). The dS, D and ETc components ranged from -7.27 to -5.89 mm, 20.45 to 64.12 mm, and 398.70 to 461.97 mm, respectively. Based on the biomass yield (Figure 4.4) biochar enhanced crop growth but the rate of ETc had no

significant effect on the dS. Biochar at 4 % had the highest drainage as compared to the other treatments as expected. This was because of the higher the biochar application rate the more the soil moisture retention between irrigation intervals leaving less space in the soil pores to hold more water at each irrigation, allowing more drainage at 4 % biochar. In addition, the 4 % biochar had smaller groundnut plants which took up less water, therefore addition of water by irrigation resulted in larger volumes of excess water loss as drainage, while the 0, 1 and 2 % biochar drained the least amount of water because the soil was not saturated and had larger plants to take up more water (Figure 4.6). Possibly in a larger soil profile (longer rooting depth) significant differences in dS and D due to biochar application rates may have been observed.

The effect of water application rates on the change in soil water storage (dS), drainage (D), crop evapotranspiration (ETc), are displayed in Figure 4.9. The water application rates had no significant effect on dS ($P = 0.394$) but significantly affected the D and ETc components ($P < 0.001$ and $P < 0.001$, respectively). The dS, D and ETc ranged from -7.27 to -5.89 mm, 10.95 to 79.45 mm, and 329.98 to 508.3 mm, respectively. The drainage was highest where 100 % PWR was applied as compared to the 40 % and 70 % PWR because more water was applied to that soil each day. The ETc was highest where 100 % PWR was applied, followed by 70 and 40 % PWR, respectively. Applying 40 % PWR resulted in a 35 % decrease in ETc. The trend of decrease in ETc with a decrease in water applied to the soil was expected because as C3 crop species begin to get water stressed, photorespiration increases as stomata begin closing to reduce the loss of water by transpiration (Akhkha *et al.*, 2011; Marschner, 2012).

Gypsum, biochar and water application rates had no significant interactive effect on any of the water balance components (Appendix D).



Figure 4. 6 Effect of 100 % PWR, 0 kg/ha gypsum and biochar at 0, 1, 2 and 4 % (left to right) on root and shoot growth at maturity (182 days)

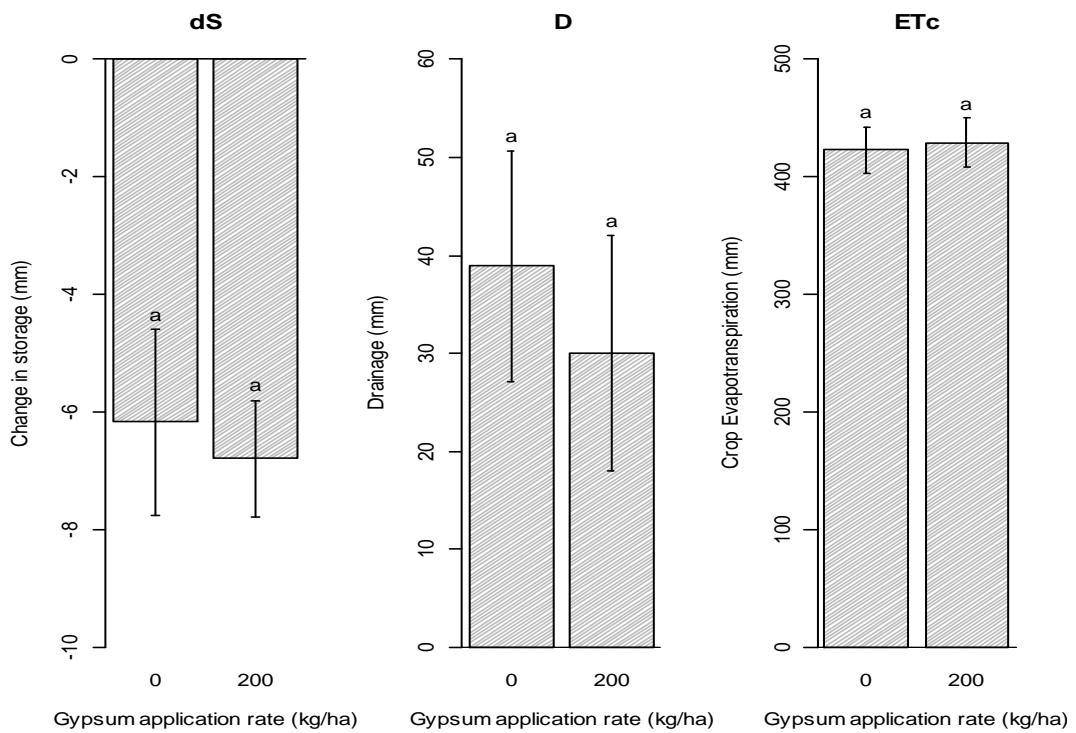


Figure 4. 7. Effect of gypsum application on soil water balance components; change in storage (dS), drainage and crop evapotranspiration (ETc)

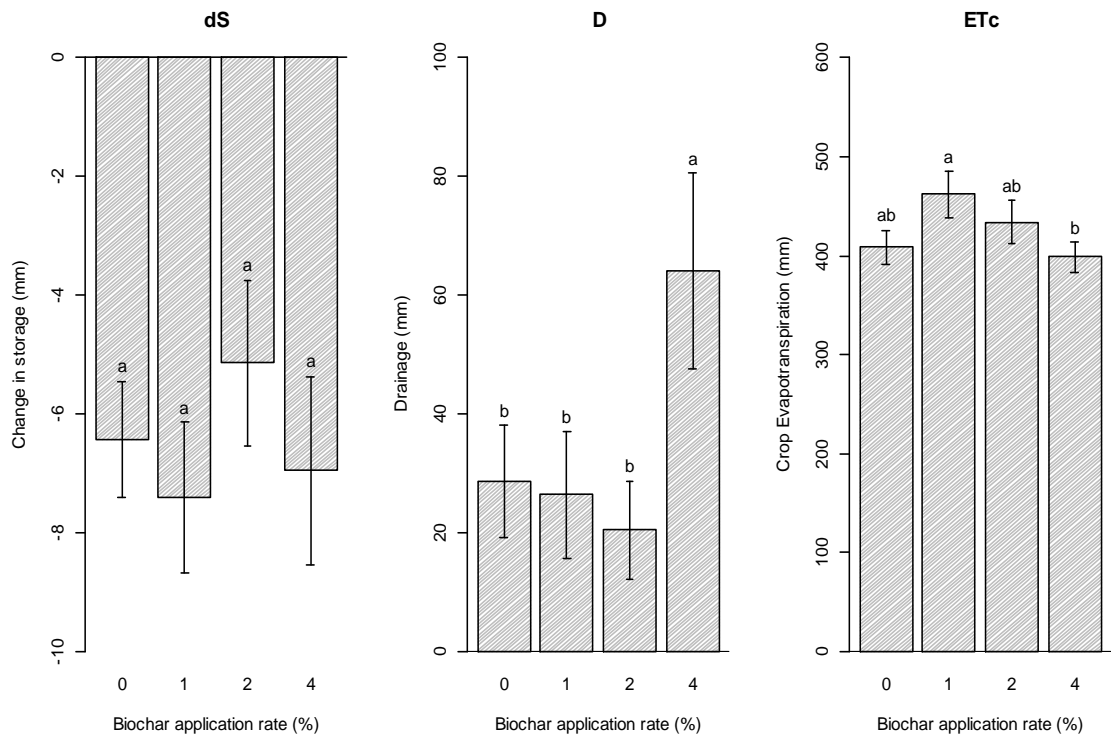


Figure 4. 8. Effect of biochar application on soil water balance components; change in storage (dS), drainage (D) and crop evapotranspiration (ETc)

