

**BIOCHAR IMPACT ON THE WATER RELATIONS OF NERICA RICE GROWN  
ON A COMPACTED RHODIC KANDIUSTALF**

**BY**

**ADEBOLA ESTHER ADESOYIN (10803022)**

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**INTEGRI PROCEDAMUS**

SEPTEMBER 2021

**DECLARATION**

I hereby declare that, except for references to other researchers' works, which have been duly cited and acknowledged, this work is the result of my research carried out and has not been presented elsewhere either in part or in whole for another degree.



24/09/2021

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Adebola Esther Adesoyin  
(Student ID: 10803022)

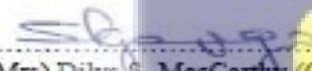
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24/09/2021

.....  
Professor (Dr) Samuel G. K. Adiku (Principal Supervisor)

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Date



24/09/2021

.....  
Dr (Mrs) Dilys S. MacCarthy (Co-Supervisor)

.....  
Date



**DEDICATION**

I dedicate this work from the beginning to the end unto God Almighty. To Him be all the Glory, Hallelujah! I also dedicate the Thesis to my parents: Mr and Mrs Adebuseyi Adesoyin for their prayers and great encouragement throughout the program.



## ACKNOWLEDGEMENT

From the beginning of this work to its end, I give all the glory unto God who strengthened me all through. All the praise be unto Him.

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## ABSTRACT

Soil compaction has become a major challenge in tropical agriculture due to the increasing use of heavy agricultural machinery for tillage. Soil compaction sets in a spiral of soil degradation processes through reduced infiltration increased runoff and soil erosion. Ultimately, soil and crop productivity are impaired. Several remedial measures have been proposed to minimize soil compaction-induced degradation. Among these is biochar application to soils. Though the impact of biochar on enhancing soil physical properties is increasingly reported in the literature, data in Ghana continue to be scant and research also continues to lag on this front. The focus of this was three-fold. First, the impact of biochar application on compacted soils with regard to their physical and hydraulic properties such as the bulk density, moisture characteristic, runoff and infiltration, was investigated using laboratory studies. Second, the growth, yield and water use efficiency of upland rice (*Nerica 14*) under a range of biochar-amended compacted soils were studied under greenhouse conditions. For laboratory and greenhouse studies, the soil used was Toje series (Rhodic Kandistalf). In a final study, two (2) biochar-modified runoff models were assessed for their suitability in predicting runoff from biochar-amended compacted Toje series.

The laboratory study was a Completely Randomized Design (CRD) in factorial arrangement with three (3) compaction levels (Field D1= 1.3 Mg/m<sup>3</sup>; medium D2 = 1.5 Mg/m<sup>3</sup> and high bulk density D3 = 1.7 Mg/m<sup>3</sup>), rice husk biochar at 3 rates (B0, B10 and B20 corresponding to 0, 10 and 20 ton/ha, respectively) was used. The treatment units which were in PVC pipes of 20 cm height and 16 cm diameter were irrigated from a rainfall simulator. Data were collected on the infiltration and saturated hydraulic conductivity. The variation of bulk density with biochar application was also determined.

The soil moisture characteristic (SMC) was determined on samples of the various treatments using the Haines equipment and the dominant soil pore size was derived from the SMC.

In the case of the greenhouse study, a similar experimental arrangement was used but with the PVC column heights of 40 cm. In addition, *NERICA* rice was planted and intermittently irrigated until maturity. There were 3 levels of irrigation (low: seasonal irrigation = 338.5 mm; medium = 419 mm and high = 569.5 mm).

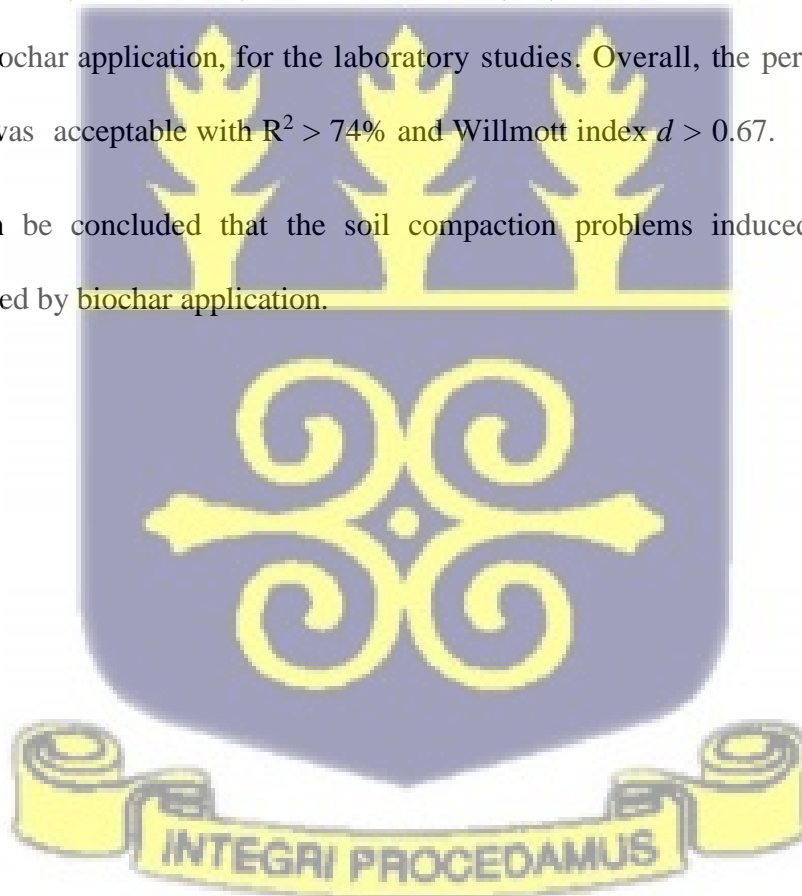
Both biochar application rate and bulk density and their interactions showed significant effects on the pore size and saturated hydraulic conductivity ( $K_{sat}$ ). The dominant pore size increased from 0.0075 cm for the very high compacted soil (D3) at 0 ton/ha biochar application to 0.015 cm for low compacted soil (D1) at 20 ton/ha biochar application. Similarly, the  $K_{sat}$  was lowest (0.78 cm/h) for D3 with no biochar application and highest for D1 with 20 ton/ha biochar application. The increased pore size for the low density and high biochar application may explain the high  $K_{sat}$  values since according to Poiseuille's Law, the water flow rate is proportional to the 4<sup>th</sup> power of the pore radius. It was observed that biochar application significantly reduced the bulk density. Soil compaction also significantly impacted infiltration parameters. Data analysis based on Horton's (1948) infiltration model showed that the highest value for the initial infiltration rate,  $i_0 = (134.7 \text{ cm/s})$  was observed for D1 with 20 ton/ha biochar application rate and least (7.7 cm/s) for D3 at 0 ton/ha biochar application rate. With respect to Philip's (1957) infiltration equation, the sorptivity,  $S$ , was highest (12.1 cm/min<sup>0.5</sup>) for D1 at 20 ton/ha biochar and least for D3 (2.06 cm/min<sup>0.5</sup>) at 0 ton/ha biochar. The biochar-induced parameters used to predict the runoff using the modified Horton and Philip's equations predicted the laboratory determined infiltration into compacted soils ( $R^2 = 0.75$ ).

The greenhouse results showed that biochar application reduced the bulk density, offsetting the soil compaction effect on plant growth as well as the runoff, drainage and evapotranspiration components of the water balance. The actual seasonal evapotranspiration ( $ET_a$ ) was reduced with increasing soil bulk density for each water regime. The highest yield was recorded for the treatment

combination of the high-water regime, 10 ton/ha biochar application and bulk density, D1. In general, the grain yield response to soil compaction was in the  $D1 > D2 > D3$ . The Water Use Efficiency (WUE) decreased with increasing density levels except for D2. Biochar had only a small significant effect on the WUE of the compacted soils. The input of the biochar and soil compaction modified  $ETa$  in the Doorembos and Kassam (1979) yield production function showed that rice yields under varying soil compaction and biochar application could be satisfactorily predicted ( $R^2 = 0.67$ ; Willmott  $d$ -index (0.89).

Runoff was well predicted using the models of Ive *et al.* (1976) and the USDA Natural Resource Conservation Service (NRCS, 1972) Curve Number (CN) that were modified to respond to soil compaction and biochar application, for the laboratory studies. Overall, the performance of the two modified models was acceptable with  $R^2 > 74\%$  and Willmott index  $d > 0.67$ .

In general, it can be concluded that the soil compaction problems induced by tillage can be effectively addressed by biochar application.



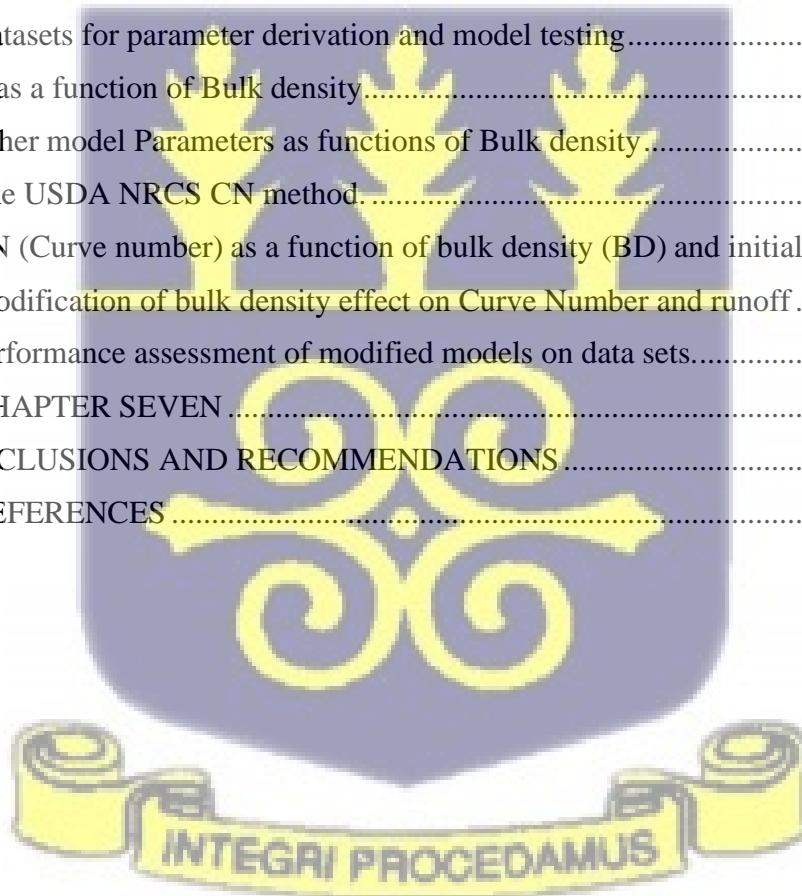
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## CHAPTER ONE

### 1 INTRODUCTION

#### 1.1 Background

Agriculture is the dominant industry in most developing countries of the world, especially West African countries. As part of the efforts to achieve food security, many governments are eagerly following the modernization of agriculture because it is a better alternative approach to other traditional methods (such as manual cultivation). In our society today, the term “modernized agriculture’ has been used synonymously with mechanization, which refers to the use of tractors, heavy agriculture machinery, and fertilizer application to achieve intensification of crop production. Studies in Ghana have shown that mechanization rates have increased significantly among farmers (Diao *et al.*, 2018) and the use of secondhand tractor has gained widespread adoption (Houssou *et al.*, 2013). Though mechanization may enhance labour productivity, it is also often associated with soil degradation. Mechanization or the use of tractors or other heavy agricultural machinery may not be suitable for all types of soils. For instance, for poorly structured soils, the continuous use of heavy machinery would lead to soil compaction.

It is also observed that the frequency of high rainstorms has increased in many countries worldwide, apparently due to climate change which is associated with an increased frequency of extreme rainfall events. Adiku (2019) observed shifts in rainfall patterns favouring high intensities at several locations in northern Ghana. A combination of high rainstorms and soil compaction would result in increased runoff and erosion with associated nutrient losses. Fertilizer loss results in economic loss and environmental degradation. Excess nutrient losses from the soil into water

bodies can result in eutrophication and methemoglobinemia owing to a high influx of nitrates leading to the death of aquatic organisms and blue-baby disease, respectively.

Soil compaction is becoming a severe agricultural problem in poorly structured soils. It is often seen as the most challenging type of soil degradation in arable lands because it is an insidious process (McGarry, 2003). Soil compaction causes the rearrangement of soil particles and reduction in macroporosity and total pore space by stresses which can be caused by both internal (increasing pore water suction during drainage and drying) and external (machinery) forces. The leading cause of subsoil compaction in agricultural soils is the use of heavy-duty machinery, especially heavy air carts, harvesters and chaser bins. Other stresses may come from tillage, stock trampling and overburden pressure. Compact soils restrict crop, pasture production, and increase nutrient leaching and the emission of greenhouse gasses.

The degradation effects of soil compaction induced on several millions of hectares of cultivated land have also been reported on a global scale (Oldeman *et al.*, 1991). The adverse effects of soil compaction on soil quality and crop production are manifold. They include reduction in soil pore spaces, reduction in water infiltration rate into the soil, decrease in the rate of water penetration into the soil root zone and the subsoil, increase in the potential of surface water ponding, water runoff, and soil erosion. The reduction in air and water holding capacity of the soil, crushing of soil aggregates, reduction in crop emergence due to soil crusting, restriction of root growth, limiting the soil volume explored by roots and root penetration into the subsoil, and the restriction of root exploration which decreases nutrients uptake are other manifestations of soil compaction effect. These factors will eventually result in increased stress to the crop, reduce crop yield (Radford *et al.*, 2000; Hamza and Anderson, 2005; Mckenzie, 2016) and reduced crop yield.

## 1.2 Problem statement and justification

As soil compaction reduces soil productivity due to its resultant effects of high bulk density and decreased porosity. Several amendments have been proposed by researchers to offset the effect of high soil bulk density. In recent times, the application of biochar has been reported to significantly improve soil physical and hydraulic properties, due to its large surface area and presence of internal micropores, which aid increase the overall soil porosity (Nguyen *et al.*, 2004; Mukherjee *et al.*, 2011). Thus, researchers have identified the use of biochar as a good soil amendment material (Mukherjee and Lai, 2013, Xie *et al.*, 2015).

The biochar technology has proven to be effective in enhancing soil and crop productivity but still has low adoption rates among farmers in the tropics. It is worthy of note that even when successfully applied to soil, large quantities of biochar can be lost in runoff and erosion under heavy rainstorms when field soil cover is low. However, after stabilization, biochar application may eventually reduce runoff and erosion (Khademalrasoul *et al.*, 2019).

Many studies have been conducted on use of biochar in amending soil physiochemical properties and crop productivity (Castellini *et al.*, 2015; Ajayi *et al.*, 2016; Obia *et al.*, 2016). Qi Liu *et al.* (2016) indicated that compaction stress on a crop could be alleviated by biochar application. This has contributed immensely to the adsorptive properties of soil, hence, altering its bulk density, pore size distribution. However, information remains scanty on quantitative data on nutrient losses by leaching and runoff in tropical agriculture. Therefore, this study was designed to examine runoff and drainage in a biochar-amended compacted soil of Ghana.

### 1.3 Hypothesis

It is the hypothesis of this study that the application of biochar to alleviate compaction challenges in soils is due to several effects. Firstly, the increase in soil porosity due to biochar application would increase the time to runoff and erosion, giving sufficient time for infiltration. Secondly, the high-water absorption ratio of hydrophilic biochar would increase water retention in the soils and reduce the frequency of soil desiccation. Third, the reduction of runoff on biochar-amended compacted soils, even under high rainfall storms, would enhance crop growth better than non- biochar amended soils. Therefore, a better understanding of the impact of biochar application on soil physical and hydraulic properties would enhance the development of appropriate management practices that would reduce the rate of soil degradation. To date, data on these important factors continue to lack in Ghana as well as tropical literature.

Furthermore, since plant responses to compaction depend strongly on changes in the soil water regime (Gomez *et al.* 2002), quantitative data on soil water storage and nutrient losses by leaching and runoff is required for careful diagnosis of the problem. Controlled greenhouse and laboratory conditions experiments were designed for this study for which the research questions (RQ) were as follows:

RQ1: Will a soil conditioner (biochar) improve root and shoot growth and yield caused by compaction under all rainfall regimes?

RQ2: Will biochar technology be able to offset the effects of soil compaction on runoff and drainage losses of applied nutrients?

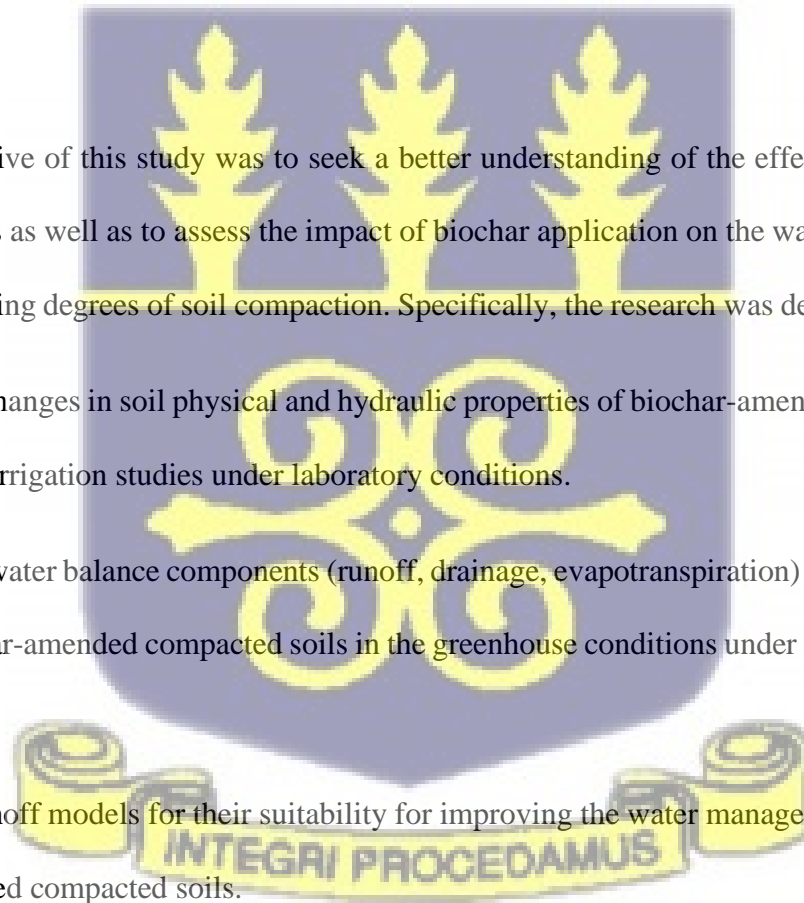
RQ3: Will the inclusion effects of biochar in soil hydrologic models enhance the simulation of the runoff component of the water balance equation, thereby assessing its impact on crop growth and yield on Toje series, a Rhodic Khandiustalf of Ghana?

It is also hypothesized that the slow pace of soil degradation research in many developing countries can be attributed to the high costs of field experimentation, especially when resources are also lacking. Field research is also often time-consuming and location-specific, there is a limitation to the extrapolation of results. In recent times, simulation models have been shown to be additional effective tools for analyzing the impact of a host of management practices on soil and crop productivity. In a recent study, (Adiku *et al.*, 2021) developed a model for assessing the impact of soil degradation on soil water and nutrient balance as well as maize yield. The model could be applied at various locations including Ghana, Zimbabwe and India. Thus, it is hypothesized that the use of modelling approaches would also support the assessment of biochar impact on soil degradation and crop yields.

#### 1.4 Objectives

The overall objective of this study was to seek a better understanding of the effect of biochar on soil physical properties as well as to assess the impact of biochar application on the water balance and rice growth under varying degrees of soil compaction. Specifically, the research was designed to:

- (i) determine the changes in soil physical and hydraulic properties of biochar-amended compacted soils during controlled irrigation studies under laboratory conditions.
- (ii) determine the water balance components (runoff, drainage, evapotranspiration) and rice growth and the yield on biochar-amended compacted soils in the greenhouse conditions under 3 irrigation regimes, and
- (iii) assess two runoff models for their suitability for improving the water management of crops grown on biochar-amended compacted soils.



## CHAPTER TWO

### 2 LITERATURE REVIEW

#### 2.1 Rice production in Ghana

Rice (*Oryza sativa*) is a major staple food in West Africa and demand has doubled in recent years due to the high population growth rate in the region (Seck *et al.*, 2010). As the staple food of more than half of the world's population, its high production variability has many concerns for global food security, especially, in sub-Saharan Africa (SSA) where there is a fast-growing disparity between domestic production and consumption (Seck *et al.*, 2010). This situation has caused large importation of rice by many governments in the region.

In Ghana, there is low dependence of locally produced rice by consumers as they depend largely on imported rice (Abel *et al.*, 2014), which accounts for 50-70% of domestic consumption. However, in recent years, branded local rice varieties have seen an improvement in quality (Ayeduvor *et al.*, 2008). Various quality traits exist in the traditional and modern varieties namely, drought tolerance, weed tolerance, good milling and higher yields, which are being promoted in northern Ghana (Ragasa *et al.*, 2013). Rice is produced under three main conditions: upland rainfed, lowland rainfed and irrigated ecologies (Seck *et al.*, 2010). In Ghana, the proportions of upland rainfed, lowland rainfed and irrigated rice produced domestically are given as 12.7%, 30.4%, and 57.0 %, respectively (Buri *et al.*, 2011)

A new variety/ offspring produced from the cross-breed of two species of *Oryza sativa* L. (Asian rice) and *Oryza glaberrima* Steud. (African rice) called NERICA (New Rice for Africa) which has high yielding potential and the ability to survive in a harsh environment was developed and adopted (Manneh, 2004). It is referred to as upland rice as it can thrive well in rain-fed upland ecosystems. In Ghana, the government executed a project in the year 2003 called the Nerica Rice Dissemination Project (NRDP)

to promote the production of locally produced rice, which has a higher yield, to achieve food security and also alleviate poverty (Abel *et al.*, 2014). However, there are different genotypes of this improved rice that are produced among which are NERICA 4, 5, 8, 10 and 14. Its ability to perform better than the other traditional varieties (Ndebeh *et al.*, 2018) in terms of drought tolerance, better fertilizer response and higher yields have been reported (Evenson & Gollin, 2003). It is thus the focus of this study to investigate the response of the upland NERICA to soil and climate factors such as soil water regimes and soil compaction.

## 2.2 Tillage practices and crop production

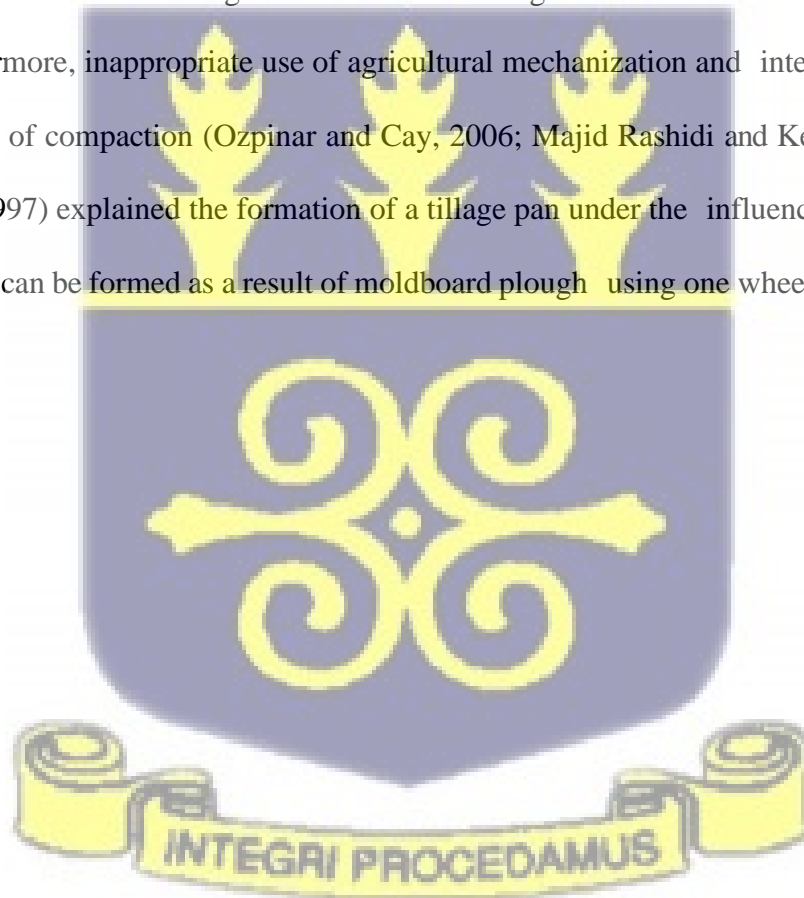
The history of land tillage is well documented in the literature (Derpsch, R. 1998). In the early century -10,000 years ago, planting has been done largely manually and weeds growing around crops were removed by hand using traditional implements such as cutlasses and hoes to till the land for cultivation. Such implements were appropriate for food production to meet low demands. With a population estimated to reach 2.5 billion out of 10 billion by 2050, production must increase drastically to offset the -equilibrium.

The several approaches pursued to increase food production include the increase in cultivated land area, including sometimes the cultivation of marginal lands and modernization of agriculture (intensification by increasing fertilizer application + conventional tillage). Undoubtedly, the modernization of agriculture has increased both the land area cultivation and the productivity of the land.

Tillage is the mechanical manipulation of soil for planting and cultivation of crops, involving the breaking, digging and rearrangement of soil for sowing and can be divided into primary and secondary tillage. Tillage is used in controlling weeds, incorporating amendments. Mechanized form of farming uses heavy implements such as tractors, ploughs, and harvester for the function of tilling soil, but small-scale farmers may also use animals in tilling the soil. This mechanized form of agriculture has helped in

various ways; by increasing the production of crops for increasing population, boosting labour productivity, and reducing drudgery (Fonteh, 2010) compared to subsistence farming. Thus, when used adequately, mechanization can help to ameliorate and restore the problems encountered with soil (Lal, 1993; Rashidi and Keshavarzpour, 2008).

Yet, mechanization has also brought along a myriad of environmental challenges. Conventional tillage or ploughing increases mechanical stress reaching subsoil layers (McMaster *et al.*, 2013). Soil tillage affects different soil physical properties that ultimately influence plant growth and yield (Ozpinar and Cay, 2006; Majid Rashidi and Keshavarzpour, 2007; Rashidi and Keshavarzpour, 2008). Therefore, inappropriate use of mechanized tillage can accelerate the degradation and destruction of soil structure (Lal, 1993). Furthermore, inappropriate use of agricultural mechanization and intense tillage operations lead to the problem of compaction (Ozpinar and Cay, 2006; Majid Rashidi and Keshavarzpour, 2007). Seixas and Tim (1997) explained the formation of a tillage pan under the influence of tillage, and how subsoil compaction can be formed as a result of moldboard plough using one wheel in-furrow.





**Plate 2.1. Ruts created by a wheeled tractor during a rainy season that caused compaction preventing percolation of water (Cambi et al., 2015)**

## **2.3 Environmental effects on crop growth and yield**

### *2.3.1 Influence of soil compaction*

The issue of soil compaction is of great significance in upland rice production in Ghana, since, like any other intensified upland crop, modernization has increased the use of conventional tillage, where heavy machinery is increasingly used to till the land. Josiah *et al.* (2008) indicated that of the three main tillage practices employed in Ghana, namely conventional, conservation and minimum tillage, the adoption of conventional tillage increased by 7% within a space of three years. This suggests that the production of the NERICA rice is also increasingly produced on mechanically tilled lands and soils.

Soil compaction influences soil physical, biological and chemical properties, which in turn have a direct effect on the growth and yield of a wide range of crops (Kayombo and Lal, 1993; Ozpinar and Cay, 2006; Yusuf, 2006; Rashidi and Keshavarzpour, 2008). Soil compaction may reduce the soil oxygen content of the root zone (Ozpinar and Isik, 2004) and increase mechanical impedance that limits

root growth (Ocloo *et al.*, 2014; Elfadil and Salih, 2017). Soil compaction has been reported to inhibit the downward rooting/ elongation of crop roots (Ozpinar and Cay, 2006) because roots can develop an only to maximum stress above which they cannot grow/magnify in soils (Seixas and Tim, 1997). Studies have reported the negative impacts of soil compaction on root dry matter yield reduction (Asady *et al.*, 1985; Lipiec and Håkannsson, 2000). A 40% reduction in dry root mass was reported to have been caused by an increase in bulk density from 1.3 to 1.9 Mg/m<sup>3</sup> (Ocloo *et al.*, 2014). An analysis of variance from this work showed that soil compaction influenced soybean root mass with the lowest mass at 1.9 Mg/m<sup>3</sup> compared to the density of 1.1 Mg/m<sup>3</sup>. However, Ozpinar and Cay (2006) reported no effects on the lateral spread of roots. A study carried out to access the soil water and soil strength on irrigated sandy soil found out that a compacted soil layer restricted the elongation of maize roots and confined the roots to almost entirely the topsoil (Laboski *et al.*, 1998). However, the growth of maize root was stimulated by 21-28 weeks after planting which was not significantly different from the control of density 1.3 Mg/m<sup>3</sup> (Ozpinar and Cay, 2006).

In an experiment on soil aggregation and root growth of perennial grasses carried out in Brazil, it was observed that the root development of all species decreased at the subsoil layer due to compression of aggregated soil, high bulk density and low macro-porosity. At the topsoil, however, the root development was higher due to recovery of soil physical conditions by the grassroots causing new aggregates to form and a reduction in the density of the soil (Stumpf *et al.*, 2016). In another study, it was observed that upland rice root penetrated only 0-10 cm depth at a compaction level of 1.5 Mg/m<sup>3</sup>. In general, the effect of soil compaction on plant growth can be described according to Henderson (1989) as:

$$\% Y = 100 - 32.4 \times (PR - PR_{crit}) \quad 2.1$$

where % Y is the percentage of the maximum forage growth attained due to increased penetration

resistance and  $PR_{crit}$  is the critical penetrometer resistance beyond which growth declines. According to Henderson (1989),  $PR_{crit} = 1$  MPa. Root elongation is not only influenced by penetration resistance but also by other factors such as anaerobic conditions (Seixas and Tim, 1997), and initiation of laterals on the same axis, which is modified by compacted soils (May *et al.*, 1967). The reduction of root growth will impact root functions in the uptake and supply of water and nutrients, inability to support the crops for anchorage, impair the growth of shoot and reduce crop yield.

The use of irrigation to offset the adverse impact of soil compaction on crop growth is often unsuccessful because of increased runoff which washes the fertilizers away. In general, the adverse effects of mechanical tillage are often insidious and remain unnoticeable until irreparable “damage” is done to the soil.

### 2.3.2 Temperature and water stress on crop development

Crop development (i.e., phenology) is a function of the environmental temperature. The popular day-degree (GDD, °C d) formula:

$$GDD = (T_{av} - T_b) * t \quad 2.2$$

where  $T_{av}$  is the ambient average temperature °C,  $T_b$  is the base temperature °C and  $t$  is the chronological time between any two development stages (day) expresses the link between temperature and crop development. The  $GDD$  and  $T_b$  are genetic traits for a given crop variety and these have been determined for several crops (see Hundal *et al.*, 2003).

Other environmental factors such as soil water and nutrient availability also affect the development of crops. Seeds require a substantial amount of water before emergence. Abrecht and Carberry (1993) opined that maize silk and tassel initiation were delayed, primarily by slowing the rate of leaf appearance when severe water stress was imposed for 19 days succeeding emergence, but consequent developmental stages were reached earlier. This was in contrast to the finding made by Campos *et al.*

(2004), who reported that under water-stressed conditions, anthesis and silking for maize (*Zea mays* L.) happened a little later and the anthesis-silking interval increased.

It is important to note that crops' response to water stress may vary and depend on time and severity of imposed stress, as well as species and genotypes differences (McMaster *et al.*, 2008). The effect of water stress can cause the early maturity of crops. Rosenow *et al.* (1983) found that the development of sorghum cultivars that differed in the stay-green trait under severe water deficits responded equally over the entire growing season, nonetheless, severe water deficits developed quickly near the flowering stage and caused cultivars lacking the stay-green trait to mature earlier. This may explain why for a particular crop, the effects of water stress may differ for different developmental stages. From different studies carried out on different cereal crops, the water stress effects on developmental stages are more pronounced from the onset of flowering and afterwards, and seed filling duration shortened, causing early physiological maturity (McMaster *et al.*, 2008; Wolf 2002; McMaster *et al.*, 2003, 2005; Campos *et al.*, 2004; Farre and Faci 2006).

The combination of temperature and humidity, which is the Vapour Pressure Deficit (VPD) is another major determinant of crop development. Several studies have shown that VPD (how much more room there is in the air for more water vapour) controls the evaporation and transpiration process (Leonardi *et al.*, 2000; Zhang *et al.*, 2017; Grossiord *et al.*, 2020). The higher the temperature, the higher the VPD, leading to the partial closure of the stomatal conductance (to reduce water loss and acute strain in the xylem). Plant often tolerates high transpiration up to a VPD peak and beyond this peak, photosynthesis and growth are reduced and causing a hydraulic failure (Grossiord *et al.*, 2020). This is due to the higher difference in vapour pressure between leaf and air. Pressure act on the plant from the leaves to the roots causing drying and heating and the resulting drought increases the stress effect on the plant (Dai 2013; Peter, 2016). On the contrary, the lower the temperature,

the higher the humidity and the lower the VPD (Peter, 2016), impairing transpiration and crop growth, in general. The crop remains “lazy”.

Photosynthetic responses to vapour pressure deficit were conducted in the tropical rainforest of Australia and it was reported that tropical trees showed a greater increase in water use efficiency with increasing VPD (Cunningham, 2005). However, under high leaf-air vapour pressure deficit, some other studies reported decreasing rate of stomatal transpiration called feed-forward response rather than feedback in the former (Cunningham, 2004; Whitley *et al.*, 2013).