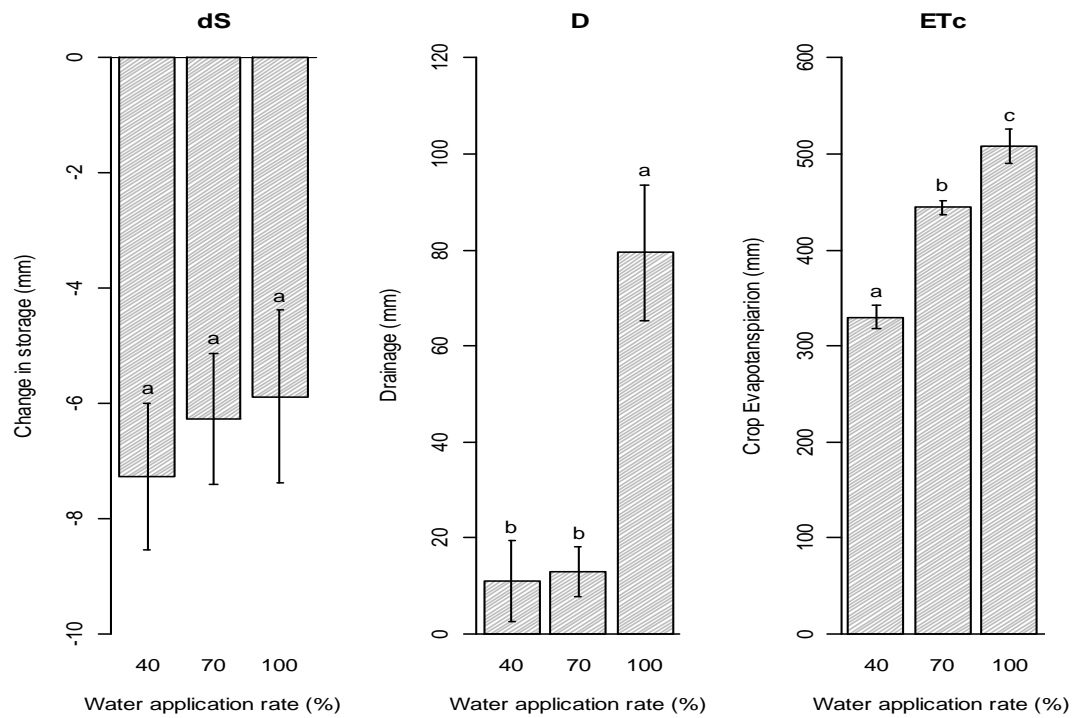


Figure 4. 9. Effect of water application on soil water balance components; change in storage (dS), drainage (D) and crop evapotranspiration (ETc)

4.9 Effect of Gypsum, Biochar and Water application rates on crop evapotranspiration-evaporation ratios (ETc/Eo and ETc/ETo)

A growing crop loses water to the atmosphere by transpiration and from the soil surface as evaporation (Eo). These two processes coincide making it difficult to measure separately, therefore, they are measured as evapotranspiration (ET) where, nearly 100% of ET at sowing comes from evaporation, while more than 90% of ET at full crop cover comes from transpiration (Allen *et al.*, 2000).

The ETc/Eo ratio is a measure that compares the loss of moisture through crop evapotranspiration (ETc) to soil evaporation (Eo). If the ETc/Eo ratio is greater than one, it means there was more moisture loss through ETc and less lost by Eo and vice versa. The effect of gypsum, biochar and water application rates had on the groundnut crop evapotranspiration-evaporation ratios (ETc/Eo) are shown in Figure 4.8. The ETc/Eo ratio for gypsum at 0 and 200 kg/ha was at 0.86 and 0.88, respectively which were not significantly different ($P = 0.735$). The biochar application rate had no significant effect ($P = 0.638$) on the ETc/Eo ratio. The ETc/Eo ratio ranged from 0.82 to 0.94 for biochar at 0, 1, 2 and 4 % application rates. The water application rate had a significant effect ($P < 0.001$) on the ETc/Eo ratio. The ETc/Eo ratios because of water application at 40, 70 and 100 % PWR ranged from 1.04 and 0.62. There wasn't much of a difference in the ETc/Eo ratio as a result of gypsum application because the crop was about the same size (Figure 4.5) which meant the crop cover was roughly the same. If the application of gypsum enhanced crop growth a difference would have been expected. Though the 1 and 2 % biochar application rates had higher biomass yields (Figure 4.4) and higher ETc/Eo ratios because of larger crop covers, they were not significantly different among biochar treatments. The ETc/Eo ratio increased with an increase in the water application rate which followed a similar trend to the yield increase (Figure 4.5). The optimum water application rate, 100 % PWR had an ETc/Eo ratio greater than one (1) which agrees with literature that as a crop develops full crop canopy, the greater part of ET comes from transpiration (Allen *et al.*, 2000). Overall, the effects of gypsum and biochar application rates on the ETc/Eo ratios show that the crop had not yet attained full crop cover as the water loss due to Eo was greater than transpiration.

The crop evapotranspiration-potential evapotranspiration (ETc/ETo) ratio is the comparison of how the actual crop performed to how a reference crop would perform in the same geographic location, with regard to evapotranspiration. The potential

evapotranspiration (ET_o) is the evapotranspiration expected from a reference crop in a given climatic location. The reference crop is a hypothetical grass well-watered with a fixed height (0.12 m), surface resistance (70 s m⁻¹), albedo (0.23) and complete ground cover (Allen *et al.*, 2000; Hillel, 2004). The ET_c is the actual crop evapotranspiration as earlier defined which differs from the ET_o based on the following factors; albedo (reflectance) of the crop-soil surface, crop height, evaporation from the exposed soil surface and canopy resistance (Allen *et al.*, 2000).

The effects of gypsum, biochar and water application rates had on groundnut crop evapotranspiration-potential evapotranspiration (ET_c/ET_o) ratios are shown in Figure 4.10. The ET_c/ET_o ratios for gypsum at 0 and 200 kg/ha were at 0.79 and 0.8, respectively. Application of gypsum had no significant effect ($P = 0.75$) on the ET_c/ET_o ratios. The ET_c/ET_o ratios for biochar at 0, 1, 2 and 4 % ranged from 0.75 to 0.87. Application of biochar also had no significant effect ($P = 0.574$) on the ET_c/ET_o ratios. However, the water application rate had a significant effect on the ET_c/ET_o ($P < 0.001$) ratios, which ranged from 0.62 to 0.95 for water at 40, 70 and 100 % PWR. The effect of gypsum, biochar and water application rates on the ET_c/ET_o ratios all followed similar trends to that of their respective evapotranspirations in Figure 4.7. The ET_c component constituted 60 – 80 % of ET_o during a growing season because the lower the soil moisture regime, the lower the ET_c (Hillel, 2004). The effect of gypsum, biochar and water application rates on the ET_c/ET_o ratios all fell within this range, with the 1 % biochar and 100 % PWR giving higher values of 87 and 95 %, respectively. The 100 % PWR had the highest ET_c/ET_o ratio because it was the optimum amount of water to supply the crop, therefore, the soil was always well watered to allow optimum growth and processes such as ET_c to take place at their highest rate was expected. The 1 % biochar also had a higher ET_c/ET_o ratio because it notably enhances crop growth which favour processes such as ET_c because 1 % biochar retained sufficient moisture in the soil.