### 2.3.3 Water use efficiency

Water Use Efficiency (WUE) is a major indicator of the response of a crop to water availability. From the point of view of an agronomist, it is the total yield/dry matter produced per total water evaporated and transpired from the soil surface and leaf surface respectively in the same season (Abbate, 2004). However, from the farmer’s viewpoint, it is the seed yield produced per the rainfall amount. Water use efficiency is important in determining the rate at which plants used moisture applied for optimum growth and yield of crops. Also, it is important in interpreting nutrient uptake, especially nitrogen which is taken up by mass flow. Hence the WUE is also used in the estimation of the nitrogen use efficiency, NUE (Kappen *et al.*, 2000).

Several researchers have related the changes in WUE with climatic conditions such as vapour pressure deficit, average relative humidity etc. (Arkely, 1963; Bierhuizen and Slatyer 1965) and limitation to water supply which can be water stress conditions. Amongst the climatic conditions, VPD has a greater effect on the WUE under non-limiting soil water conditions (Abbate *et al.*, 2004). High WUE in water limiting conditions caused the closure of stomata restricting the rate of transpiration in the day. On the contrary, plants growing under severe and moderate water stress at early and middle stages may exhibit increased WUE (Ge *et al.*, 2012). Yin *et al.* (2005) reported increased WUE under

water stress conditions. Almost half the increase in WUE was reported under water-stress conditions and a 50-100% increase in the well-watered condition of upland rice. When the rate of photosynthesis increases under reduced transpiration levels, WUE increased significantly by 65% (Karaba *et al.*, 2007). It is important to note that total biomass increases both in well-watered conditions and water stress conditions, however, the contributing factor differs. For example, in well-watered conditions, the shoot growth contributes mainly to the total biomass while for the stressed condition, the root growth contributes to the total biomass. Similar effects are reported by other researchers (Marron *et al.*, 2002; Siemens and Zwaizek 2003; Zhang *et al.*, 2004).

The question of water use efficiency improvement has become a challenge in agricultural sustainability security especially in semi-arid areas where there is a limited supply of rainfall (Bhattacharya, 2019). Araus *et al* (2002) noted that in improving WUE, photosynthetic capacity will be increased, and stomatal conductance reduced reducing the rate at which plant leaves transpires. Mulching is an option for reducing evaporation, soil temperature and thereby increase the yield and WUE (Gan *et al.*, 2013). Plastic films have also been noted to reduce evaporation than mulch by some researchers, however, problems encountered with it are negative effects on soil structure, nutrient transport and crop growth (Liu *et al.*, 2014).

#### **2.4 Soil physical properties affected by compaction**

Though there are general relationships such as equation 2.1 that relate crop yields to soil compaction, they do not offer any understanding of the responses. Why and how does soil compaction alter the soil properties to explain the plant's response? These and other questions need to be understood for the design of better management practices. As indicated earlier, soil compaction was defined as the re-arrangement of soil particles to form denser soils and is influenced by external factors such as the weight of tractor's wheel, animal's trampling feet, hefty machinery trafficking (Jamshidi *et al.*,

2008), regular chemical fertilizer application and intense tillage operations (Shafiq *et al.*, 1994) to cause a reduction in the volume of soil which affects the productivity of soil and environmental quality (Seixas and Tim, 1997). Soil compaction caused by agricultural machinery movement was also related to the initial soil water content (Shafiq *et al.* 1994). In other words, soils can be more compacted as the water content increases, but this rise comes to a peak or maximum bulk density (MBD), and thereafter, the bulk density declines at higher water content. The density of soil increases as the soil gets wetter to the wetter/ dryer the soil, the more difficult it can be compacted. This relationship is otherwise called the proctor test. Compaction has been considered a big threat or problem to the fertility of agricultural soil which resulted in degradation of 68000 km<sup>2</sup> area globally (Oldeman *et al.*, 1991), especially the compaction of sub soil which is considered more problematic due to its inability to ameliorate. In addition, changes in soil physical properties are more noticeable in this compacted topsoil (Berli *et al.*, 2004).

With regards to this effect, a higher level of compaction can be said to have negative impacts on the physical properties of soil (Cambi *et al.*, 2018). In evaluating it, various physical properties are being used which includes bulk density (Reichert *et al.*, 2018), macro-porosity (Holthusen *et al.*, 2018), soil strength, penetration, soil, resistance, soil porosity (Cambi *et al.*, 2018), dominant pore radius sizes, soil hydrological properties, and air & water fluxes (Reichert *et al.*, 2009). All these aforementioned factors can cause a reduction in penetration of root, extraction of water and growth of the plant (Kirkegaard *et al.*, 1992; Passioura, 2002).

#### 2.4.1 Soil bulk density and porosity

Bulk density is the ratio of the mass of solids in a medium to its total volume and can be expressed in g cm<sup>-3</sup> or Mg m<sup>-3</sup>. Machines induce compaction leading to higher bulk densities after traffic (Evy Ampoorter *et al.*, 2012), thus increasing the bulk density of soil is the focal direct effect of

compaction (Adekalu and Osunbitan, 2001; Berli *et al.*, 2004; Reichert *et al.*, 2009). However, increasing bulk density does not necessarily impede crop growth and yield. Indeed, at some increased density levels, it can encourage soil water storage and support root anchorage. On the other hand, soil compaction can also significantly aid good seed-soil contact (Elfadil and Salih, 2017). This explains that each soil type has its limits of acceptable bulk density for adequate growth and yield of crops (Reichert *et al.*, 2009).

The ideal bulk density was reported by (Seixas and Tim, 1997) for different soil textures, stating less than 1.40 gcm<sup>-3</sup> for sandy clay loam, sandy loam and silty clay loam soil. Cambi *et al.* (2018) found out that the passing of the first vehicle significantly affected the soil's physical properties before forest logging and 7 days after the start of logging. The study from Shafiq *et al.* (1994) likewise reported that with eight passing of tractors, the bulk density of clay loam soil increased by 15% and 7% under 0.095 kg/kg and 0.155 kg/kg soil water contents respectively at 0-10 cm depth. At 40-70% of soil water contents, a significant increase in bulk density was reported but at 70- 100% of available water, there was no further increase in the density of soil. Consistent tillage, rainfall occasions and other subsequent disturbance events can re-compact agricultural soils thereby increasing the density (Hunsnjak *et al.*, 2001). Edwards, 1988 likewise recorded increased bulk density in his study of compaction problems on soil physical properties. Also, from the study of Lamandé *et al.*, 2018, who tested the effects of traffic on soil physical properties, the loading effects increased the bulk density of the topsoil from 1.32 Mgm<sup>-3</sup> to 1.45 Mgm<sup>-3</sup> which caused low air permeability into the soil. As compaction levels increase, the dry densities also increase (Berli *et al.*, 2004). A six-year study on the effects of continuous mechanized tillage on Alfisol was conducted in Nigeria and the density of the soil increased by 11.7% at 0-10 cm depth (Kayombo and Lal, 1993). This direct effect of compaction on bulk density has led to changes in other soil physical properties.

The compaction effect on the increase in bulk density causes an indirect effect on porosity. In other words, the increase in bulk density causes a decrease in soil porosity (Culley *et al.*, 1982, Ampoorter E. *et al.*, 2007). Porosity also referred to as void fraction (air & water) is the fraction ratio of the volume of voids to the total volume of the soil expressed in percentage or fraction. Compaction in turn affects the macro-pores which are important for air and water passage in the soil. The changes in the total porosity of soil are affected by the pore size distribution modifications (Lipiec *et al.*, 2006). Bigger pores are reduced as the soil particles are more intricately connected, causing lower air permeability (Edwards, 1988), this disconnects the movement of water and nutrient to the root of crops (Seixas and Tim, 1997). This makes the soil more susceptible to erosion and fertility reduction.

#### 2.4.2 Soil structure

Soil structure is referred to as the arrangement and grouping of individual soil particles into aggregates of different shapes and sizes which can be platy, columnar, prismatic, granular and blocky. The soil structure can also be affected by the effect of tillage operations, especially poorly structured soil. Compaction of soil causes changes (Kayombo & Lal, 1993), and deterioration of soil structure (Rashidi and Keshavarzpour, 2007) and can lead to more enormous soil structure with little or no natural voids. Also, the inherent properties of the soil (such as increased soil organic matter, and high sesquioxide) can increase the rate at which the soil can be compacted.

#### 2.4.3 Soil hydraulic properties

The soil porous system in relation to the soil structure gives an accurate and better understanding and explanation of the soil hydrological properties (Crawford, 1994; Kutilek, 2004). In this respect, as the soil structure takes another form and size as a result of compaction, changes are made to the porous system which in turn changes the hydraulic properties such as water infiltration and percolation, hydraulic conductivity, and soil moisture retention. Macro pores (soil big pores) are being reduced,

causing a reduction in water infiltration into the soil (Shafiq *et al.*, 1994) implying the susceptibility of the soil to erosion (Ampoorter *et al.*, 2007). Infiltration is the amount/volume of water entering into the soil via a permeable medium per unit area through the upper surface. Infiltration rate is the rate at which water enters the soil profile. Both are controlled by the pore size distribution (PSD) and pores alleyway and increase with an increasing effective pore diameter of soil (Kutílek, 2004; Lipiec *et al.*, 2006). A study carried out in Nigeria on long-term tillage indicated that it caused more compaction on ploughed watersheds than no-tillage which reduced cumulative infiltration from 65 cm to 5 cm from the year 1976 to 1980. This sudden decline was reported to cause structural collapse and elimination of transmission pores (Lal, 1985). Compaction causes a reduction of conductive properties due to the corresponding reduction of mean effective pore diameter of soil (Kuncoro *et al.*, 2004)

Compaction induces breakdown of soil structure, which in turn reduces hydraulic conductivity drastically (Olu *et al.*, 1987; Edwards, 1988; Kayombo and Lal, 1993). It was reported that with increasing bulk density, hydraulic conductivity decreases and likewise penetration resistance decreases with increasing soil moisture (Edwards, 1988). He plotted the relationship between bulk density and saturated hydraulic conductivity which gave the best fit of 96% correlation of determination. Ocloo *et al.*, 2014 reported the reduction of saturated hydraulic conductivity with increasing density which varied between 25.6 and 44.2 mm/day at 1.1 and 1.9 Mg/m<sup>3</sup> respectively. In the study conducted by Reichert *et al.*, 2009 he reported that with an increase in the degree of compactness which “relates to the field bulk density to the bulk density reached through the soil compaction test in a laboratory”, the soil macro-porosity and hydraulic conductivity reduced significantly. These changes in the hydraulic and aeration properties of soil can diminish the nutrient uptake by plants resulting in poor crop growth. However, compacted soil with its finest pores still holds water strongly. It holds more water at field capacity than the un-compacted soils (Currie

1984, Cambi *et al.*, 2015), even when the water is not readily available for plant use.

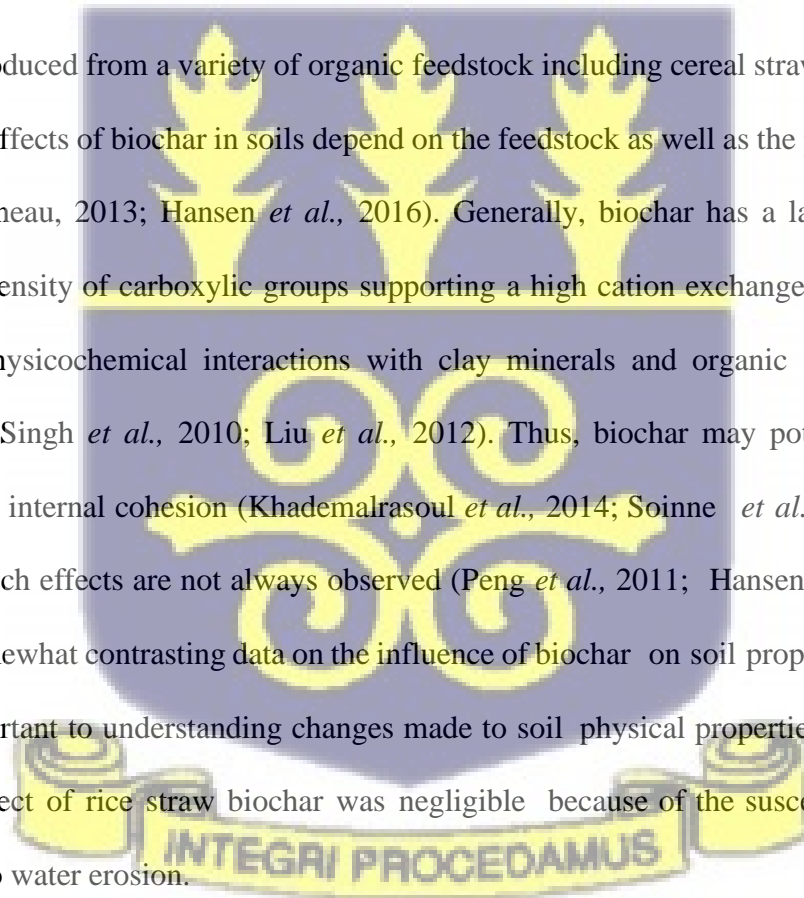
## 2.5 Management of soil compaction

The best way is to avoid soil compaction in all possible ways (Hatley *et al.*, 2005). Literature has recommended the law of ‘do not plough when the soil is too wet or too dry’, however with the demand of achieving food security for an ever-increasing population, it is difficult not to apply mechanization to the production of food (Batey, 2009). It is therefore important to manage the impact of soil compaction on agricultural lands for soil and crop productivity. To ameliorate soil compaction problems is of pronounced importance for food security, global warming mitigation, as well as soil sustainability and productivity (Liu *et al.*, 2017). In achieving this, different methods have been proposed in the literature (Lal *et al.*, 2004) which are compaction prevention or compaction alleviation. In preventing the effects of compaction, it is important to decrease the normal stress or the axle load by decreasing wheel traffic and encouraging conservation tillage, also by improving soil macro-porosity. However, an already induced compaction on soil could be alleviated either by sub-soiling (deep ploughing/chiseling) or land-use change (agroforestry or fallowing) or the use of amendment (practicing mulching, cover crop and biochar). Some researchers have suggested the use of mulching in alleviating the effect of soil compaction (Adekalu *et al.*, 2006). However, large quantities of mulch are required, and their ameliorative effect is short-lived. Qi Liu *et al.* (2016) indicated that compaction stress on a crop could be alleviated by biochar application.

Biochar is a product of pyrolysis produced under little or no oxygen which has recalcitrant carbon and acts as an alternative to alleviate the problem of soil compaction owing to its porous structure, large surface area and hydrophilic properties (Asai *et al.*, 2009; Lee *et al.*, 2013). It is an amendment that enhances the soil physical, chemical and biological properties of soil (Lehmann *et al.*, 2011; Mukherjee and Lal, 2013). Biochar is a carbon-rich material produced by pyrolysis of biomass under

anaerobic or oxygen-limited conditions (Atkinson *et al.*, 2010; Lehmann and Joseph, 2009). In recent years, there has been an increased interest in the potential of biochar as a soil amendment to improve soil structural properties and carbon sequestration (Xie *et al.*, 2015). Specifically, biochar with a low hydrogen-to-carbon ratio and a crystalline carbonaceous structure is kinetically stable in soils (Schimmelpfennig and Glaser, 2012; Sun *et al.*, 2014; Wang *et al.*, 2016) and may lead to long-term changes in soil properties (Atkinson *et al.*, 2010). Application rates of biochar that have led to improved soil structural properties typically range between 0.5 to 5 kg m<sup>-2</sup> (Major, 2010; Sun *et al.*, 2013), and effects have been observed after rather short soil/biochar equilibration periods of 6 to 15 months (Liu *et al.*, 2012; Jien and Wang, 2013).

Biochar can be produced from a variety of organic feedstock including cereal straw, wood, and animal manures, and the effects of biochar in soils depend on the feedstock as well as the pyrolysis conditions (Ladygina and Rineau, 2013; Hansen *et al.*, 2016). Generally, biochar has a large specific surface area with a high density of carboxylic groups supporting a high cation exchange capacity, which, in turn, facilitates physicochemical interactions with clay minerals and organic matter in the soil (Lehmann, 2007; Singh *et al.*, 2010; Liu *et al.*, 2012). Thus, biochar may potentially improve soil aggregation due to internal cohesion (Khademalrasoul *et al.*, 2014; Soinnie *et al.*, 2014; Sun and Lu, 2014), although such effects are not always observed (Peng *et al.*, 2011; Hansen *et al.*, 2016). Hence, because of the somewhat contrasting data on the influence of biochar on soil properties, sizes and type of biochar is important to understanding changes made to soil physical properties. Peng *et al.* (2016) found that the effect of rice straw biochar was negligible because of the susceptibility of the fine-textured biochar to water erosion.



## 2.6 Biochar effects on crop yield

One of the constraints related to the Crop yield of *Oryza sativa* in the savannah area of Brazil was said to be water limitation caused by rainfall variability (de Melo Carvalho *et al.*, 2013). de Melo Carvalho *et al.*, (2013) reported that short-term biochar's application effects in the savannah region of Brazil can be evident on the grain yield of aerobic rice under less favourable conditions i.e., water limiting conditions. Under non-limiting conditions, it was reported that biochar did not show any observable effect on the grain yield of rice. Similarly, literature reported the positive effect of the biochar- inorganic fertilizer interaction on the growth and yield of cereals (Zhang *et al.*, 2012; Petter *et al.*, 2012).