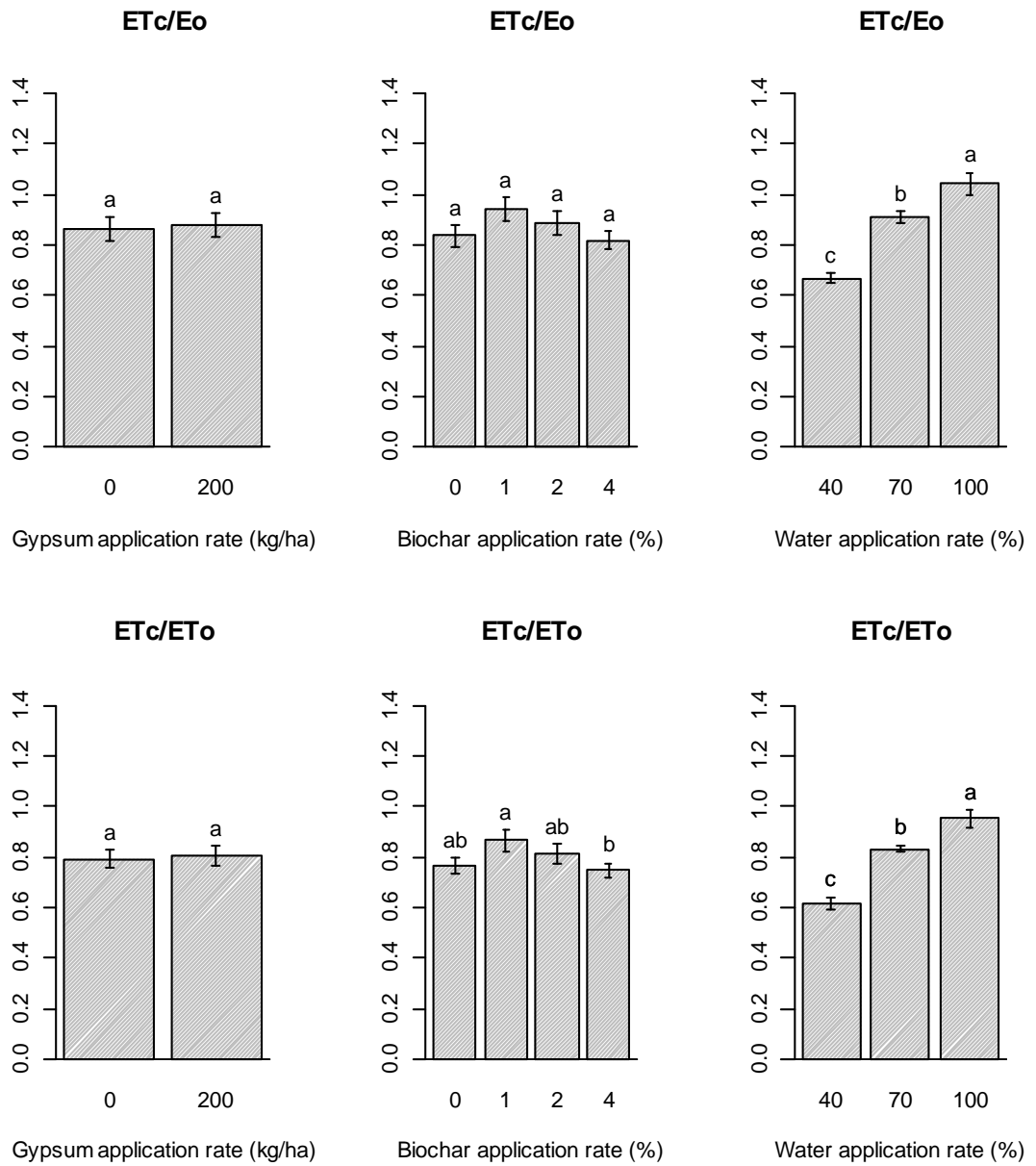


Figure 4. 10 Effect of gypsum, biochar and water on crop evapotranspiration- evaporation ratios (ET_c/E_o and ET_c/ET_o)

4.10 Effect of gypsum, biochar and water application rates on water use efficiency (WUE)

The WUE is defined as a ratio of the biomass produced to the crop evapotranspiration (Songsri *et al.*, 2009). The WUE is a physiological trait that can be associated with yield performance because the crop's ability to have a high WUE even under moisture stress shows its adaptive ability under water stress (Songsri *et al.*, 2013). For this study, the shoot, root and total biomass WUE are discussed to understand how the groundnut crop used a unit of water to produce a given quantity of shoot, root and total biomass. The

effect of gypsum, biochar and water application rates on the WUE for root, shoot and total biomass are shown in Figure 4.11.

The WUE of the shoot biomass (WUE_S) for gypsum applied at 0 and 200 kg/ha were 0.024 and 0.025 g/mm, respectively. Application of gypsum had no significant ($P = 0.637$) effect on the WUE_S . The WUE_S for biochar applied at 0, 1, 2 and 4 % ranged from 0.014 to 0.029 g/mm. The biochar application rates had a significant effect ($P < 0.001$) on the WUE_S . The WUE_S for water applied at 40, 70 and 100 % ranged from 0.017 to 0.029 g/mm. The water application rates had a significant effect ($P < 0.001$) on the WUE_S . Application of gypsum had no significant effect on the WUE_S because it did not change shoot biomass and crop evapotranspiration that are used in the calculation of WUE_S . Application of biochar at 0, 1 and 2 % gave similar WUE_S values which were much higher than at 4 % biochar. The 4 % biochar had the lowest WUE_S because it had the lowest shoot biomass because the crop growth was retarded due to the unfavourable water-logged root environment the crop had. The severely stressed crop at 40 % PWR had the lowest WUE_S as expected because there was insufficient water in the root zone (Songsri *et al.*, 2013). However, at 70 % PWR the WUE_S was statistically equivalent to the 100 % PWR due to moderate stress which made the root zone moist enough for the crop to adjust stomatal behaviour to adapt to the moderate moisture stress (Akhkha *et al.*, 2011; Songsri *et al.*, 2013).

The WUE of the root biomass (WUE_R) for gypsum applied at 0 and 200 kg/ha were 0.0059 and 0.0063 g/mm, respectively. Gypsum application had no significant ($P = 0.425$) effect on the WUE_R . The WUE_R for biochar applied at 0, 1, 2 and 4 % ranged from 0.0039 to 0.0069 g/mm. The biochar application rates had a significant effect ($P < 0.001$) on the WUE_R . The WUE_R for water applied at 40, 70 and 100 % ranged from 0.0059 to 0.0064 g/mm. The water application rates had no significant effect ($P = 0.81$) on the WUE_R . The effect of the gypsum and biochar application rates on the WUE_R followed the same trend as their effects on the WUE_S as was expected. However, the effect of the water application rates on the WUE_R was not significant and did not follow the trend of its effect on the WUE_S . This shows that regardless of the amount of water applied, the groundnut crop could efficiently produce the same quantity of root DM per volume of water supplied.

The WUE of the total biomass (WUE_T) for gypsum applied at 0 and 200 kg/ha were 0.030 and 0.031 g/mm, respectively. Application of gypsum had no significant ($P =$

0.591) effect on the WUE_T . The WUE_T for biochar applied at 0, 1, 2 and 4 % ranged from 0.018 to 0.033 g/mm. The biochar application rates had a significant effect ($P < 0.001$) on the WUE_T where at 4 % biochar the WUE_T reduced by 45%. The WUE_T for water applied at 40, 70 and 100 % ranged from 0.018 to 0.036 g/mm, representing a 50 % reduction in WUE at 40 % PWR. The water application rates had a significant effect ($P < 0.001$) on the WUE_T . The effects of the gypsum, biochar and water application rates on the WUE_R followed the same trend as their effects on the WUE_S as was expected. The water application rates effect on the WUE_T trends were also similar to that of the DM yield in Figures 4.4 and 4.5, where 0 % to 2 % biochar gave the higher ET_c and 4 % gave the lowest ET_c . Leaching of nutrients due to high drainage and excess water creating anaerobic conditions in the root zone affected the development of the crop (Figure 4.9) and hence, the total biomass and ET_c reduced and it negatively affected the WUE_T . The effect of water on the WUE_T was that the less water that was applied the lower the WUE_T therefore, the more stressed (Figures 4.5 and 4.9) the crop was, the less it was able to use water efficiently. These findings are in agreement with Songsri *et al.* (2009) who looked at different groundnut varieties and on average they followed a similar trend.

The application of gypsum, biochar and water had no interactive effects on the WUE_S , WUE_R or WUE_T .

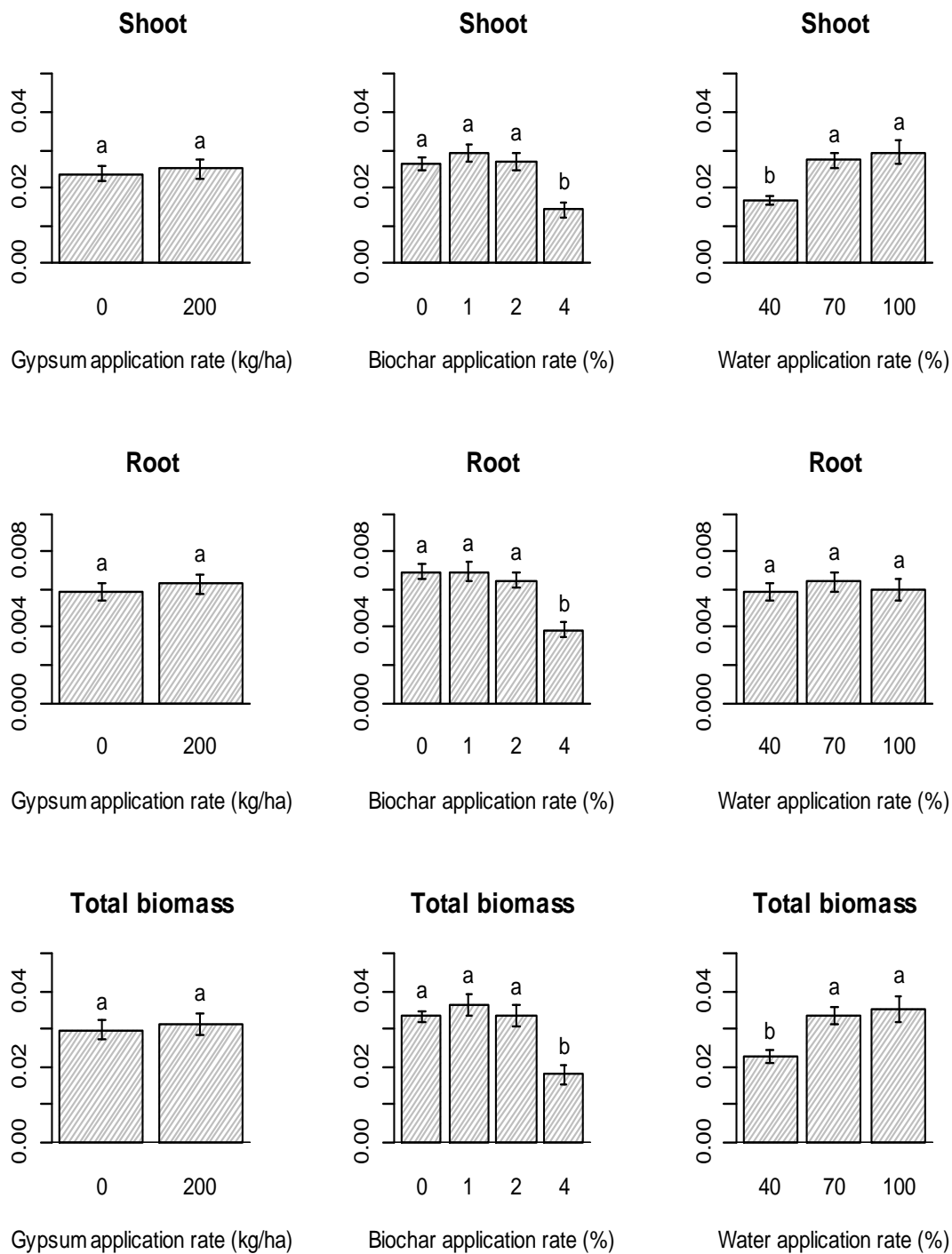


Figure 4. 11 Effect of biochar, gypsum and water on Water Use Efficiency (WUE) of Shoot, Root and Total Biomass

4.11 Effect of gypsum, biochar and water application rates on the groundnut crop coefficient (K_c)

The K_c is defined as an estimate of consumptive water use by crops based on evapotranspiration values (ratio of ET_c to ET_o) (Stannard *et al.*, 2013). The groundnut crop coefficients (K_c) were calculated for each month in dekadal intervals during the growing period (Lazzara and Rana, 2009). The 2nd dekad of April, 1st dekad of June and 2nd dekad of August, were used as representative values for the $K_{c\ in}$, $K_{c\ mid}$ and $K_{c\ end}$.

Table 4.4 shows the effect of the gypsum application rate on the groundnut crop coefficient (K_c) during the growing period at dekadal intervals. The K_c range was from 0.68 to 1.03 across gypsum treatments during the groundnut growing season. At 0 kg/ha gypsum the $K_{c\ in}$, $K_{c\ mid}$ and $K_{c\ end}$ were 0.719, 1.03 and 0.75, respectively and 0.73, 1.02 and 0.68 at 200 kg/ha gypsum. Application of gypsum had no significant effect on the K_c at all stages of growth because the amount of gypsum applied to the low calcium soil was too low to enhance crop growth. The $K_{c\ in}$ was higher than the expected 0.4, $K_{c\ mid}$ was lower than 1.15 and $K_{c\ end}$ was slightly greater than 0.6 (Allen, 2000).

Table 4.5 shows the effect of the biochar application rate on the groundnut crop coefficient (K_c) during the growing period at dekadal intervals. The K_c range was from 0.62 to 1.10 across biochar treatments. At 0 % biochar the $K_{c\ in}$, $K_{c\ mid}$ and $K_{c\ end}$ were 0.710, 1.01 and 0.77; at 1 % biochar were 0.76, 1.10 and 0.78; at 2 % biochar were 0.68, 0.94 and 0.74; at 4 % biochar 0.74, 1.02 and 0.66. During the initial stages of crop development 4 % biochar had a significant ($P = 0.04$) positive effect (3rd dekad of April) on the K_c value as compared to the other three treatments, which could be as a result of the soils ability to retain more moisture although at that stage they were all receiving the optimal PWR. As the crop approached mid-development, there was no significant difference in K_c among treatments, but as it moved towards the end of the season, the K_c at 4 % was the lowest but not significantly different from the other three treatments.

Table 4.6 shows the effect of the water application rate on the groundnut crop coefficient (K_c) during the growing period at dekadal intervals. The K_c range was from 0.43 to 1.34 across water treatments. At 40 % PWR the $K_{c\ in}$, $K_{c\ mid}$ and $K_{c\ end}$ were 0.720, 0.66 and 0.45; at 70 % PWR were 0.70, 1.07 and 0.77; at 100 % PWR were 0.75, 1.34 and 1.01. During the initial stages of crop development, there was no significant difference between the water treatments because they had not yet been started. After the water

treatments were introduced (2nd dekad of May), water had a significant effect on the K_c value during each dekad until maturity. The K_c value decreased with the decrease in water applied because low moisture reduces crop transpiration which affects the ET_c hence, the K_c (Akhkha *et al.*, 2011; Songsri *et al.*, 2013).

The $K_{c\ in}$ across treatments was much higher than the expected 0.4 for sub-humid climates (Allen *et al.*, 2000) as they were between 0.68 and 0.75. This was because the groundnut crop was irrigated daily and during the initial and development period $K_{c\ in}$ is a function of the wetting interval and potential evaporation rate. Therefore, frequent irrigation significantly increased the $K_{c\ in}$ (Allen *et al.*, 2000).

The general trend across treatments was that during the growing season, the K_c at the initial stage was low then began to increase reaching its maximum during mid-season because at that stage it had achieved full canopy cover, towards the end of the season it began to decline. The end-season decline was affected by the growth characteristics of the groundnut crop and irrigation management during that period (Allen *et al.*, 2000).

Table 4. 4. Effect of Gypsum on the groundnut Crop coefficient (Kc) for each dekad of the growth period

Month	April	April	May	May	May	June	June	June	July	July	July	Aug	Aug	Aug	Sept
Dekad	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1
0 kg/Ha	0.72 ^a	0.80 ^a	0.88 ^a	0.95 ^a	0.99 ^a	1.03 ^a	0.97 ^a	0.94 ^a	0.92 ^a	0.78 ^a	0.85 ^a	0.81 ^a	0.71 ^a	0.75 ^a	0.08 ^a
200 kg/Ha	0.73 ^a	0.80 ^a	0.87 ^a	0.96 ^a	0.99 ^a	1.02 ^a	0.96 ^a	0.96 ^a	0.89 ^a	0.82 ^a	0.87 ^a	0.82 ^a	0.68 ^a	0.73 ^a	0.05 ^a
Grand Mean	0.72	0.80	0.88	0.96	0.99	1.03	0.97	0.95	0.91	0.80	0.86	0.82	0.70	0.74	0.07
LSD	0.05	0.02	0.02	0.04	0.10	0.13	0.13								
CV (%)	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
<i>P-value</i>	0.80	0.75	0.87	0.62	0.96	0.92	0.94	0.74	0.73	0.44	0.72	0.82	0.55	0.67	0.29

Significance codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Means followed by the same letter in a column are not significantly different at $\alpha=0.05$

Table 4. 5. Effect of Biochar on the groundnut Crop coefficient (Kc) for each dekad of the growth period