Awad *et al.* (2018) reported on the high yield of rice produced after the application of biochar and concluded that it is an excellent strategy for tackling the problems associated with producing rice sustainably around the world.

## 2.7 Biochar modification to the effect of soil compaction on soil physical and hydraulic properties

### 2.7.1 Soil bulk density

Biochar application to soil has been observed by many researchers to reduce the density of soil (Revell *et al.*, 2012; Githinji, 2014; Głab *et al.*, 2016; Y. Zhang *et al.*, 2021). Jeff White (2018) carried out a study on the relationship between bulk density and biochar from 0 to 80 ton/ha, he plotted a graph of the relationship and reported that the bulk density reduced from 1.34 to 0.37 Mg/m<sup>3</sup>. Other studies also described these effects of biochar on bulk density, a positive result was shown in a laboratory incubation study, however, different effects were observed in coarse-textured soils (Abel *et al.*, 2013; Artiola *et al.*; 2012; Periera *et al.*, 2012). These studies stated that reductions of bulk density to approximately 25% with 40 g/kg biochar, however, 8% reduction of bulk density was recorded with 50 g/kg chicken litter biochar in a Virginia sandy loam (Revell *et al.*, 2012). Soil structure changes

and adjustment of soil aggregate sizes are also a factor in the biochar modification to soil bulk density and other properties. We could also indicate the reduction of bulk density and increased porosity to the changes occurring in soil structure and adjustment of soil aggregate sizes (Tejada and Gonzalez, 2007; Jien and Wang, 2013). Githinji, 2014 described the relationship between bulk density and biochar application rates, he reported a significant 0.99% correlation of determination. The bulk density decreased from 1.33 Mg /m<sup>3</sup> for the soil without biochar to 0.36 Mg/m<sup>3</sup> for 100% biochar rate.

### 2.7.2 Infiltration and infiltration rate

Compaction problem happens at the expense of pores within the soil, this affects the remaining pores to transmit water and air within the soil. Poiseuille's law stated that the flow of fluid through a permeable medium is proportional to the fourth power of the effective pore diameter within that medium. In compacted soil, pores become thinner and directly affect the infiltration of water into the soil. In other words, if the pore size is reduced by 50%, then the flow of water would be reduced by 1-16<sup>th</sup>. Biochar application to soil has been said to improve soil water retention/ soil hydraulic properties. Głab *et al.*, 2016 in their study of biochar effects on soil hydrological properties of sandy soil, reported the improvement of soil water retention properties though noting its dependence on biochar particle size and rates. A higher rate of biochar was found to increase the available water capacity of the soil. Other studies also confirmed the correlation between soil physical quality and biochar rates (Herath *et al.*, 2013; Mukherjee and Lal, 2013). Głab *et al.*, 2016 reported a decreasing trend of cumulative infiltration with increasing biochar rates which was explained by the hydrophobic nature of the organic matter present in the biochar used.

### 2.7.3 Saturated hydraulic conductivity

One other modification of biochar is on saturated hydraulic conductivity ( $K_{sat}$ ). This is the ability at which the pores of a saturated soil transmit water under a hydraulic gradient. Various research has

been carried out on the effect of biochar application to soil hydraulic changes caused by many factors which may be a degree of saturation, bulk density, particle size distribution, water contents etc. all these factors contribute to the flow of water through saturated pores.

Biochar application significantly increases soil porosity, soil permeability, and soil saturated hydraulic conductivity (Oguntunde *et al.*, 2008). Asai *et al.* (2009b) studied the biochar amendment techniques for upland rice production on soil physical properties in Laos and reported increased saturated hydraulic conductivity of the topsoil. There was an increase in total porosity and pores >0.25 mm in diameter exhibiting the best structural stability index after the application of biochar to compacted soil (Wang and Zhang, 2019).

Some biochar made from plant material has been established through studies to increase the number of macropores and mesopores in clay soils, an example is straw biochar combined with soil particles to form stable large aggregates (Sun and Lu, 2014). Similarly, the addition of biochar can change the reorganization of soil pores altering the soil pore distribution. Nelissen *et al.* (2015) found that biochar application at the rate of 20 tons/ha increased the soil water contents, the total porosity and  $K_{sat}$  in Sandy loam soil. However, this effect was more obvious after two years of application. With all these positive results shown by different researchers, there are however, opposite results of biochar reported. 1- 50 tons/ha of hay biochar was applied to sandy soil, and after three years of sampling, no increase was reported in the soil water retention and saturated hydraulic conductivity (Jeffery *et al.*, 2015). Similarly, another researcher applied 20 tons/ha miscanthus biochar on loamy and sandy loam soil, and after 15 to 30 months, it was reported that no significant effect was observed on bulk density, porosity, and saturated hydraulic conductivity (Moragues-Saitua *et al.*, 2017). Głab *et al.*, 2016 also reported a decreasing trend of saturated hydraulic conductivity with increasing biochar rates which was explained by the hydrophobic nature of the organic matter present in the biochar used. This has caused controversy about whether biochar is efficient in improving soil's physical properties

or not.

## 2.8 Simulation of runoff from biochar-amended compacted soils.

Soil compaction directly affects the bulk density and porosity, which in turn determines runoff and infiltration terms of the water balance equation, given by:

$$\pm \Delta W = P + I - ET - Q - DR \quad 2.3$$

where P/I is the rainfall/Irrigation, ET is evapotranspiration, Q and Dr are runoff and drainage, respectively. The runoff term is a major determinant of the partitioning of applied water (rainfall and/or irrigation) between surface losses and soil water replenishment, and hence of significance to crop yields (Seixas and Tim, 1997). Adekalu *et al.* (2006) also observed that soil compaction significantly increased runoff on a Nigerian Alfisol and Inceptisol with high-intensity rainfall of 100 mm/hr.

It is, therefore, desirable to derive the effect of bulk density on the runoff. Furthermore, as biochar application modifies the bulk density, then relating runoff to bulk density would also capture biochar application effects, provided a bulk density-biochar relation is previously derived.

Runoff modelling has therefore been a major hydrological activity and several equations have been published in the literature. Two of the most commonly employed in crop modelling are the USDA Natural Conservation Service Curve Number (SCS-CN) model (Rallison 1980), and the Ives *et al.* (1976) model. The strengths of both models are that they require the input of the daily rainfall instead of hourly intensities that are not commonly available to model users. Further input required is the initial soil water storage and soil type and surface conditions, soil water and soil conditions only. The two models have not been derived to account for extreme soil compaction effects or biochar application effects. Indeed, it is only in recent studies that the effects of bulk density have

been directly included in the USDA Curve Number model (Pugh, 2020). For the Ives *et al.* (1976) model, there are currently no functions to account for soil compaction effects on runoff.

### 2.8.1 NRCS-CN runoff model

Different analytical and numerical models have been used, especially in USDA Soil Conservation Service to develop runoff models. The most common is that by Rallison (1980). This model is the most used to quantify the extent of runoff from a small watershed. It is easy to use as it provides the required soil information in Look UP Tables (LUTs) for varying soil, management and slope conditions. The daily runoff,  $Q$  (mm) from a given rainfall is determined as:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad 2.4$$

where,  $Q$  =Runoff depth (mm)       $Q = 0$  if  $P < 0.2S$

$P$ = rainfall,  $S$  = potential maximum retention (mm) which is defined as.

$$S = \frac{25400}{CN} - 254 \quad 2.5$$

and  $CN$  is the Curve Number, obtained from  $CN = \frac{25400}{S+254}$       2.6

#### 2.8.1.1 Limitations of NRCS-CN runoff model

The input data for the model were collected from a large pool of field-measured runoff data from fields of varying acreages. Thus, the model is somewhat empirical. As such, several weaknesses have been identified. First, various hydrologic soil groups can be affected by other factors/variables which were not initially considered by SCS-CN (Brezonik *et al.*, 2000). This includes slope, organic content etc. which can impact the hydrologic behaviour of the soil (Willard, 2010). Secondly, it was pointed out by Smith and Eggert (1978) that the curve numbers (CN) generated from other experiments were different from those published in Tables. Data by Pugh, 2020 also demonstrated the effect of physical and chemical properties (bulk density, pH, hydraulic conductivity) on the CN as it can affect the hydrologic behaviour of the soil. The effect of the initial soil water content on runoff has now been receiving some attention. Therefore, it can be deduced that the CN method may oversimplify the

runoff prediction problem (McCuen, 2002, Downer and Ogden, 2011, Pugh, 2020) especially with regard to soil compaction. For this current study, the interest is how to include a bulk density effect in the NRCS CN method.

### 2.8.2 TSTWO runoff model

The Ives et al (1976) was developed in a response to address some of the shortcomings of the USDA CN method. The model was adopted and validated in the TSTWO crop model. The model estimates runoff from natural watersheds using inputs such as the daily rainfall and the antecedent average soil water content of the top 20 cm of the soil. The daily runoff is estimated using.

$$Q = (P - c)f_1(P) + Pf_2(\theta) \quad 2.7$$

where  $Q$  is runoff (mm),  $c$  is a constant and

$$f_1(P) = 0.346 + 0.00691P \quad (P > 50)$$

$$f_1(P) = 0 \quad (P \leq 50)$$

$$f_2(\theta) = -1.19 + 7.41\theta \quad (0.16 \leq \theta \leq 0.268)$$

$$f_2(\theta) = 0.0 \quad (\theta < 0.16)$$

$$f_2(\theta) = 0.8 \quad (\theta > 0.268)$$

#### 2.8.2.1 Limitations of TSTWO runoff model

Despite the simplicity and ease of use of the model for runoff prediction of small catchments, it is limited to a specific amount of rainfall (95 mm). These high daily intensity rains may become frequent common under climate conditions. The main limitation, about the current study, relates to the fact that the multiple coefficients of the functions are soil type or condition-specific and hence must be related to soil compaction parameters (e.g., bulk density) and management (e.g., biochar application). This will remain a major focus and task in this study.

## CHAPTER THREE

### 3 MATERIALS AND METHODS

#### 3.1 Soils

Three sets of studies were carried out in this research. The first was directed to the understanding of the impact of soil compaction on the physical and hydraulic properties of biochar-amended soils. The second was to investigate crop growth response to the compacted amended soils. Finally, to simulate runoff from biochar-amended compacted soil using two runoff models. For all the studies, the soils were sampled from the University of Ghana Farms, located within the Greater Accra Region of the Coastal Savannah zone of Ghana. The site carries vegetation of tallgrass savannah, receiving an annual rainfall of 900 mm (MoFA 2018), which is bi-modally distributed with the major season lasting from April to July and a minor season from September to November. The relative humidity ranges between 59 % in the afternoon and 93 % at night with a mean annual temperature of about 28 °C (Dowuona *et al* 2012).

Toje soil series, classified as *Rhodic Kand* according to USDA Soil Taxonomy and Nitisols according to WRB (Eze, 2008) was used in this research because it was the most commonly cropped soil under conventional tillage, with visual signs of both surface and subsoil compaction and also bear similarities with soils (texture) used for upland rice cultivation. Literature data showed that the soil is a sandy clay loam containing 51.7 % sand, 30.8 % clay and 17.5 % silt and is located within the coastal savanna zone of Ghana at the upland positions of the University of Ghana farm.

#### 3.2 Laboratory experiments

The laboratory experiments were designed to understand how soil compaction influences the physical and hydraulic properties of soils and to what extent the application of biochar could alleviate any adverse effects. A series of experiments were conducted in the Soil Physics Workshop

of the Department of Soil Science, University of Ghana from September 2020 to March 2021. The data collected in the experiments include runoff from compacted soil columns, infiltration from the columns, hydraulic conductivity and soil moisture retention/characteristics, among others.

### 3.2.1 Setup of the laboratory experiments

Twenty-seven (27 PVC) pipes, each with a height of 20 cm and diameter of 16 cm with an area of 201 cm<sup>2</sup> were used for these studies. Runoff holes were made at the height of 4.5cm from the top of the column (Plate 3.1) to collect runoff while the column end caps at the bottom were perforated to allow free drainage. The columns were packed with soils to three (3) bulk density values (D1 = 1.3, D2 = 1.5 and D3 = 1.7 Mg/m<sup>3</sup>) with the top 5 cm below the runoff hole compacted. The top 5 cm of the soils in the columns also received different biochar application rates of 0, 10 and 20 ton/ha (Table 3.2). The soil beneath the compacted zone in each column was packed to the field bulk density of D1 = 1.3 Mg/m<sup>3</sup>. All the treatments were replicated 3 times.

#### 3.2.1.1 Laboratory experiment 1: Runoff studies

Rainfall simulators, similar to those for the screen house studies, were used in the experiments. Following the packing of the soil columns, they were pre-saturated and allowed to drain for 2 days. The columns were weighed and subjected to 5 irrigation events of 25 mm, 15 mm, 50 mm, 100 mm, 70 mm, with about 5 to 15 days intervals between the events. The irrigation durations varied such that the application intensities corresponded to 32.6, 34, 37.0, 38.4, and 37.5 mm/h. For each irrigation event, data collected include time to runoff onset, rainfall infiltrated before runoff onset, total runoff, and total drainage. Each column was weighed after each irrigation event.

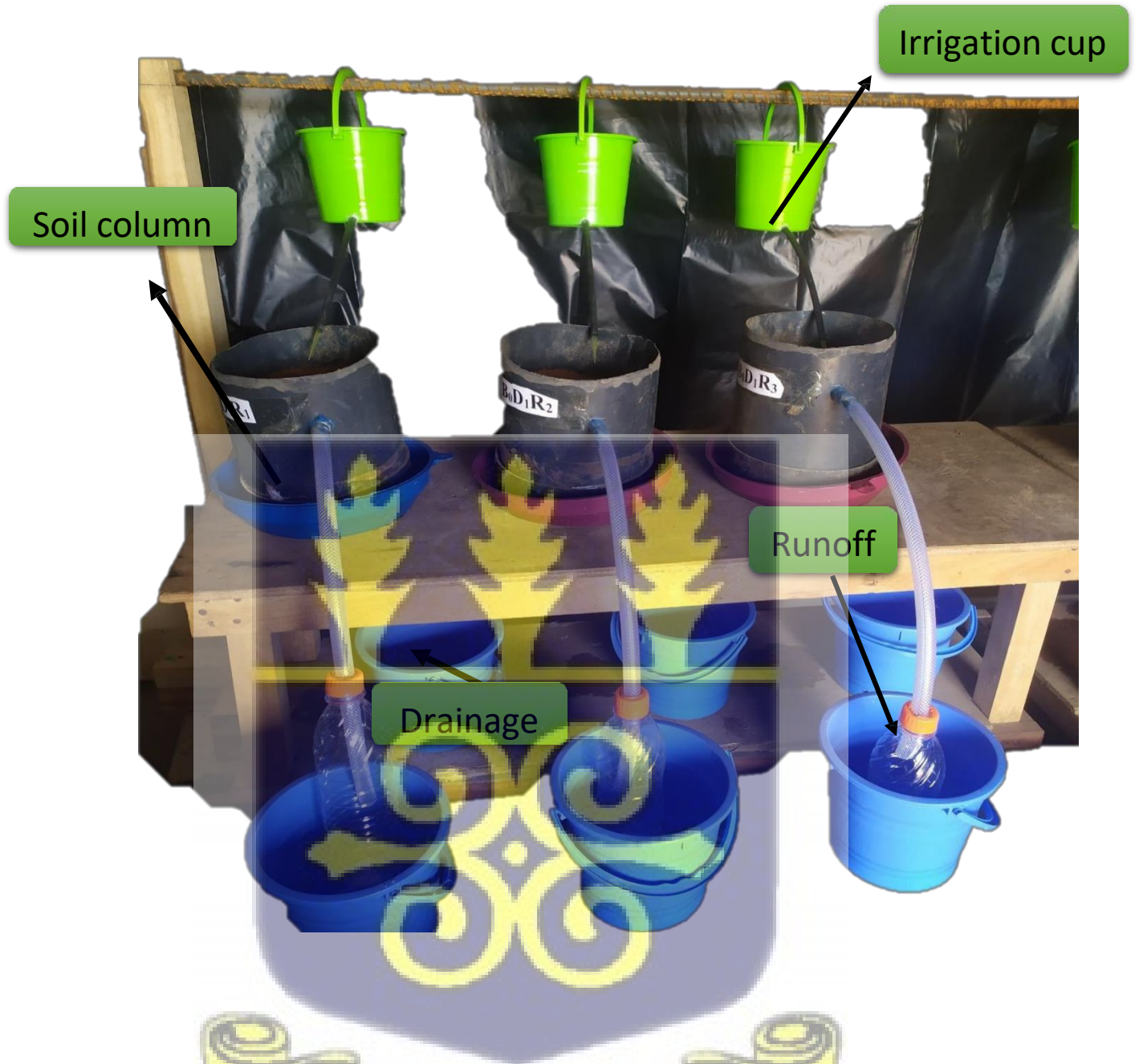


Plate 3.1: Set-up of the laboratory experiment

INTEGRI PROCEDAMUS

**Table 3.1 Treatment combination and description**

Densities	Rice husk biochar rates		
	0 ton/ha	10 ton/ha	20 ton/ha
Field bulk density (D1 = 1.3 Mg/m <sup>3</sup> )	B0 D1	B10 D1	B20 D1
Medium bulk density (D2=1.5M g/m <sup>3</sup> )	B0 D2	B10 D2	B20 D2
High bulk density (D3 =1.7 Mg/m <sup>3</sup> )	B0 D3	B10 D3	B20 D3

The data from the experiments were used to determine the parameters of two runoff models. The first was the model by Ives et al (1976). This model was developed for sheet runoff from agricultural soils and have been validated and used extensively for crop growth modelling in Australia. The model is given by:

Australia. The model is given by:

$$Q = (P - c)f_1(P) + Pf_2(\theta) \tag{3.1}$$

where  $Q$  is runoff (mm),  $c$  is a constant and

$$f_1(P) = 0.346 + 0.00691P \quad (P > 50)$$

$$f_1(P) = 0 \quad (P \leq 50)$$

$$f_2(\theta) = -1.19 + 7.41\theta \quad (0.16 \leq \theta \leq 0.268)$$

$$f_2(\theta) = 0.0 \quad (\theta < 0.16)$$

$$f_2(\theta) = 0.8 \quad (\theta > 0.268)$$

How soil compaction and biochar application affect the value of  $c$  is of interest to this study because according to Ives *et al.* (1976), the parameter  $c$  will vary with soil conditions.