Month	April	April	May	May	May	June	June	June	July	July	July	Aug	Aug	Aug	Sept
Dekad	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1
0 %	0.71 ^{ab}	0.78 ^b	0.88 ^{ab}	0.96 ^a	0.98 ^a	1.01 ^a	0.92 ^a	0.89 ^a	0.91 ^{ab}	0.74 ^a	0.81 ^{ab}	0.81 ^{ab}	0.70 ^a	0.77 ^a	0.10 ^a
1 %	0.76 ^a	0.80 ^{ab}	0.87 ^{ab}	0.97 ^a	1.02 ^a	1.10 ^a	1.04 ^a	1.01 ^a	0.98 ^a	0.88 ^a	0.96 ^a	0.90 ^a	0.75 ^a	0.78 ^a	0.00 ^b
2 %	0.68 ^b	0.80 ^{ab}	0.89 ^a	0.96 ^a	1.00 ^a	1.04 ^a	1.02 ^a	0.98 ^a	0.94 ^{ab}	0.831 ^a	0.93 ^a	0.84 ^{ab}	0.72 ^a	0.74 ^a	0.07 ^{ab}
4 %	0.74 ^{ab}	0.82 ^a	0.86 ^b	0.95 ^a	0.96 ^a	0.94 ^a	0.89 ^a	0.90 ^a	0.79 ^b	0.75 ^a	0.75 ^b	0.71 ^b	0.62 ^a	0.66 ^a	0.09 ^{ab}
Grand Mean	0.72	0.80	0.88	0.96	0.99	1.02	0.97	0.95	0.91	0.80	0.86	0.81	0.90	0.74	0.07
LSD	0.07	0.03	0.03	0.05	0.14	0.19	0.19								
CV (%)	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
<i>P</i> -value	0.92	0.04 *	0.27	0.84	0.70	0.336	0.63	0.99	0.20	0.95	0.522	0.21	0.28	0.17	0.882

Significance codes: 0 ‘****’ 0.001 ‘***’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Means followed by the same letter in a column are not significantly different at $\alpha=0.05$

Table 4. 6. Effect of Water on groundnut Crop coefficient (Kc) for each dekad of the growth period

Month	April	April	May	May	May	June	June	June	July	July	July	Aug	Aug	Aug	Sept
Dekad	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1
40 %	0.72 ^a	0.79 ^a	0.88 ^a	0.85 ^c	0.68 ^c	0.66 ^c	0.62 ^c	0.61 ^c	0.56 ^c	0.57 ^c	0.60 ^a	0.51 ^c	0.43 ^c	0.45 ^c	0.00 ^b
70 %	0.70 ^a	0.79 ^a	0.88 ^a	0.97 ^b	1.04 ^b	1.07 ^b	1.07 ^b	1.00 ^b	0.98 ^b	0.87 ^b	0.94 ^b	0.89 ^b	0.76 ^b	0.77 ^b	0.07 ^{ab}
100 %	0.75 ^a	0.81 ^a	0.87 ^a	1.06 ^a	1.25 ^a	1.34 ^a	1.21 ^a	1.24 ^a	1.19 ^a	0.98 ^a	1.06 ^c	1.07 ^a	0.91 ^a	1.01 ^a	0.13 ^a
Grand Mean	0.72	0.80	0.88	0.96	0.99	1.02	0.97	0.95	0.91	0.81	0.87	0.82	0.70	0.74	0.07
LSD	0.06	0.03	0.03	0.02	0.03	0.09	0.10								
CV (%)	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
<i>P</i> -value	0.33	0.25	0.68	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.01 **

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Means followed by the same letter in a column are not significantly different at $\alpha=0.05$

CHAPTER 5: CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

The study has shown that applying biochar to the soil significantly increased the pH of the strongly acidic soil to neutral. Applying biochar to the soil significantly increased the CEC of the soil. Applying biochar to the soil at rates of 1 % and 2 % w/w BC significantly increased leaf chlorophyll concentration (at V3, R1 and R3 growth stages) and DM yield while biochar applied at the highest rate (4 %) did not. Based on the results, biochar application at 1.42 % gave the best response for groundnut production. Applying biochar to the soil had no significant effect on the ET_c while the highest rate (4 %) negatively affected crop WUE. Gypsum applied at 200 kg/ha did not have a significant influence on the chlorophyll concentration, dry biomass yield, ET_c and crop WUE. There was no significant effect of the combination of applying gypsum and biochar on the chlorophyll concentration, dry biomass yield, ET_c and crop WUE under water stress conditions.

5.2 Recommendations

Further studies, under water stress in field conditions should be carried out to determine the effect of biochar on the groundnut productivity. However, it is strongly recommended that under field conditions application of biochar should be restricted to permanent planting stations as such as basins and rip lines.

Higher application rates of gypsum than those used in this study should be investigated to assess the effect on groundnut biomass and kernel yield under water stress conditions in the field.

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APPENDICES

Appendix A: Effect of Biochar application rates on pH

	Df	Sum Sq	Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.00	0.00	0.046		0.83
Biochar	1	55.30		55.30	672.482	<2e-16 ***
Residuals	93	7.65	0.08			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

1	2	3	4
5.003333	6.024583	6.380833	7.147500

Study: gnut2.aov ~ "Biochar"

LSD t Test for pH

Mean Square Error: 0.08223943

Biochar, means and individual (95 %) CI

	pH	std	r	LCL	UCL	Min	Max
1	5.003333	0.2178884	24	4.887089	5.119577	4.59	5.34
2	6.024583	0.2681819	24	5.908339	6.140827	5.47	6.44
3	6.380833	0.2947205	24	6.264589	6.497077	5.84	6.88
4	7.147500	0.2217960	24	7.031256	7.263744	6.70	7.74

alpha: 0.05; Df Error: 93

Critical Value of t: 1.985802

t-Student: 1.985802

Alpha : 0.05

Least Significant Difference 0.1643938

Means with the same letter are not significantly different

Groups, Treatments and means

a	4	7.1475
b	3	6.380833
c	2	6.024583
d	1	5.003333

Appendix B: Effect of Water application rate on CCI at V3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0	0.14	0.002	0.961
Water	1	56	56.25	0.985	0.324
Residuals	93	5310	57.10		

1 2 3

1 2 3

Study: gnut.aov ~ "Water"

LSD t Test for chloro1

Mean Square Error: 57.09928

Water, means and individual (95 %) CI

	chloro1	std	r	LCL	UCL	Min	Max
1	26.49063	6.433649	32	23.83800	29.14325	8.8	44.6
2	27.79688	9.620156	32	25.14425	30.44950	10.0	71.4
3	28.36563	6.104869	32	25.71300	31.01825	18.5	41.0

alpha: 0.05; Df Error: 93

Critical Value of t: 1.985802

t-Student: 1.985802

Alpha : 0.05

Least Significant Difference 3.751382

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	28.36563
a	2	27.79688
a	1	26.49063

Appendix C: Effect of Water application rate on CCI at R1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	40	40.48	0.882	0.350
Water	1	3	3.02	0.066	0.798
Residuals	93	4268	45.89		

1 2 3

1 2 3

Study: gnut.aov ~ "Water"

LSD t Test for chloro2

Mean Square Error: 45.89366

Water, means and individual (95 %) CI

	chloro2	std	r	LCL	UCL	Min	Max
1	28.58438	6.310928	32	26.20624	30.96251	17.2	39.7
2	29.09062	7.386097	32	26.71249	31.46876	16.4	44.1
3	28.15000	6.651655	32	25.77186	30.52814	17.0	40.1

alpha: 0.05; Df Error: 93

Critical Value of t: 1.985802

t-Student: 1.985802

Alpha : 0.05

Least Significant Difference 3.363197

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	29.09062
a	1	28.58438
a	3	28.15

Appendix D: Effect of Water application rate on CCI at R3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	210	209.6	2.641	0.108
Water	1	479	478.7	6.033	0.016 *
Residuals	89	7063	79.4		

Signif. codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

4 observations deleted due to missingness

1 2 3

1 2 3

Study: gnut.aov ~ "Water"

LSD t Test for chloro3

Mean Square Error: 79.35782

Water, means and individual (95 %) CI

	chloro3	std	r	LCL	UCL	Min	Max
1	30.71250	10.489619	32	27.58345	33.84155	7.0	50.6
2	28.05862	6.973343	29	24.77170	31.34554	10.4	47.1
3	25.21935	9.134966	31	22.04023	28.39848	9.5	47.4

alpha: 0.05; Df Error: 89

Critical Value of t: 1.986979

t-Student: 1.986979

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	1	30.7125
ab	2	28.05862
b	3	25.21935

Appendix E: Effect of Biochar application rate on CCI at V3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0	0.14	0.002	0.961
Biochar	1	1	0.89	0.015	0.901
Residuals	93	5366	57.69		

1 2 3 4

1 2 3 4

Study: gnut.aov ~ "Biochar"

LSD t Test for chloro1

Mean Square Error: 57.69452

Biochar, means and individual (95 %) CI

	chloro1	std	r	LCL	UCL	Min	Max
1	23.29583	4.784438	24	20.21692	26.37475	8.8	29.5
2	32.98750	9.345509	24	29.90859	36.06641	20.1	71.4
3	29.01250	7.098580	24	25.93359	32.09141	10.0	41.0
4	24.90833	3.669014	24	21.82942	27.98725	18.1	33.0

alpha: 0.05; Df Error: 93

Critical Value of t: 1.985802

t-Student: 1.985802

Alpha : 0.05

Least Significant Difference 4.354242

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	32.9875
ab	3	29.0125
bc	4	24.90833
c	1	23.29583

Appendix F: Effect of Biochar application rate on CCI at R1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	40	40.48	0.890	0.348
Biochar	1	39	39.10	0.859	0.356
Residuals	93	4232	45.51		

1 2 3 4

1 2 3 4

Study: gnut.aov ~ "Biochar"

LSD t Test for chloro2

Mean Square Error: 45.50567

Biochar, means and individual (95 %) CI

	chloro2	std	r	LCL	UCL	Min	Max
1	22.90000	3.150293	24	20.16559	25.63441	17.0	30.9
2	33.46667	5.274439	24	30.73226	36.20107	21.6	43.3
3	33.16250	5.816454	24	30.42809	35.89691	20.7	44.1
4	24.90417	4.614672	24	22.16976	27.63857	16.4	34.7

alpha: 0.05; Df Error: 93

Critical Value of t: 1.985802

t-Student: 1.985802

Alpha : 0.05

Least Significant Difference 3.867034

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	33.46667
a	3	33.1625
b	4	24.90417
b	1	22.9

Appendix G: Effect of Biochar application rate on CCI at R3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	210	209.59	2.507	0.117
Biochar	1	102	101.66	1.216	0.273
Residuals	89	7440	83.59		

4 observations deleted due to missingness

1 2 3 4

1 2 3 4

Study: gnut.aov ~ "Biochar"

LSD t Test for chloro3

Mean Square Error: 83.59467

Biochar, means and individual (95 %) CI

	chloro3	std	r	LCL	UCL	Min	Max
1	24.10000	4.791569	24	20.39168	27.80832	17.8	35.5
2	33.69583	6.036734	24	29.98752	37.40415	19.5	40.9
3	33.16087	9.471812	23	29.37279	36.94894	20.4	50.6
4	20.40476	8.495792	21	16.44040	24.36912	7.0	32.2

alpha: 0.05; Df Error: 89

Critical Value of t: 1.986979

t-Student: 1.986979

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	33.69583
a	3	33.16087
b	1	24.1
b	4	20.40476

Appendix H: Effect of Gypsum application rate on CCI at V3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0	0.14	0.002	0.961
Gypsum	1	87	87.21	1.536	0.218
Residuals	93	5279	56.77		

1 2

1 2

Appendix I: Effect of Gypsum application rate on CCI at R1

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0	0.14	0.002	0.961
Gypsum	1	87	87.21	1.536	0.218
Residuals	93	5279	56.77		

1 2

1 2

Appendix J: Effect of Gypsum application rate on CCI at R3

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	210	209.59	2.478	0.119
Gypsum	1	14	14.34	0.170	0.681
Residuals	89	7527	84.58		

4 observations deleted due to missingness

1 2

1 2

Appendix K: Effect of Water application rate on DM

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	13	12.7	0.238	0.627
Water	1	2173	2173.2	40.736	7.41e-09 ***
Residuals	90	4801	53.3		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1 2 3

1 2 3

Study: gnut.aov ~ "Water"

LSD t Test for biomass

Mean Square Error: 53.34718

Water, means and individual (95 %) CI

	biomass	std	r	LCL	UCL	Min	Max
1	7.312812	2.119877	32	4.747694	9.877931	2.66	10.44
2	15.054667	5.337144	30	12.405423	17.703910	0.92	24.87
3	19.035484	11.223148	31	16.429321	21.641647	3.63	40.22

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	19.03548
b	2	15.05467
c	1	7.312812

Appendix L: Effect of Biochar application rate on DM

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	13	12.7	0.175	0.6764
Biochar	1	445	445.0	6.134	0.0151 *
Residuals	90	6529	72.5		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1 2 3 4

1 2 3 4

Study: gnut.aov ~ "Biochar"

LSD t Test for biomass

Mean Square Error: 72.54919

Biochar, means and individual (95 %) CI

	biomass	std	r	LCL	UCL	Min	Max
1	13.737500	4.733988	24	10.283380	17.19162	7.31	22.46
2	17.548333	10.244625	24	14.094214	21.00245	6.44	40.22
3	15.506087	9.295105	23	11.977677	19.03450	4.69	37.76
4	7.647727	6.621369	22	4.040017	11.25544	0.92	27.23

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	17.54833
a	3	15.50609
a	1	13.7375
b	4	7.647727

Appendix M: Effect of Gypsum on DM

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	13	12.72	0.165	0.686
Gypsum	1	31	30.94	0.401	0.528
Residuals	90	6943	77.15		

3 observations deleted due to missingness

1 2

1 2

Appendix N: Effect of Gypsum application rates on dS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	4	4.02	0.096	0.757
Gypsum	1	9	9.42	0.226	0.636
Residuals	90	3759	41.77		

3 observations deleted due to missingness

1	2
-6.170652	-6.792766

Appendix O: Effect of Biochar on dS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	4	4.02	0.096	0.757
Biochar	1	1	0.72	0.017	0.896
Residuals	90	3768	41.87		

3 observations deleted due to missingness

1	2	3	4
-6.422917	-7.411250	-5.140435	-6.948182

Appendix P: Effect of Water application on dS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	4	4.02	0.097	0.756
Water	1	30	30.50	0.734	0.394
Residuals	90	3738	41.54		

3 observations deleted due to missingness

1	2	3
-7.270625	-6.267000	-5.885161

EFFECT OF TREATMENT INTERACTIONS ON dS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	4	4.02	0.095	0.7583
Gypsum	1	9	9.42	0.223	0.6377
Biochar	1	1	0.75	0.018	0.8943
Water	1	31	31.02	0.736	0.3935
Gypsum:Biochar	1	9	9.33	0.221	0.6393
Gypsum:Water	1	10	10.04	0.238	0.6269
Biochar:Water	1	156	155.57	3.689	0.0582
Gypsum:Biochar:Water	1	11	10.73	0.254	0.6153
Residuals	84	3542	42.17		

Signif. codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

Appendix Q: Effect of Gypsum on D

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	8	8	0.002	0.961
Gypsum	1	1868	1868	0.544	0.463
Residuals	90	309147	3435		

3 observations deleted due to missingness

1 2
38.92870 29.98894

Appendix R: Effect of Biochar on D

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	8	8	0.002	0.9606
Biochar	1	11001	11001	3.300	0.0726
Residuals	90	300014	3333		

Signif. codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3	4
28.60083	26.37250	20.44783	64.11545

Study: gnut2.aov ~ "Biochar"

LSD t Test for D

Mean Square Error: 3333.494

Biochar, means and individual (95 %) CI

	D	std	r	LCL	UCL	Min	Max
1	28.60083	46.70210	24	5.187084	52.01458	0	125.50
2	26.37250	51.80073	24	2.958751	49.78625	0	181.56
3	20.44783	40.57088	23	-3.469502	44.36515	0	150.62
4	64.11545	80.67387	22	39.660591	88.57032	0	214.31

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	4	64.11545
b	1	28.60083
b	2	26.3725
b	3	20.44783

Appendix S: Effect of Water application on D

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	8	8	0.003	0.956
Water	1	73195	73195	27.699	9.54e-07 ***
Residuals	90	237821	2642		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
10.95094	12.89067	79.45323

Study: gnut3.aov ~ "Water"