The second model is the USDA Soil Conservation Service Curve Number (CN) method, which was developed in the USA and is widely used for the simulation of runoff in medium catchments. The model

is also widely used in crop growth modelling to estimate runoff. The model is given as:

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad 3.2a$$

where  $S$  is a water retention parameter given by:

$$S = \frac{25400}{CN} - 254 \quad 3.2b$$

with CN being the curve number, which is a function of a host of factors such as texture, and other soil conditions. Though CN values are tabulated for different soil conditions, the particular way soil compaction and biochar application affect the CN is largely unknown. This is also of interest to this study.

### 3.2.1.2 Laboratory experiment 2: Infiltration studies

After the last irrigation event, the columns were allowed to dry for 15 days for the soil columns to dry out and thereafter, infiltration experiments were conducted. The runoff holes were sealed, and a water head of 4.5 cm was imposed on each column and the time taken for the level to drop by 1 cm was recorded. After each drop, the head was topped up to the initial level and the procedure was repeated. A set of 7 to 8 data points was obtained for each treatment.

The data obtained were used to plot the graphs of the cumulative infiltration  $I$  with time and the infiltration rate,  $i$  curves. The infiltration rate curves were fitted with the parameters of two models. First, the Horton (1948) infiltration equation was used:

$$i = ic + (io - ic)e^{-kt} \quad 3.3a$$

and

$$I = ict + \frac{(io-ic)}{k} (1 - e^{-kt}) \quad 3.3b$$

where  $io$  is the initial infiltration rate,  $ic$  is the final infiltration rate in cm/min and  $k$  is the decay constant (how fast the curve fall depending on texture). The curves were fitted using SigmaPlot

(Version 14.0). All parameters in the equation were derived as a function of bulk density which is influenced by biochar application.

The second model used was that of Philip (1957) as:

$$i = 0.5S_0t^{-0.5} + Bt \quad 3.4a$$

And,

$$I = S_0\sqrt{t} + B \quad 3.4b$$

where  $S_0$  is the sorptivity (the ability of the soil to absorb water) and B is a constant, approximately equal to the saturated hydraulic conductivity. The  $S$  for the various treatments were obtained as the slope of the plot of  $I$  vs.  $\sqrt{t}$  for the initial times. All parameters in the equation were derived as a function of bulk density derived as a function of biochar application.

### 3.2.1.3 Laboratory experiment 3: Saturated hydraulic conductivity

Two days after the infiltration experiments, the soil in the columns was re-sampled using cylinders of 5.0 cm internal diameter and 16 cm length and used for the determination of the saturated hydraulic conductivity,  $K_{sat}$ . The columns were pre-saturated and the constant head permeameter method was used for the determination.

A constant head of 1 - 3.5 cm water was maintained over the top of the soil in the columns and the outflow from the bottom was collected every 3 minutes and measured. Darcy's Law was applied as:

$$Q = \frac{V}{At} = -K_{sat} \frac{\Delta\psi h}{\Delta z} \quad 3.5a$$

where  $q$  is the water flux ( $\text{cm}^3/\text{cm}^2 \text{ s}$ ),  $K_{sat}$  is the saturated hydraulic conductivity (cm/s), and  $\Delta\psi h/\Delta z$  is the hydraulic potential gradient. Given a soil length of  $L$  cm, a cross-sectional area of  $A$  ( $\text{cm}^2$ ) and a water head of  $H$  (cm), the  $K_{sat}$  was determined as:

$$\frac{V}{A} = -K_{sat} \left( \frac{H+L}{L} \right) t \quad 3.5b$$

The plot of  $V/A$  vs.  $t$  yielded a slope value of  $m$  (slope) =  $K_{sat} \left( \frac{h+L}{L} \right)$ , enabling the calculation of  $K_{sat}$ .

### 3.2.1.4 Laboratory experiment 4: Soil moisture Retention

The soil moisture retention experiment was carried out a day after the saturated hydraulic conductivity experiment, the soil columns were re-sampled using cores of 4.5 cm height and 4 cm internal diameter. The columns were pre-saturated and the Haines funnel method for high energy 0-80 cm was used for the determination of matric potential.

The cores were carefully placed on the porous funnel plate for direct plate/ soil contact, the water level was raised to the 0 cm depth until equilibrium was achieved at both funnel burette and porous plate, after which a height gradient of 10 cm was applied, at this instance, pressure gradient applied caused water to move/drain from the soil sample until equilibrium was reached and the flow stopped, and the height of the water was assessed. This process was repeated till a height gradient of 80 cm was imposed.

Immediately at equilibrium, the drained samples were carefully removed from the Haines chamber and weighed on a weighing balance and their weight was recorded, they were left for 24 hours, and the samples were weighed again before been placed in an oven at 105 °C for two days. The samples were re-weighed again, and the gravimetric and volumetric water contents were calculated.

The plot of matric potential ( $\psi_m$ ) and volumetric water content ( $\theta_v$ ) gave the different slopes of  $C$  at different matric potential points.

$$C = \frac{\Delta\theta_v}{\Delta\psi_m} \tag{3.6a}$$

$$\psi = \frac{-2T}{r} = \frac{-0.15}{r} \tag{3.6b}$$

The graph of the relationship between  $C$  and the matric potential was plotted and used to get the

dominant pore radius ( $r$ ) for each treatment.

### 3.3 Biochar- bulk density relationship

Given that the impact of biochar on soil physical properties is primarily through the alteration of the bulk density or porosity (Głąb *et al.*, 2016; Zhang *et al.*, 2021), a separate experiment was conducted to establish the relationship for the Toje soil series used in this research. For this, six biochar rates, namely 0, 5, 10, 20, 40 and 60 ton/ha were applied to 4 kg of soil samples. The treatments were replicated twice and left in the open for incubation for 30 days. During this period, the average air temperature was 38 °C and the samples were irrigated from time to time to simulate normal conditions. At the end of the 30 days, four (4) core samples were taken from each treatment and used to determine the bulk density.

### 3.4 Screen-house studies of crop response to compacted biochar amended soils.

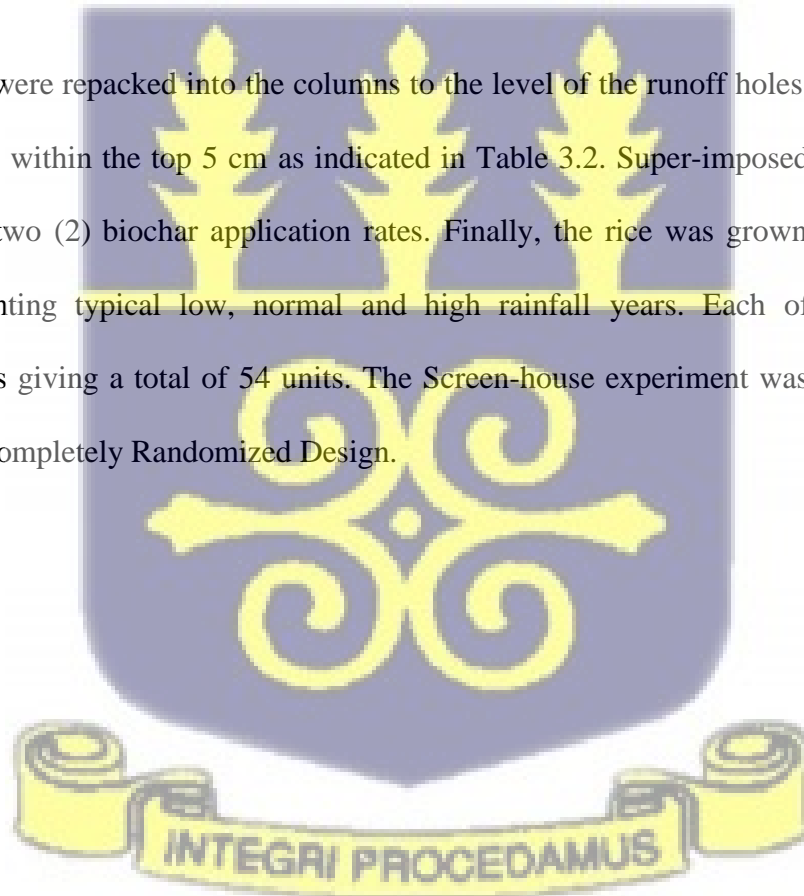
The first study was a screen house experiment designed to assess the response of upland rice NERICA 14 (*Oryza glaberrima* L.) to soil compaction and the effect of biochar application as an ameliorative measure. The experiment was carried out at SINNA'S Garden of the Department of Crop Science, University of Ghana. A screen house was constructed as a rainout shelter. The transparent plastic roof did not obstruct with radiation received in the shelter (Plate 3.2).

Sampled Toje series was sieved through a 4 mm-sieve and repacked into PVC columns of an internal diameter of 16.0 cm giving a cross-sectional area of 201 cm<sup>2</sup>. The length of the columns was 40 cm. The PVC columns had a runoff hole drilled at 4.5 cm below the upper end, whereas the lower end was closed with an end cap but with drilled holes to allow drainage (Plate 3.2). The runoff was collected in plastic bottles volume of 70 ml through a hose of 1.5 cm thickness and 1.2 cm inner diameter connected to the PVC columns. Drainage water was collected in plastic bowls placed beneath the columns.



**Plate 3.2: Set-up of the screen house experiment.**

The sieved soils were repacked into the columns to the level of the runoff holes to achieve three (3) bulk densities within the top 5 cm as indicated in Table 3.2. Super-imposed on the bulk density treatments were two (2) biochar application rates. Finally, the rice was grown under three rainfall regimes, representing typical low, normal and high rainfall years. Each of the treatment was replicated 3 times giving a total of 54 units. The Screen-house experiment was laid out in factorial arrangement in Completely Randomized Design.



**Table 3.2: Screen house treatment description.**

Compaction levels	Biochar rates	Low water (W1=338.5 mm)	Medium water (W2 =419.1 mm)	High water (W3=569.5 mm)
<b>Field bulk density (D1 = 1.30 Mg/m<sup>3</sup>)</b>	0 ton/ha (B0)	B0 D1	B0 D1	B0 D1
	10ton/ha (B10)	B10 D1	B10 D1	B10 D1
<b>Medium bulk density (D2 = 1.50 Mg/m<sup>3</sup>)</b>	0 ton/ha (B0)	B0 D2	B0 D2	B0 D2
	10ton/ha (B10)	B10 D2	B10 D2	B10 D2
<b>High bulk density (D3 = 1.75 Mg/m<sup>3</sup>)</b>	0 ton/ha (B0)	B0 D3	B0 D3	B0 D3
	10ton/ha (B10)	B10 D3	B10 D3	B10 D3

### 3.4.1 Soil compaction levels

The three different bulk densities imposed (field bulk density, medium bulk density and high bulk density) represented by D1, D2, and D3, respectively in Table 3. were achieved by compacting the soil using rammer of 5 kg weight for different numbers of strokes. In the case of the field bulk density (D1), no ramming was carried out, but the columns were packed to a bulk density of 1.31 Mg/m<sup>3</sup>. Since the soil compaction effect was limited to the top 5 cm, the top 4.5 cm of the PVC was corked with a 4.5 cm wooden plug and the column turned upside down and filled with soil to a depth of 5 cm. This was then ramped until the desired density was achieved. The rest of the column was then filled with soil to the field density. The desired bulk densities were determined from Proctor curves (density-water content relationships) established in a prior experiment. The proctor curve indicated that when the soil water content was 60% of Field Capacity (FC), the highest bulk density of 1.75 Mg/m<sup>3</sup> could be achieved for 30 strokes of the ramming. Hence, for the highest bulk density, the

soil was pre-wetted to 65 % FC before packing into the compacted 5 cm space. For treatments receiving biochar application, the biochar-soil mixture was separately prepared and filled into the 5 cm space below the runoff hole.

#### 3.4.2 Preparation of rice husk biochar (RHB)

Rice husks obtained from the waste product of harvested rice at Soil and Irrigation Research Centre (SIREC), University of Ghana, was used as the feedstock for biochar preparation. The material was charred using a locally made *Kon tiki* kiln at a temperature of 350 °C at SIREC Kpong. The amendment (Rice husk biochar) was applied at two levels (0 and 10 ton/ha biochar). The rates were specifically selected based on earlier studies which indicated improvement of soil physical properties at a biochar application rate of 10 ton/ha.

#### 3.4.3 Water regimes

The three water regimes used in this study (low, normal and high; Table 3.2) were determined following the construction of a cumulative rainfall frequency distribution for the site using 41 years rainfall data of the major season (April to July) for the Greater Accra Region. Rainfall corresponding to the 25<sup>th</sup> percentile was taken as low; the median was taken as normal and 75<sup>th</sup> percentile as high rainfall. The high rainfall regime year was 2003, the medium rainfall year was 1970 and the low rainfall year was 1984. The water regimes were W3 = 569.5 mm, W2 = 419.1 mm and W1 = 338.5 mm. The daily irrigation for each water treatment followed the rainfall amount and distribution of the years. The duration for each irrigation event was 2 hours and the water was delivered via specially constructed rainfall simulators (Plate 3.2). The rainfall simulators delivered water through plastic pipette tips from a height of 3 cm above the soil surface. In situations of very long dry spells between rainfall events, 5 mm of water was applied to all treatments.

#### 3.4.4 Planting and agronomic practices

Rice was planted on 19<sup>th</sup> August 2020 at three (3) seeds per column and thinned to one (1) plant 7 Days after Planting (DAP). Prior to planting, all columns were copiously watered and allowed to drain for 3 days. On the day of thinning, fertilizer was applied at the recommended rates of 60 kg N /ha, 45 kg P<sub>2</sub>O<sub>5</sub> /ha and 45 kg K<sub>2</sub>O/ha using Ammonium sulphate (split application), Triple superphosphate and Muriate of potash as sources. The nitrogen fertilizer was split applied in 2 doses. All treatments received ample water application during the first 7 days after which the water regimes treatments were imposed.



**Plate 3.3: Screen house layout of rice growth at the stem elongation stage**



### 3.4.5 Measurements and Data collection

#### 3.4.5.1 Plant development and growth

Plant development data recorded include days to emergence, 50% flowering and maturity. For these, columns were tagged from planting and to maturity, the above-ground biomass was harvested with a sickle and separated into grains and stover. The stover was oven-dried at 70 °C for three days and the dry weight was determined. For grain yield determination, the panicles were separated from the above-ground shoot at maturity and air-dried after which the grains are removed from the panicles, the unfilled were separated from the filled. The filled grains were then weighed on the weighing scale and recorded as grain weight.

For the determination of the below-ground growth, the columns were saturated and allowed to drain for two days, after which the columns were turned upside down, the end caps removed, and the soil gently pushed out of the columns (Plate 3.4). The soil column was then cut into the three soil layers or sections as it was packed earlier, (0- 4.5 cm, 4.5-10 cm, and 10--35 cm).

The soils sections were washed in bowls and the roots in each section separated. The roots were oven-dried at 70 °C for three days and weighed on a sensitive Mettler balance. The soils in the bowls were oven-dried at 70 °C for four days and the dried weight was determined. This was used to determine the actual bulk densities of the different depths along the soil column.





**Plate 3.4: Root distribution in the soil profile.**

### **3.4.5.2 Environment and water balance components**

Throughout the study, data were taken in the screen house on temperature (maximum, minimum) and humidity on daily basis using BioTemp Hygrometer. To determine the daily potential evaporation, a beaker of water was set in the screen house and the water evaporated daily was determined by weighing the beaker. The water was re-topped whenever necessary.

To determine the water balance components, all the 52 columns were weighed before the onset of the study and were weighed at maturity before harvest. The daily irrigation and runoff were recorded for each treatment. Drainage was measured 24 hours after irrigation.

Fifty (50) ml of the aliquot from runoff and drainage water was analyzed for electrical conductivities to determine the dissolved ions lost.

The actual seasonal total evapotranspiration,  $ET_a$  (mm) for each treatment was determined using the water balance equation which is given as equation 3.1. Since the total runoff, drainage and rainfall amount are known values, the  $ET_a$  was calculated as:

$$ET_a = P - Q - D_R \pm \Delta W \quad 3.7$$

where P is irrigation (mm), Q is runoff (mm),  $D_R$  is drainage and  $\pm W$  is the change in soil water storage (mm), determined as the difference in weight of the soil column at the onset and end of the experiment.

The Water Use Efficiency (WUE) was determined as:

$$WUE = \frac{\text{Grain weight (kg/ha)}}{\text{Total evapotranspiration (mm)}} \quad 3.8$$

### 3.5 Prediction of grain yield as a function of water, bulk density and biochar application

The impact of soil compaction and biochar application on rice yield was predicted via the  $ET_a$  since growth correlates with water use (de Wit 1958). Hence, a relationship between the water balance components (Q+DR), bulk density (D), biochar application rate (BC) and water regime (W) was developed in form of multiple regression as:

$$Q + DR = a + bW + cD + dBC \quad 3.9$$

The coefficients a, b, c and d were determined with a selected set of the observed data using the statistical software MINITAB (Version 12). Given a water regime, bulk density and biochar application, the loss terms Q and DR in equation 3.1 can be predicted and with knowledge of the change in water storage, the expected  $ET_a$  can also be predicted. Doorenbos- Kassam (1979) provided a relationship between  $ET_a$  and yield, given by:

$$\left(1 - \frac{Y_a}{Y_p}\right) = Ky \left(1 - \frac{ET_a}{ET_p}\right) \quad 3.10$$

where  $K_y$  is a constant (= 1.25 for rice),  $\frac{Y_a}{Y_p}$  is the ratio of actual to potential yield,  $\frac{ET_a}{ET_p}$  is the ratio of actual to potential evapotranspiration. Therefore, the actual yields can be predicted from the predicted  $ET_a$ .

The equation was evaluated by comparing predicted rice yield for various bulk densities and biochar applications with the observed. The degree of agreement was assessed using 3 statistical indicators:

The coefficient of determination,  $R^2$ .

$$R^2 = \left[ \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]}} \right]^2$$

3.11a

The Root Mean Square Error (RMSE) is given by:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (yield_{simulated_i} - yield_{observed_i})^2}$$

3.11b

and the Willmott d-index (Willmott *et al.*, 2012) is given by:

$$d = 1 - \frac{\sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (|S_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

3.11c

where  $S_i$  is simulated data,  $n$  is the total number of observations and  $\bar{O}$  is the mean of the observed data.

$R^2$  Values greater than 0.5 shows better performance while at 1 gives the perfect agreement. Perfect agreement between the simulated and observed is attained when  $d = 1$ . The d-index takes values between 0 (poor) and 1 (perfect) agreement. A low value of RMSE indicates a good agreement between predicted and observed.

### 3.6 Soil Characterization

A range of the basic physical and chemical properties of the Toje series used in this research was

determined in the General Laboratory of the Department of Soil Science, University of Ghana. The soils were from the top plough layer of 20 cm. The procedures for the soil analysis are described below.

### 3.6.1 Soil physical properties

#### 3.6.1.1 Soil Bulk Density

The field bulk density of the soil was determined using the standard core method. The height and diameter of the core sampler used were taken and recorded to obtain its volume. The core sampler was then inserted into the top layer of the soil and was carefully removed using a knife. Excess soil attached around the soil core was trimmed off, soils in the core sampler were transferred into the moisture can. The moisture cans were placed inside the oven at 105<sup>0</sup>c till constant weight was achieved. The moisture was left inside the desiccator to cool down before weighing. The bulk density was then calculated as follows.

Mass of oven-dry soil + can represent = W1 (g) Mass of can represented = W2 (g)

Mass of soil (Ms) = Mass of oven-dry soil+ can (W1) – Mass of the can (W2)

$$\text{Bulk density } (\rho_b) = \frac{\text{mass of oven dried soi (Ms)}}{\text{volume of core (cm}^3\text{)}} \quad 3.12$$

$$\text{where volume of core} = \pi r^2 h = \pi * 2.5^2 * 5 = 98.17 \text{ cm}^3$$

#### 3.6.1.2 Particle size distribution

The percentage of sand, silt and clay of the soil was determined using the Bouyoucos hydrometer method modified by Day (1951). The soil was air-dried and sieved using a 2 mm sieve to remove gravel and stones. 40 g of the soil was weighed into a dispersion cup and 100 mL of 5% Calgon (hexametaphosphate solution) was added to the soil and the mixture was made up to 250 ml and left

overnight and placed on a horizontal mechanical shaker for 2 hours. The suspension was transferred into a graduated sedimentation cylinder and made up to 1000 ml mark with distilled water and allowed to stand and equilibrate with the room temperature. A plunger was immersed into the suspension in the cylinder and moved in and out to mix the content thoroughly. The thermometer was inserted to take a reading of temperature after 5mins to measure the solids in suspension (sand), the hydrometer and temperature readings were then taken and recorded for sand. Also, at 5 hrs., readings were taken for both temperature and hydrometer for clay content, and the readings were corrected due to the temperature to estimate the clay content and at 5 hrs. The suspension was decanted into a 2.5 mm sieve and wash thoroughly under running water to obtain a coarse sand fraction. The sand content was then transferred into a moisture can and oven-dry at 105°C for 24 hours. After oven drying, it was allowed to cool in a desiccator and the mass of the sand using a weighing scale was taken.

$$(\text{Silt} + \text{Clay}) \% = \frac{\text{5 minutes hydrometer reading}}{\text{weight of soil (g)}} \times 100$$

$$\text{Clay \%} = \frac{\text{5-hour hydrometer reading}}{\text{weight of soil (g)}} \times 100$$

$$\text{Silt \%} = \% (\text{silt} + \text{clay}) - (\text{clay})\%$$

$$\text{Sand \%} = \frac{\text{oven-dry mass (g) of particles retained on the 2 mm sieve}}{\text{weight of soil (g)}} \times 100$$

3.13

The soil texture was then determined using the textural triangle.

### 3.6.2 Soil chemical properties

#### 3.6.2.1 Soil pH

The soil pH was determined by weighing 20 g of the sieved 2mm Toje series into a 50ml beaker, 20 mL of distilled water was added at the ratio of 1:1. The suspensions were stirred using a stirrer for 30 minutes and allowed to stand for 1 hour to allow all suspended soil particles to settle. A glass

electrode pH meter was standardized with two aqueous solutions of pH 4 and 7. And the pH of the prepared suspensions was measured with the glass electrode.

### 3.6.2.2 Soil organic carbon

The organic carbon of the soils was determined by the wet combustion method of Walkley and Black (1934). The method involves the reduction of the  $\text{Cr}_2\text{O}_7^{2-}$  ion by the organic matter and the un-reduced  $\text{Cr}_2\text{O}_7^{2-}$  measured by titration with ammonium sulphate. The quantity of organic matter oxidized is calculated from the amount of  $\text{Cr}_2\text{O}_7$  reduced. A 10 mL of 1 M potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) solution and 20 mL of concentrated sulphuric acid ( $\text{H}_2\text{SO}_4$ ) was added to 0.5 g of soil in a conical flask and swirled three times. It was then digested for 30 minutes in a fume cupboard for an oxidation reaction to be completed. The  $\text{K}_2\text{CrO}_7$  remaining in the solution after the digestion was titrated against 0.2 M ferrous ammonium sulphate using barium diphenylamine sulphonate as the indicator to a green endpoint.

The titre values were used to calculate the % C from the formula below:

$$\%C = \frac{0.3[10-(XN)] \times 1.33}{w} \times 100 \quad 3.14$$

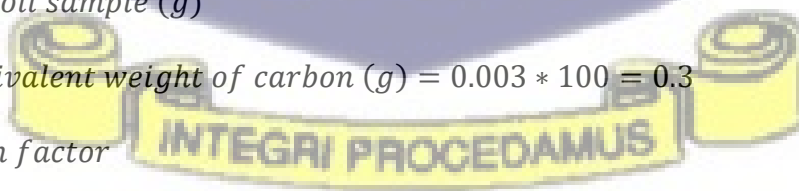
where  $X = \text{titre value of ferrous ammonium sulphate (mL)}$

$N = \text{normality of ferrous ammonium sulphate of } \text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$

$W = \text{Weight of soil sample (g)}$

$0.003 = \text{Milliequivalent weight of carbon (g)} = 0.003 * 100 = 0.3$

$1.33 = \text{correction factor}$



### 3.6.2.3 Total Nitrogen

Three replicates of two grams (2 g) of air-dried soil were each weighed into a 250 ml Kjeldahl flask

followed by the addition of a digestion accelerator, selenium catalyst and 5 ml of concentrated sulphuric acid (H<sub>2</sub>SO<sub>4</sub>). The mixtures were allowed to digest until the digest was clear, cool and then transferred with distilled water into a 50 ml volumetric flask and made up to its volume. A 5 ml aliquot was pipetted from the digest into a distillation flask, and 5 ml of 40 % sodium hydroxide (NaOH) was added and shaken for a proper mixture. The samples were then distilled and collected in 5 ml of 2 % boric acid to which about 2 drops of methylene blue indicator had been added. The distillates were then titrated against 0.01 N HCl (Bremner, 1960) which changed the colour from green to a red endpoint.

The amount of N (%) was calculated using the relationship:

$$\%N = \frac{\text{Molarity of HCl} \times \text{titre volume} \times 0.014 \times \text{volume of extractant}}{\text{Weight of soil sample} \times \text{volume of aliquot}} \times 100 \quad 3.15$$

#### 3.6.2.4 Cation exchange capacity (CEC)

Three replicates of ten grams (10 g) of the soil sample were weighed into an extraction bottle, and 100 mL of 1 M ammonium acetate solution was added. The bottle with its content was shaken for 30 minutes on a mechanical shaker. The content was filtered through a No. 42 Whatman filter paper and the sample was leached four times with 25 mL of methanol to wash off excess ammonium. Afterwards, another 25 mL of 1 M acidified potassium chloride was used to leach the soil four times. A 5 mL aliquot of the leachate was taken into a Markham distillation apparatus and 5 mL of 40 % NaOH solution was added and distilled. The distillate was collected into 5 ml of 2 % boric acid to which about two drops of methyl red and methylene blue indicators were added. The distillate was back titrated against 0.01 M HCl to a purplish endpoint. The cation exchange capacity was then calculated from the number of moles of HCl consumed in the back titration in  $\text{cmol} \cdot \text{kg}^{-1}$ .

### 3.7 Physical and chemical properties of the Rice Husk Biochar

#### 3.7.1 Bulk density of rice husk biochar

The bulk density of the rice husk biochar was determined by filling 100 ml glass cylinders with rice husk biochar, dried in an oven at 70 °C for 24 hours. It was tapped to compact the materials (Ahmenda *et al.*, 1997) and the bulk density was calculated as.

$$\text{Bulk density} = \frac{\text{weight of dry rice husk biochar (g)}}{\text{volume of packed biochar (cm}^3\text{)}} \quad 3.16$$

#### 3.7.2 Rice husk biochar pH (1:10 in water)

Pancitronic MV 88 pH glass electrometer was used to determine the pH of the rice husk biochar. Two grams (2 g) of the rice husk biochar which was air-dried was weighed into a 100 mL beaker and twenty milliliters (20 ml) of distilled water was added to the sample, stirred for 30 minutes and allowed to equilibrate at room temperature. The pH meter was then standardized using a buffer solution at pH 4.0, 7.0 and 9. The electrode was placed in the suspension and recorded as pH in water.

#### 3.7.3 Determination of total nitrogen

Total nitrogen of the RHB was examined by the modified Kjeldahl digestion method (Bremner, 1965). The nitrogen in the 0.2 g sample was converted to ammonium by digestion with concentrated sulphuric acid using the catalyst selenium. The ammonium formed was then determined by distilling the digest with a strong alkali (40 % NaOH) and titrated with a standard acid as described in Section 3.6.2.3.

#### 3.7.4 Determination of cation exchange capacity

Three replicates of ten grams (10 g) of rice husk biochar were weighed into extraction bottles, and 100 mL of 1 M ammonium acetate solution was added. The CEC of the Rice husk biochar was afterwards determined using the method described in section 3.6.2.4.

### **3.7.4.1 Statistical analysis**

Microsoft Excel (Version 2016) was used for data entry and graphical representation. Experimental data were analyzed with the Analysis of Variance (ANOVA) technique using GenStat statistical software (12th edition, 2009), and means were separated using the Duncan Multiple Range Test and compared at a 5% level of significance.



## CHAPTER FOUR

### 4 RESULTS AND DISCUSSION: I

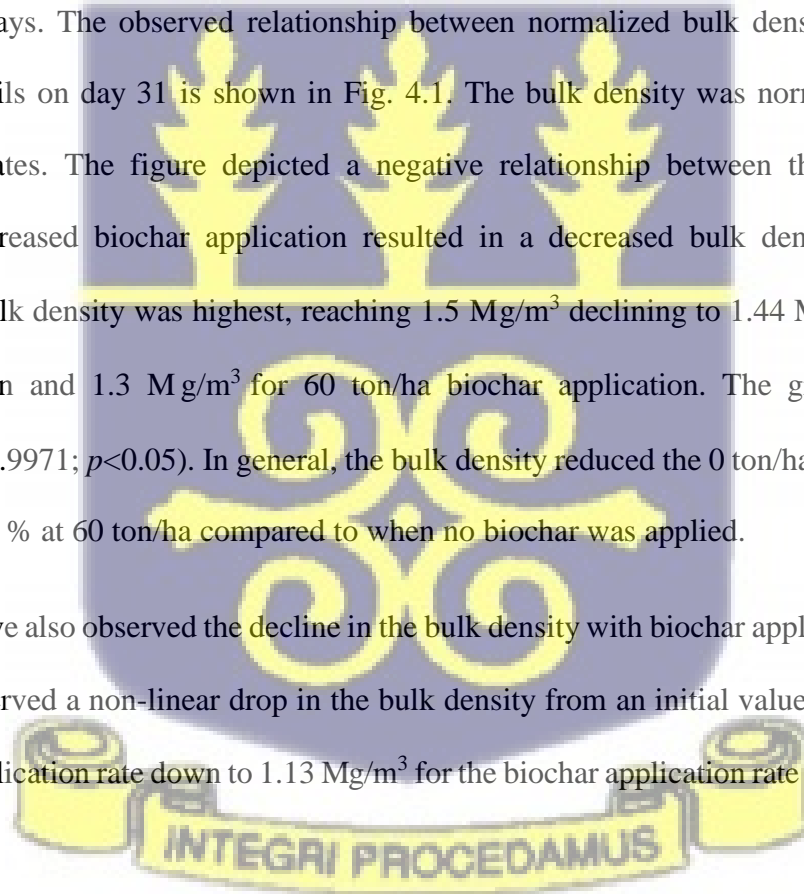
#### EFFECT OF BIOCHAR APPLICATION ON THE PHYSICAL AND HYDRAULIC PROPERTIES OF COMPACTED TOJE SOIL

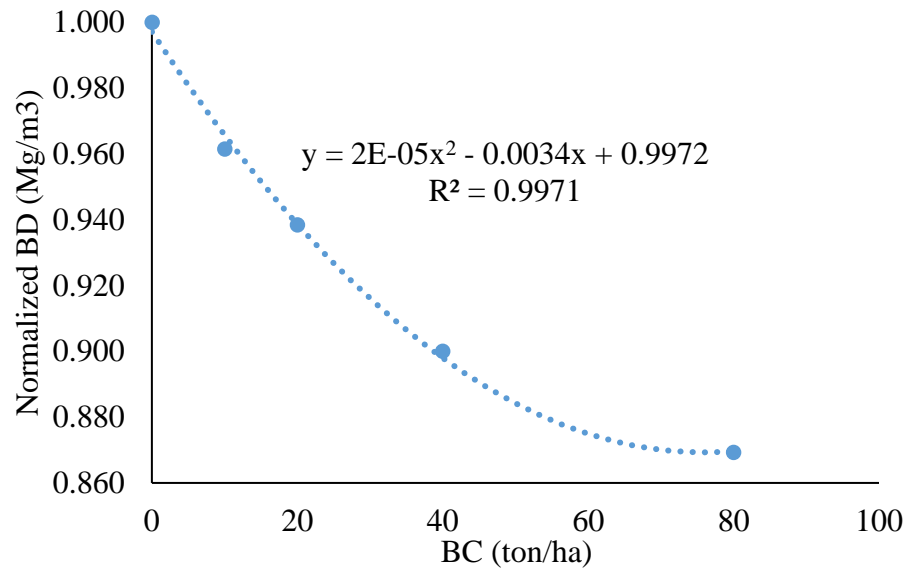
##### 4.1 Effect of biochar application on the physical properties of compacted soil

###### 4.1.1 Soil bulk density

The bulk density of repacked Toje soils decreased with rice husk biochar application. The biochar- soil mixtures which were loosely packed into buckets were left in an open-air incubation for 31 days. During the incubation period, there were several rainfall events and the direct temperatures reached 40 °C on many days. The observed relationship between normalized bulk density and biochar rate of the sampled soils on day 31 is shown in Fig. 4.1. The bulk density was normalized and plotted against biochar rates. The figure depicted a negative relationship between the bulk density and biochar rates. Increased biochar application resulted in a decreased bulk density. At no biochar application, the bulk density was highest, reaching 1.5 Mg/m<sup>3</sup> declining to 1.44 Mg/m<sup>3</sup> for 20 ton/ha biochar application and 1.3 Mg/m<sup>3</sup> for 60 ton/ha biochar application. The graph showed a good correlation ( $R^2 = 0.9971$ ;  $p < 0.05$ ). In general, the bulk density reduced the 0 ton/ha biochar application bulk density by 13 % at 60 ton/ha compared to when no biochar was applied.

Several studies have also observed the decline in the bulk density with biochar application. Walters and White (2018) observed a non-linear drop in the bulk density from an initial value of 1.35 Mg/m<sup>3</sup> at 0 ton/ha biochar application rate down to 1.13 Mg/m<sup>3</sup> for the biochar application rate of 80 ton/ha.





**Fig. 4.1: Relationship between the bulk density and biochar application, after 31 days of incubation.**

Other studies also described similar patterns of the biochar effects on bulk density (Periera *et al.*, 2012; Abel *et al.*, 2013. Revell *et al.* (2012) reported an 8% reduction of bulk density when 50 g/kg (5 ton/ha) chicken litter biochar was applied to a Virginia sandy loam. On the contrary, a few studies also reported no significant impact of biochar on bulk density (Artiola *et al.*, 2012; Periera *et al.*, 2012; Abel *et al.*, 2013). The bulk of the evidence clearly demonstrated the lowering effect of bulk density by biochar application.

It is evident that the same biochar application would result in different bulk densities, depending on the initial bulk density. Thus, deriving a general relation requires the answer to the question: by how much would the initial bulk density change for a given biochar application rate. To answer this question, the data were normalized and used to arrive at the relation:

$$\text{Bulk density} = BD_0(2 \times 10^{-5} * BC^2 - 0.0034 \times BC + 0.9972) \quad 4.1$$

where  $BD_0$  is the initial bulk density ( $Mg/m^3$ ), and  $BC$  is the biochar application rates (ton/ha). With this relation, the bulk density for any biochar application rate can be determined.

4.1.2 Soil moisture constants

The application of biochar affected the soil moisture constants, namely the saturated water content, which was related to the bulk density and hence porosity, and the field capacity of the soils. As shown in Table 4.1, the bulk density varied with soil compaction and biochar treatment. Biochar application generally decreased the bulk density such that even under the highest soil compaction (B0D2), application of 20 ton/ha biochar reduced the bulk density by 27% (from 1.73 to 1.27 Mg/m<sup>3</sup>).

**Table 4.1: The effect of compaction on mean pore size (r) of biochar-amended soil.**

Treatments	BD	Porosity*	$\theta_s$	$\theta_s$	$\theta_{FC}$	$\theta_{FC}$
	(Mg/m <sup>3</sup> )		g/g	cm <sup>3</sup> /cm <sup>3</sup>	g/g	cm <sup>3</sup> /cm <sup>3</sup>
B0D1	1.33	0.50	0.25	0.33	0.19	0.25
B20D1	1.1	0.58	0.32	0.35	0.16	0.18
B0D2	1.62	0.39	0.19	0.31	0.09	0.15
B20D2	1.44	0.46	0.26	0.37	0.15	0.22
B0D3	1.73	0.35	0.17	0.29	0.03	0.05
B20D3	1.27	0.52	0.27	0.34	0.14	0.18

*Porosity estimated from:  $1 - BD/2.65$*

*$\theta_s$ ,  $\theta_{FC}$ : water content at saturation and field capacity, respectively.*

Many studies on biochar application unanimously point to the reduction of bulk density and hence increased porosity (Revell *et al.*, 2012; Githinji, 2014; Głab *et al.*, 2016; Obia *et al.*, 2016; Y. Zhang *et al.*, 2021), and this can be attributed to the very low density of biochar, often reported as 0.37 Mg/m<sup>3</sup> (Walters and White, 2018).

As indicated in Table 4.1, the porosity of all the biochar applied treatments increased in consonance with the decline in bulk density. The increased porosity is to be expected (Ayodele *et al.*, 2009; Sekar

2014). The observed saturated water contents differed somewhat from what was estimated for the porosity. The values ranged from  $0.29 \text{ cm}^3/\text{cm}^3$  for the highest compacted treatments (B0D3) to  $0.35 \text{ cm}^3/\text{cm}^3$  for the least compacted treatments (B02D1).

Soil compaction also affected the field capacity of the soils, with values ranging from  $0.05 \text{ cm}^3/\text{cm}^3$  for treatment B0D3 to  $0.25 \text{ cm}^3/\text{cm}^3$  for treatment B0D1. However, the effect of biochar application on the field capacity ( $\theta_{FC}$ ) was not clear-cut. The application of biochar may increase the total porosity, especially the macro pores which would lead to high water content at saturation. However, these macro pores would drain rapidly and hence may not contribute to soil water storage. The field capacity of water may however be determined more by meso and micro pores. The observations in this study showed that the lowest field capacity was for B0D3 and the highest was for B0D1.

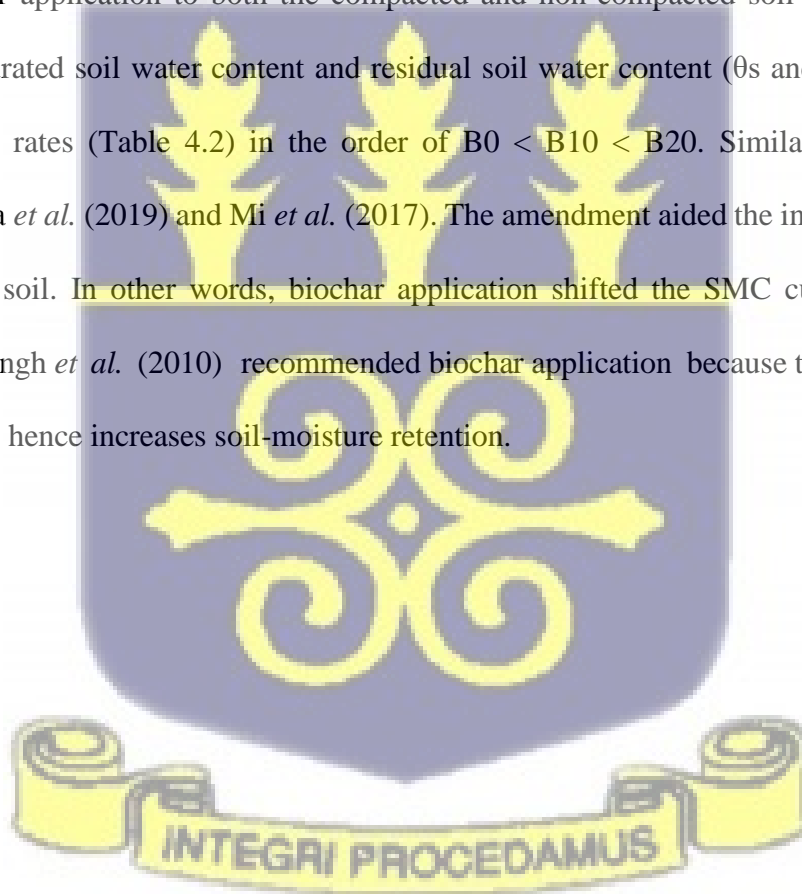
#### 4.1.3 Soil moisture characteristics (SMC)

Both soil compaction and biochar application affected the moisture characteristics curve, which reflects the relationship between soil water content and the soil water potential. Two main effects were evident. First, as shown in Fig. 4.2, the impact of soil compaction alone (B0) was to reduce the  $\theta_s$  values from  $0.25 \text{ g/g}$  for B0D1 (non-compacted soil), to  $0.20 \text{ g/g}$  for the medium compacted soil (B0D2) and further to  $0.17 \text{ g/g}$  for the highly compacted soil (B0D3). Second, the effect of biochar application shifted the entire SMC curves to the right, indicating increased water content for the same tension. The observations in this study conform to those by Walters and White (2018) who observed that biochar application to soils shifted the water retention curve movement towards the higher tension heads. Similar observations were also reported by Mollinedo *et al.* (2015). For the field bulk density soil, the application of  $20 \text{ ton/ha}$  biochar increased the  $\theta_s$  to  $0.32 \text{ g/g}$  while for the compacted soils, the  $\theta_s$  increased to about  $0.26 \text{ g/g}$ .

Several studies have investigated the effect of biochar application on moisture characteristics. The

observations generally point to the increase in the saturated moisture content (Abukari, 2019), though others have also shown that the impact depends on the size of biochar applied (Zhang *et al.*, 2021). Powdered biochar applied to coarse-textured soils would fill in the macro pores and may decrease soil moisture at saturation more than large biochar particles (Githinji, 2014; Blanco-canqui, 2017). On the contrary, coarse biochar applied to fine-textured soils (e.g., clay) would increase the micro porosity and hence the  $\theta_s$ . For the sandy clay loam soil used in this study, however, there was a clear increase in the  $\theta_s$ . This is because coarse biochar applied to the fine-textured soil opens up the macro pores and increased the saturated flow within the soil medium.

In general, biochar application to both the compacted and non-compacted soil improved soil water retention. The saturated soil water content and residual soil water content ( $\theta_s$  and  $\theta_r$ ) increased with increasing biochar rates (Table 4.2) in the order of  $B_0 < B_{10} < B_{20}$ . Similar observations were reported by Abraha *et al.* (2019) and Mi *et al.* (2017). The amendment aided the increase in mesopores of the compacted soil. In other words, biochar application shifted the SMC curves toward higher pressure heads. Singh *et al.* (2010) recommended biochar application because the practice enhanced the porosity of soil hence increases soil-moisture retention.



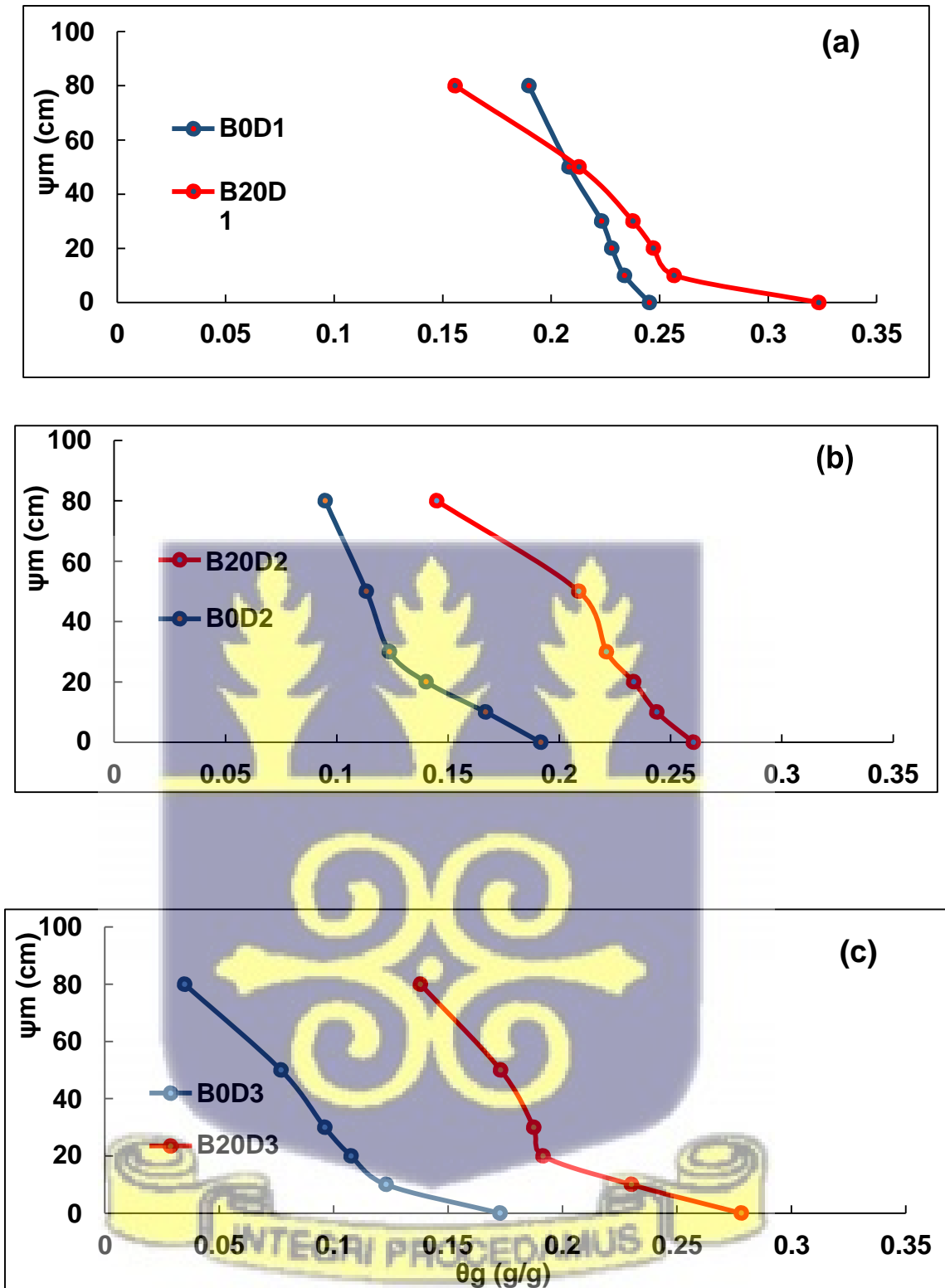
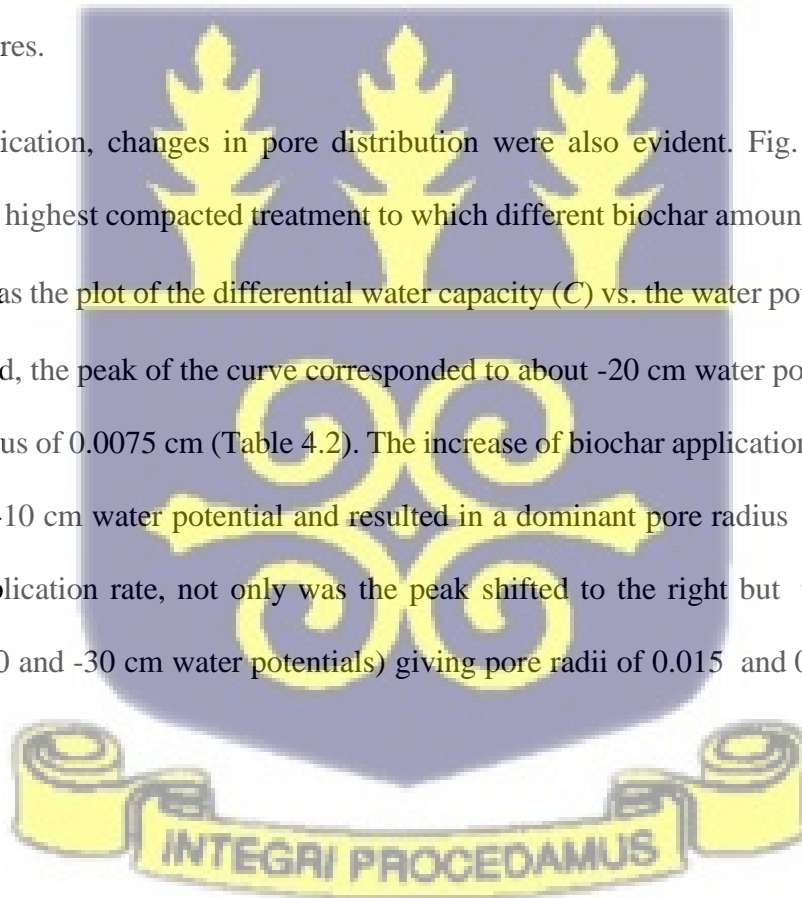


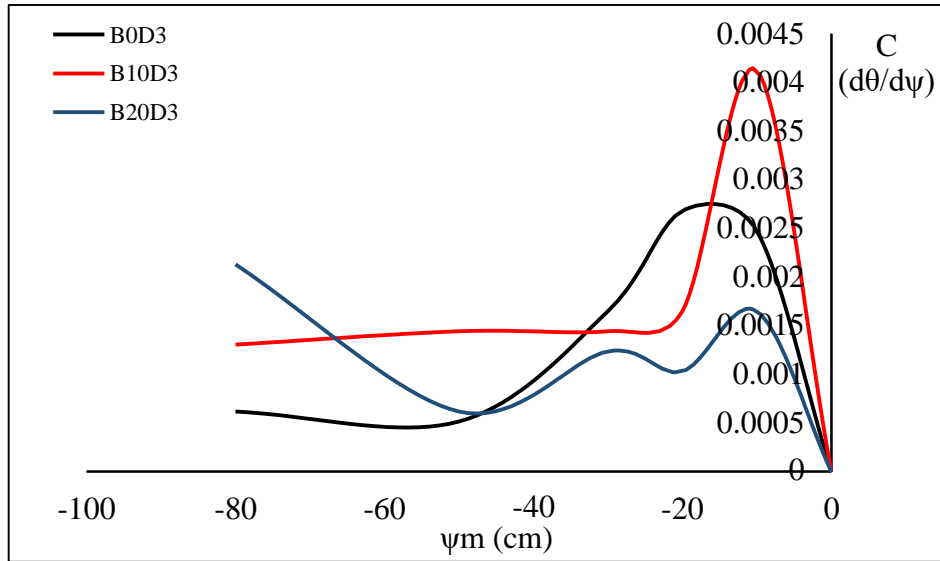
Fig 4.2: Soil water retention curve for biochar-amended compacted soils (a) at field bulk density (D1); (b) at medium bulk density (D2); and (c) at high bulk density (D3)

#### 4.1.4 Dominant pore radius

The changing shape of the *SMC* induced by soil compaction and biochar application indicate the possible changes in soil pore distribution. Assouline (1997) observed that soil compaction had an effect on the soil pore radius and greatly affects the microstructure of the soil. It is expected that soil compaction would not only narrow the range of pore sizes but generally increase meso and micro pores (Seixas and Tim, 1997). Abraha *et al.* (2019) reported that increasing bulk density led to increased micro-pores and few macro-pores. On the contrary, loosening the soil would increase the range of pores and also shift towards macro porosity (Wong *et al.*, 2018). He observed that after biochar application on a kaolin compacted clay soil, the dominant pore diameter shifted from micro pores to macro pores.

With biochar application, changes in pore distribution were also evident. Fig. 4.3 shows the pore distribution for the highest compacted treatment to which different biochar amounts were applied. The curve was derived as the plot of the differential water capacity (*C*) vs. the water potential ( $\psi$ ). When no biochar was applied, the peak of the curve corresponded to about -20 cm water potential and gives the dominant pore radius of 0.0075 cm (Table 4.2). The increase of biochar application to 10 ton/ha shifted the peak to about -10 cm water potential and resulted in a dominant pore radius of 0.015 cm. At 20 ton/ha biochar application rate, not only was the peak shifted to the right but there appeared to be multiple peaks (-10 and -30 cm water potentials) giving pore radii of 0.015 and 0.005 cm (Table 4.2).





**Fig 4.3: Pore size distribution of biochar-amended compacted soils.**

The general inference drawn is that the effect of bulk density on the dominant pore radius was in the order of B0D3 < B0D2 < B0D1, and for biochar modification in the order B20 > B10 > B0.

**Table 4.2: The effect of compaction and biochar application on the mean pore radius (r).**

Treatments	BD (Mg/m <sup>3</sup> )	BC (ton/ha)	r (cm)
B0D1	1.33	0	0.0136
B20D1	1.1	20	0.015
B0D2	1.62	0	0.0136
B20D2	1.44	20	0.015
B0D3	1.73	0	0.0075
B20D3	1.27	20	0.015

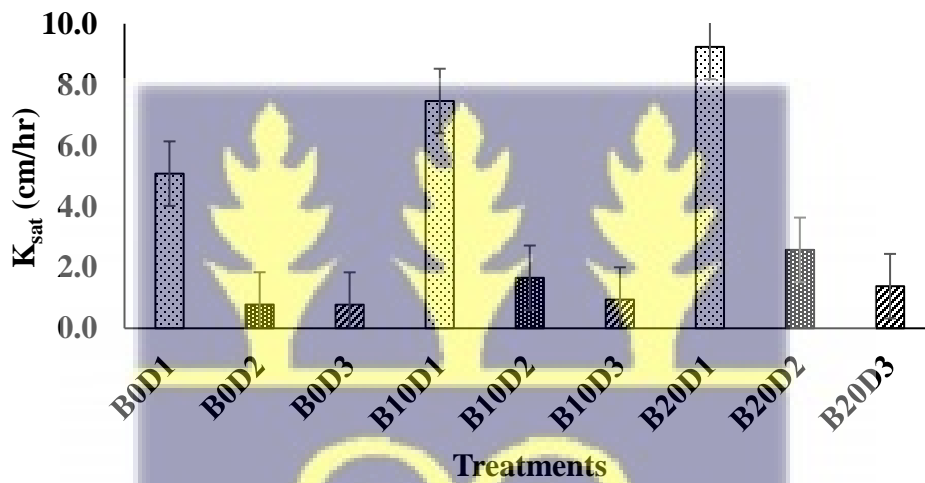
## 4.2 Effect of biochar application on the hydraulic properties of compacted soils

### 4.2.1 Saturated hydraulic conductivity ( $K_{sat}$ )

The changing pore distribution and sizes resulting from soil compaction and biochar application would not only affect the water retention but also the conductance and transport properties. Poiseuille's law states that the flow of water is directly proportional to the fourth power of the effective pore radius. Hence, it would be expected that as the pore sizes increased in biochar applied treatments, the flow, especially under saturated conditions, would also increase. As shown in Fig. 4.4, biochar, bulk density and their interaction showed a significant effect on  $K_{sat}$ . Soil compaction had a greater impact on the  $K_{sat}$ . An increase in the level of compaction decreased significantly the  $K_{sat}$ , with the highest bulk density (B0D3) having the lowest  $K_{sat}$  (= 0.777 cm/hr), though no significant differences were observed between the medium and high bulk density at all biochar rates. The reduced  $K_{sat}$  observed at both D2 and D3 can be attributed to the compaction effect. Increased compaction leads to a collapse of soil aggregates and structure which in turn reduces the transmission of water within the soil medium. The observation in this study aligned with the result by Ocloo *et al.* (2014) who reported the reduction of saturated hydraulic conductivity with increasing bulk density. In several other studies (Reichert *et al.*, 2009; Matthews *et al.*, 2010), it was reported that the increase in the degree of compactness resulted in a significant decrease in soil macro-porosity and hydraulic conductivity.

Biochar application also significantly impacted the soil hydraulic conductivity. The highest saturated hydraulic conductivity was observed in the normal bulk density under 20 tons/ha of rice husk biochar (B20D1) to be 9.24 cm/hr. This explained the modification of biochar on the bulk density. There is a relationship between the  $K_{sat}$  and biochar application rates. From our result, increasing biochar application rates caused an increase in the  $K_{sat}$  of the soil. Likewise, the same trend was observed in the D2 and D3. Despite the compaction, biochar application at 20 ton/ha

increased the  $K_{sat}$  of D2 from 0.781 to 2.575 cm/hr and D3 from 0.777 to 1.382 cm/hr. The general order was  $B_0 < B_{10} < B_{20}$ . As noted above, biochar application changed the distribution of the pores towards macro-porosity. The results of this study coincided with those of Nelissen *et al.* (2015), who found that biochar application at the rate of 20 ton/ha increased the soil water contents, the total porosity and  $K_{sat}$  in sandy loam soil. Oguntunde *et al.* (2008) also reported increasing saturated hydraulic conductivity with biochar application. Therefore, it can be concluded that biochar application can be a practice to offset soil compaction effects on soil water transport.



**Fig 4.4: Effect of soil compaction on  $K_{sat}$  of biochar-amended soil.**

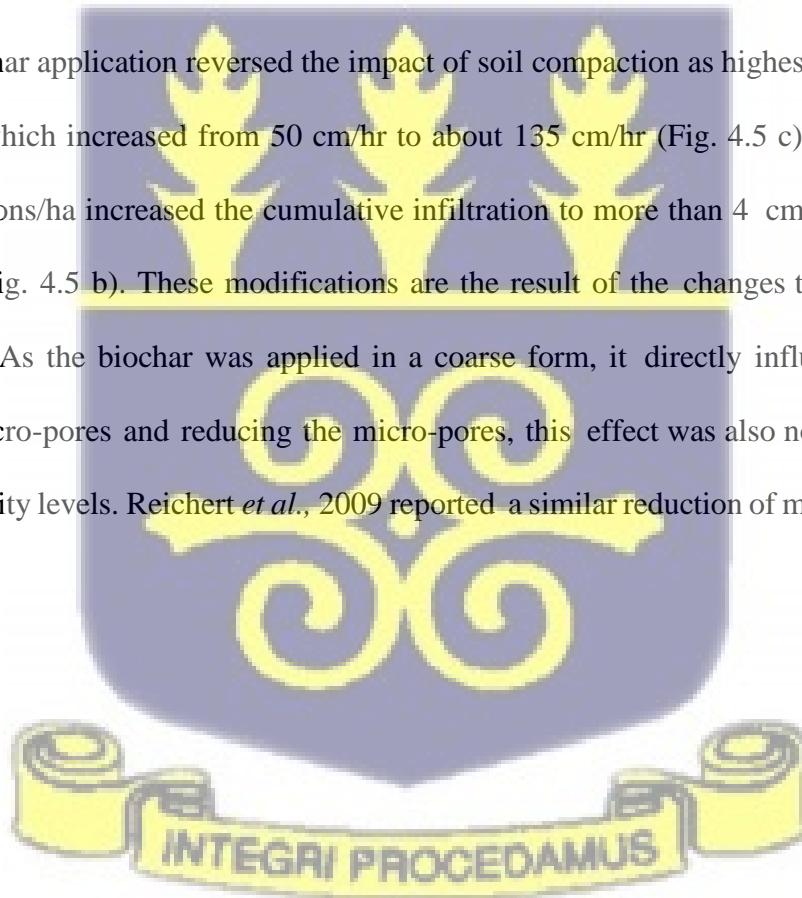
#### 4.2.2 Infiltration rates and depth

Apart from the general transport or flow or movement of water through the soils, which was described by  $K_{sat}$ , the entry of water through its upper surface into the soils is of major consequence as it partitions rainfall into runoff (loss) and soil intake. The intake is described as infiltration. Both the runoff and water intake are affected by soil conditions, which in this study are the bulk density and biochar application.

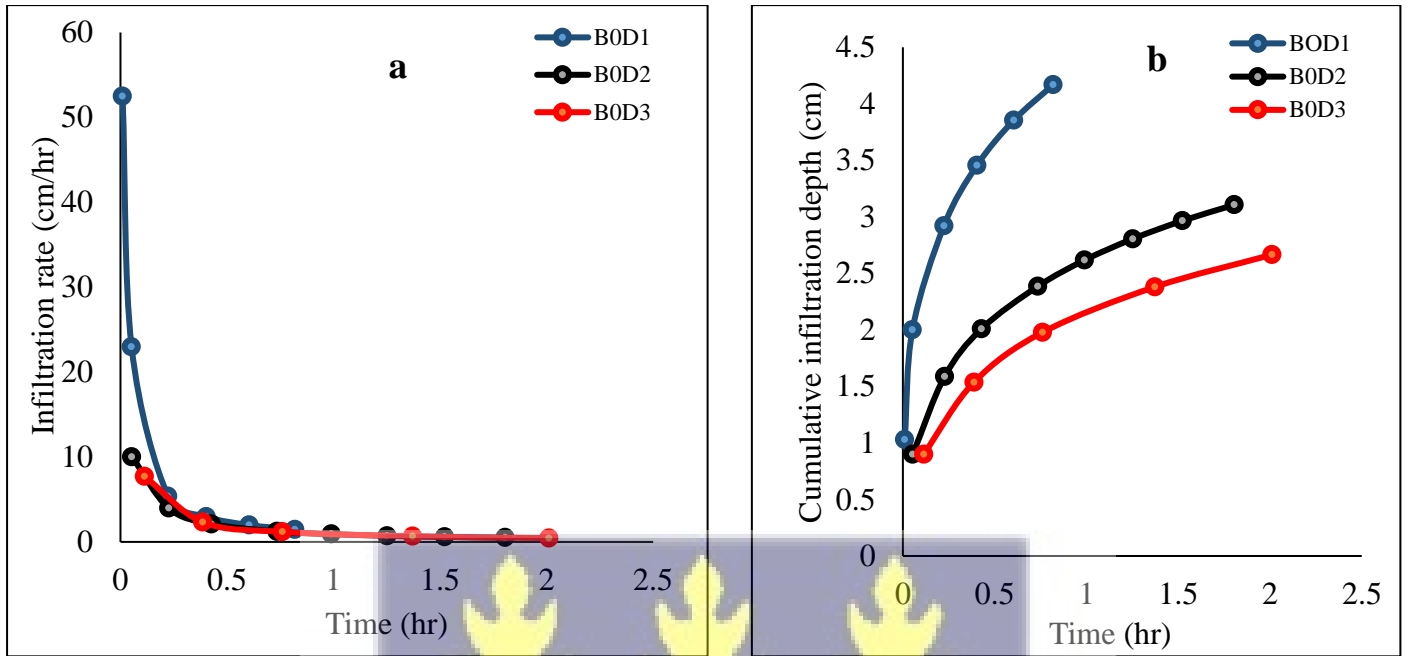
The bulk density effect on infiltration is shown in Fig. 4.5 (a, b). The field bulk density (D1)

showed the highest rate (Fig. 4.5a) of about 50 cm/h and this dropped sharply to 10 and 7 cm/hr, respectively for D2 and D3. Similarly, the cumulative infiltration was significantly affected by soil bulk density. Within 1 hr, a total of 4.2 cm of water infiltrated the soil with field bulk density (D1), while it took almost 2 hr to infiltrate 3.0 and 2.7 cm of water into D2 and D3 compacted treatments (Fig. 4.5b). Soil compaction, which has been shown to decrease pore sizes, would also lead to lower water flow because flow rates in small pores are very low. These results also conformed to those of other researchers who showed that soil compaction caused a low rate of infiltration (Pugh, 2020). High levels of compaction had a negative impact on the physical properties of soil (Cambi *et al.*, 2018) including infiltration.

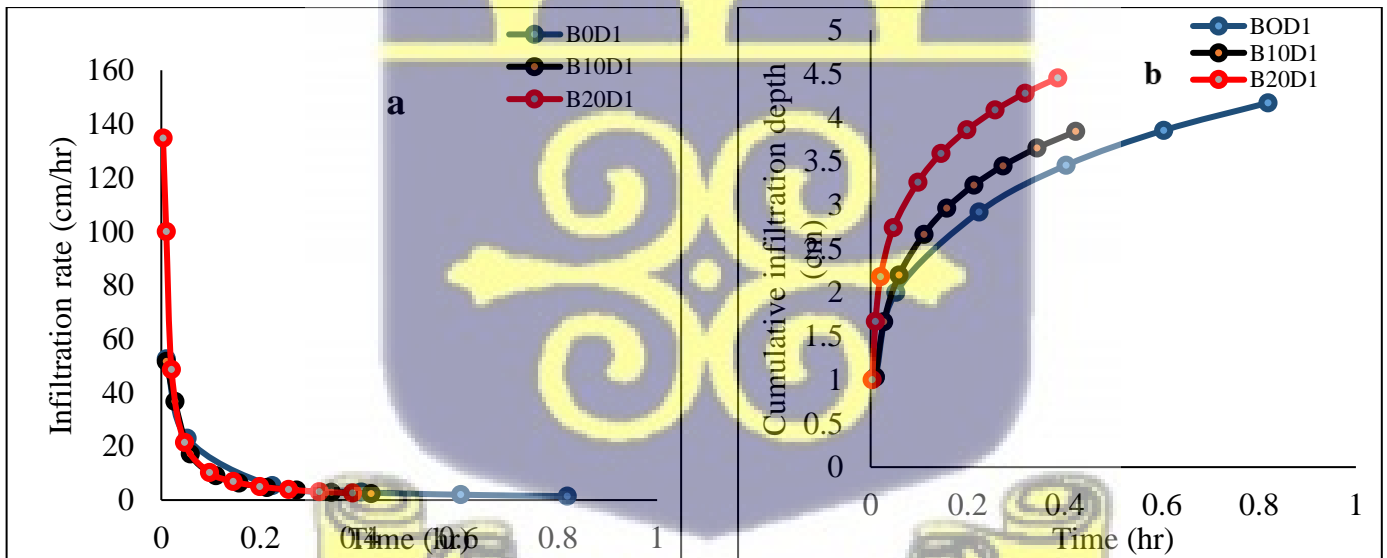
20 tons/ha of biochar application reversed the impact of soil compaction as highest infiltration rate was recorded for D1 which increased from 50 cm/hr to about 135 cm/hr (Fig. 4.5 c). Similarly, biochar application at 10 tons/ha increased the cumulative infiltration to more than 4 cm within half an hour (about 30 min) (Fig. 4.5 b). These modifications are the result of the changes the biochar has made to the pore sizes. As the biochar was applied in a coarse form, it directly influenced the pores by increasing the macro-pores and reducing the micro-pores, this effect was also noticed in the medium and high bulk density levels. Reichert *et al.*, 2009 reported a similar reduction of macro-porosity caused by compaction.



DENSITY EFFECT



BIOCHAR EFFECT



**Fig 4.5(a): Biochar effect on (a) the infiltration rate ( $i$ ) and (b) the cumulative infiltration depth ( $I$ ) of a compacted Rhodic Kandiustalf.**

4.2.3 Derivation of infiltration parameters

It is desirable to derive infiltration parameters for a given soil because this would enable the prediction of some water balance components such as the runoff. There are several infiltration models in the published literature. However, the two most popular ones are Horton’s (1948) and Philips’ (1957) models. As evident in this study, the parameters such as the infiltration rate and the cumulative infiltration were both impacted by soil bulk density and biochar application. This implies that such factors must be included in the determination of the infiltration. It is therefore the purpose of the study to present simple expressions for the determination of the infiltration parameters for the Horton’s and Philip’s models as functions of bulk density and biochar application.

Horton’s model parameters

Horton model for infiltration is given by:

$$i = i_c + (i_o - i_c) e^{-kt} \tag{4.2a}$$

and.

$$I = i_c t + \frac{(i_o - i_c)}{k} (1 - e^{-kt}) \tag{4.2b}$$

where