LSD t Test for D

Mean Square Error: 2642.457

Water, means and individual (95 %) CI

	D	std	r	LCL	UCL	Min	Max
1	10.95094	41.27410	32	-7.102326	29.00420	0.00	181.56
2	12.89067	25.45766	30	-5.754664	31.53600	0.00	114.58
3	79.45323	69.52714	31	61.111092	97.79536	0.04	214.31

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	79.45323
b	2	12.89067
b	1	10.95094

EFFECT OF TREATMENT INTERACTIONS ON DRAINAGE

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0	0	0.000	1.0000
Gypsum	1	939	939	0.188	0.6655
Biochar	1	3013	3013	0.604	0.4392
Water	1	991877	991877	98.791	<2e-16 ***
Gypsum:Biochar	1	15268	15268	3.060	0.0838
Gypsum:Water	1	354	354	0.071	0.7906
Biochar:Water	1	70	70	0.014	0.9060
Gypsum:Biochar:Water	1	637	637	0.128	0.7216
Residuals	87	434090	4990		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Appendix T: Effect of Gypsum on ETc

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	143	143	0.015	0.904
Gypsum	1	971	971	0.099	0.753
Residuals	90	880406	9782		

3 observations deleted due to missingness

1	2
423.1113	429.4853

Appendix U: Effect of Biochar on ETc

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	143	143	0.015	0.904
Biochar	1	3281	3281	0.336	0.563
Residuals	90	878095	9757		

3 observations deleted due to missingness

1	2	3	4
408.6442	461.9704	434.0383	398.6955

Study: gnut2.aov ~ "Biochar"

LSD t Test for ETc

Mean Square Error: 9756.616

Biochar, means and individual (95 %) CI

	ETc	std	r	LCL	UCL	Min	Max
1	408.6442	85.51262	24	368.5879	448.7005	304.56	544.83
2	461.9704	112.70823	24	421.9141	502.0267	299.50	613.39
3	434.0383	105.79323	23	393.1204	474.9561	294.85	609.88
4	398.6955	75.20537	22	356.8580	440.5329	315.15	557.54

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	461.9704
ab	3	434.0383
ab	1	408.6442
b	4	398.6955

Appendix V: Effect of Water application rate on ETc

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	143	143	0.034	0.854
Water	1	502236	502236	119.220	<2e-16 ***
Residuals	90	379141	4213		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
329.9822	444.3800	508.3258

Study: gnut3.aov ~ "Water"

LSD t Test for ETc

Mean Square Error: 4212.676

Water, means and individual (95 %) CI

	ETc	std	r	LCL	UCL	Min	Max
1	329.9822	59.77712	32	307.1876	352.7767	294.85	610.92
2	444.3800	36.75760	30	420.8379	467.9221	317.81	468.62
3	508.3258	84.91458	31	485.1665	531.4851	317.88	613.39

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	508.3258
b	2	444.38
c	1	329.9822

EFFECT OF TREATMENT INTERACTIONS ON ETc

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	143	143	0.033	0.856
Gypsum	1	971	971	0.226	0.635
Biochar	1	3300	3300	0.770	0.383
Water	1	501234	501234	116.960	<2e-16 ***
Gypsum:Biochar	1	8551	8551	1.995	0.161
Gypsum:Water	1	924	924	0.216	0.644
Biochar:Water	1	5402	5402	1.261	0.265
Gypsum:Biochar:Water	1	1013	1013	0.236	0.628
Residuals	84	359982	4286		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

Appendix W: Effect of Gypsum on ETc/Eo ratio

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000	0.00000	0.000	0.995
Gypsum	1	0.006	0.00572	0.115	0.735
Residuals	90	4.472	0.04969		

3 observations deleted due to missingness

1 2

0.8636957 0.8793617

Appendix X: Effect of Biochar on ETc/Eo ratio

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000	0.00000	0.000	0.995
Biochar	1	0.011	0.01108	0.223	0.638
Residuals	90	4.466	0.04963		

3 observations deleted due to missingness

1	2	3	4
0.8366667	0.9408333	0.8856522	0.8195455

EFFECT OF TREATMENT INTERACTIONS ON ETc/Eo RATIO

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0000	0.0000	0.000	0.994
Gypsum	1	0.0057	0.0057	0.216	0.643
Biochar	1	0.0112	0.0112	0.422	0.518
Water	1	2.1880	2.1880	82.774	3.77e-14 ***
Gypsum:Biochar	1	0.0269	0.0269	1.019	0.316
Gypsum:Water	1	0.0020	0.0020	0.077	0.782
Biochar:Water	1	0.0205	0.0205	0.775	0.381
Gypsum:Biochar:Water	1	0.0027	0.0027	0.104	0.748
Residuals	84	2.2204	0.0264		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

Appendix Y: Effect of Water application rates on ETc/Eo ratio

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000	0.0000	0.00	0.993
Water	1	2.192	2.1925	86.36	8.45e-15 ***
Residuals	90	2.285	0.0254		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
0.6690625	0.9120000	1.0416129

Study: gnut3.aov ~ "Water"

LSD t Test for ETc.Eo

Mean Square Error: 0.02538843

Water, means and individual (95 %) CI

	ETc.Eo	std	r	LCL	UCL	Min	Max
1	0.6690625	0.1056580	32	0.6131035	0.7250215	0.56	1.12
2	0.9120000	0.1132102	30	0.8542058	0.9697942	0.58	1.08
3	1.0416129	0.2237573	31	0.9847585	1.0984673	0.58	1.41

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	1.041613
b	2	0.912
c	1	0.6690625

Appendix Z: Effect of Gypsum on ETc/ETo ratio

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0005	0.00050	0.015	0.904
Gypsum	1	0.0035	0.00349	0.102	0.750
Residuals	90	3.0772	0.03419		

3 observations deleted due to missingness

1	2	
0.7917391	0.8038298	

Appendix AA: Effect of Biochar application rates on ETc/ETo ratio

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0005	0.00050	0.015	0.903
Biochar	1	0.0109	0.01086	0.318	0.574
Residuals	90	3.0698	0.03411		

3 observations deleted due to missingness

1	2	3	4
0.7641667	0.8650000	0.8117391	0.7468182

Study: gnut2.aov ~ "Biochar"

LSD t Test for ETc.Eto

Mean Square Error: 0.03410896

Biochar, means and individual (95 %) CI

	ETc/Eto	std	r	LCL	UCL	Min	Max
1	0.7641667	0.1603235	24	0.6892712	0.8390621	0.57	1.02
2	0.8650000	0.2115574	24	0.7901046	0.9398954	0.56	1.15
3	0.8117391	0.1966920	23	0.7352329	0.8882454	0.55	1.14
4	0.7468182	0.1401151	22	0.6685925	0.8250439	0.59	1.04

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	0.865
ab	3	0.8117391
ab	1	0.7641667
b	4	0.7468182

Appendix BB: Effects of Water application rates on ETc/ETo ratios

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0005	0.0005	0.034	0.854
Water ***	1	1.7526	1.7526	118.774	<2e-16
Residuals	90	1.3280	0.0148		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
0.6178125	0.8316667	0.9509677

Study: gnut3.aov ~ "Water"

LSD t Test for ETc.Eto

Mean Square Error: 0.014756

Water, means and individual (95 %) CI

	ETc.Eto	std	r	LCL	UCL	Min	Max
1	0.6178125	0.11137656	32	0.5751510	0.6604740	0.55	1.14
2	0.8316667	0.06948497	30	0.7876061	0.8757273	0.59	0.88
3	0.9509677	0.15898333	31	0.9076236	0.9943119	0.60	1.15

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	0.9509677
b	2	0.8316667
c	1	0.6178125

EFFECT OF TREATMET INTERACTIONS ON ET_c/ET_o RATIO

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0005	0.0005	0.034	0.855
Gypsum	1	0.0035	0.0035	0.233	0.631
Biochar	1	0.0109	0.0109	0.729	0.396
Water	1	1.7491	1.7491	116.676	<2e-16 ***
Gypsum:Biochar	1	0.0317	0.0317	2.114	0.150
Gypsum:Water	1	0.0033	0.0033	0.220	0.640
Biochar:Water	1	0.0189	0.0189	1.262	0.264
Gypsum:Biochar:Water	1	0.0039	0.0039	0.260	0.611
Residuals	84	1.2593	0.0150		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

Appendix CC: Effect of Gypsum on WUE_s

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000003	2.990e-06	0.021	0.885
Gypsum	1	0.000032	3.196e-05	0.224	0.637
Residuals	90	0.012853	1.428e-04		

3 observations deleted due to missingness

1 2
0.02375652 0.02494043

Appendix DD: Effect of Gypsum on WUE_R

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0000045	4.471e-06	0.746	0.390
Gypsum	1	0.0000039	3.851e-06	0.642	0.425
Residuals	90	0.0005397	5.997e-06		

3 observations deleted due to missingness

1 2
0.005884783 0.006306383

Appendix EE: Effect of Gypsum on WUE_T

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000015	1.514e-05	0.078	0.781
Gypsum	1	0.000056	5.640e-05	0.290	0.591
Residuals	90	0.017476	1.942e-04		

3 observations deleted due to missingness

1 2
0.02965000 0.03123404

Appendix FF: Effect of Biochar on WUE_s

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000003	0.0000030	0.024	0.87725
Biochar	1	0.001651	0.0016507	13.224	0.00046 ***
Residuals	90	0.011234	0.0001248		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1 2 3 4
0.02633750 0.02920833 0.02697391 0.01415909

Study: gnut2.aov ~ "Biochar"

LSD t Test for WUE.shoot

Mean Square Error: 0.00012482

Biochar, means and individual (95 %) CI

	WUE.shoot	std	r	LCL	UCL	Min	Max
1	0.02633750	0.007734216	24	0.021806822	0.03086818	0.0142	0.0431
2	0.02920833	0.011961639	24	0.024677655	0.03373901	0.0083	0.0556
3	0.02697391	0.011369505	23	0.022345790	0.03160204	0.0101	0.0521
4	0.01415909	0.010402640	22	0.009426952	0.01889123	0.0016	0.0418

alpha: 0.05; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	0.02920833
a	3	0.02697391
a	1	0.0263375
b	4	0.01415909

Appendix GG: Effect of Biochar on WUE_R

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0000045	4.470e-06	0.917	0.341
Biochar	1	0.0001046	1.046e-04	21.456	1.22e-05 ***
Residuals	90	0.0004389	4.880e-06		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3	4
0.006933333	0.006941667	0.006495652	0.003850000

Study: gnut2.aov ~ "Biochar"

LSD t Test for WUE.root

Mean Square Error: 4.876972e-06

Biochar, means and individual (95 %) CI

	WUE.root	std	r	LCL	UCL	Min	Max
1	0.006933333	0.001859328	24	0.006037770	0.007828897	0.0020	0.0093
2	0.006941667	0.002346305	24	0.006046103	0.007837230	0.0022	0.0115
3	0.006495652	0.002200512	23	0.005580827	0.007410477	0.0025	0.0108
4	0.003850000	0.002032299	22	0.002914615	0.004785385	0.0007	0.0077

alpha: 0.05 ; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	0.006941667
a	1	0.006933333
a	3	0.006495652
b	4	0.00385

Appendix HH: Effect of Biochar on WUE_T

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000015	0.0000151	0.091	0.76342
Biochar	1	0.002581	0.0025809	15.536	0.00016 ***
Residuals	90	0.014952	0.0001661		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

	1	2	3	4
	0.03326250	0.03613750	0.03348261	0.01800909

Study: gnut2.aov ~ "Biochar"

LSD t Test for WUE.biomass

Mean Square Error: 0.000166129

Biochar, means and individual (95 %) CI

	WUE.biomass	std	r	LCL	UCL	Min	Max
1	0.03326250	0.008197073	24	0.02803560	0.03848940	0.0162	0.0519
2	0.03613750	0.013884894	24	0.03091060	0.04136440	0.0105	0.0657
3	0.03348261	0.013171790	23	0.02814329	0.03882192	0.0134	0.0629
4	0.01800909	0.012283086	22	0.01254978	0.02346840	0.0022	0.0488

alpha: 0.05 ; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	2	0.0361375
a	3	0.03348261
a	1	0.0332625
b	4	0.01800909

Appendix II: Effect of Water application rates on WUE_s

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000003	0.0000030	0.026	0.872
Water	1	0.002491	0.0024914	21.574	1.16e-05 ***
Residuals	90	0.010393	0.0001155		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
0.01682812	0.02721000	0.02936129

Study: gnut3.aov ~ "Water"

LSD t Test for WUE.shoot

Mean Square Error: 0.000115479

Water, means and individual (95 %) CI

	WUE.shoot	std	r	LCL	UCL	Min	Max
1	0.01682812	0.005572353	32	0.01305411	0.02060214	0.0055	0.0249
2	0.02721000	0.009325987	30	0.02331222	0.03110778	0.0016	0.0435
3	0.02936129	0.014796659	31	0.02552689	0.03319569	0.0066	0.0556

alpha: 0.05 ; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	0.02936129
a	2	0.02721
b	1	0.01682812

Appendix JJ: Effect of Water application rates on WUE_R

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0000045	4.471e-06	0.741	0.392
Water	1	0.0000004	3.500e-07	0.058	0.810
Residuals	90	0.0005432	6.036e-06		

3 observations deleted due to missingness

1	2	3
0.005881250	0.006406667	0.006022581

Appendix KK: Effect of Gypsum on WUE_T

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000015	0.0000151	0.091	0.763597
Water	1	0.002557	0.0025572	15.368	0.000172 ***
Residuals	90	0.014975	0.0001664		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

1	2	3
0.02270000	0.03361333	0.03539032

Study: gnut3.aov ~ "Water"

LSD t Test for WUE.biomass

Mean Square Error: 0.0001663926

Water, means and individual (95 %) CI

	WUE.biomass	std	r	LCL	UCL	Min	Max
1	0.02270000	0.007333705	32	0.01816979	0.02723021	0.0084	0.0331
2	0.03361333	0.011572790	30	0.02893455	0.03829212	0.0022	0.0534
3	0.03539032	0.017337442	31	0.03078762	0.03999303	0.0085	0.0657

alpha: 0.05 ; Df Error: 90

Critical Value of t: 1.986675

t-Student: 1.986675

Alpha : 0.05

Minimum difference changes for each comparison

Means with the same letter are not significantly different

Groups, Treatments and means

a	3	0.03539032
a	2	0.03361333
b	1	0.0227

EFFECT OF TREATMET INTERACTIONS ON WUE_s

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000003	0.0000030	0.030	0.863721
Gypsum	1	0.000032	0.0000320	0.316	0.575339
Biochar	1	0.001653	0.0016531	16.363	0.000116 ***
Water	1	0.002458	0.0024585	24.334	4.04e-06 ***
Gypsum:Biochar	1	0.000000	0.0000003	0.003	0.960216
Gypsum:Water	1	0.000005	0.0000050	0.049	0.824497
Biochar:Water	1	0.000143	0.0001431	1.416	0.237342
Gypsum:Biochar:Water	1	0.000106	0.0001061	1.050	0.308416
Residuals	84	0.008486	0.0001010		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

EFFECT OF TREATMET INTERACTIONS ON WUE_R

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.0000045	4.470e-06	0.888	0.349
Gypsum	1	0.0000039	3.850e-06	0.765	0.384
Biochar	1	0.0001049	1.049e-04	20.827	1.7e-05 ***
Water	1	0.0000003	2.500e-07	0.050	0.824
Gypsum:Biochar	1	0.0000005	4.700e-07	0.094	0.760
Gypsum:Water	1	0.0000000	0.000e+00	0.000	1.000
Biochar:Water	1	0.0000106	1.062e-05	2.109	0.150
Gypsum:Biochar:Water	1	0.0000006	6.200e-07	0.122	0.727
Residuals	84	0.0004229	5.030e-06		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

EFFECT OF TREATMET INTERACTIONS ON WUE_T

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.000015	0.0000151	0.105	0.747
Gypsum	1	0.000056	0.0000564	0.389	0.534
Biochar	1	0.002585	0.0025850	17.840	6.06e-05 ***
Water	1	0.002515	0.0025148	17.356	7.48e-05 ***
Gypsum:Biochar	1	0.000001	0.0000012	0.008	0.927
Gypsum:Water	1	0.000005	0.0000052	0.036	0.851
Biochar:Water	1	0.000076	0.0000758	0.523	0.471
Gypsum:Biochar:Water	1	0.000122	0.0001225	0.845	0.361
Residuals	84	0.012172	0.0001449		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness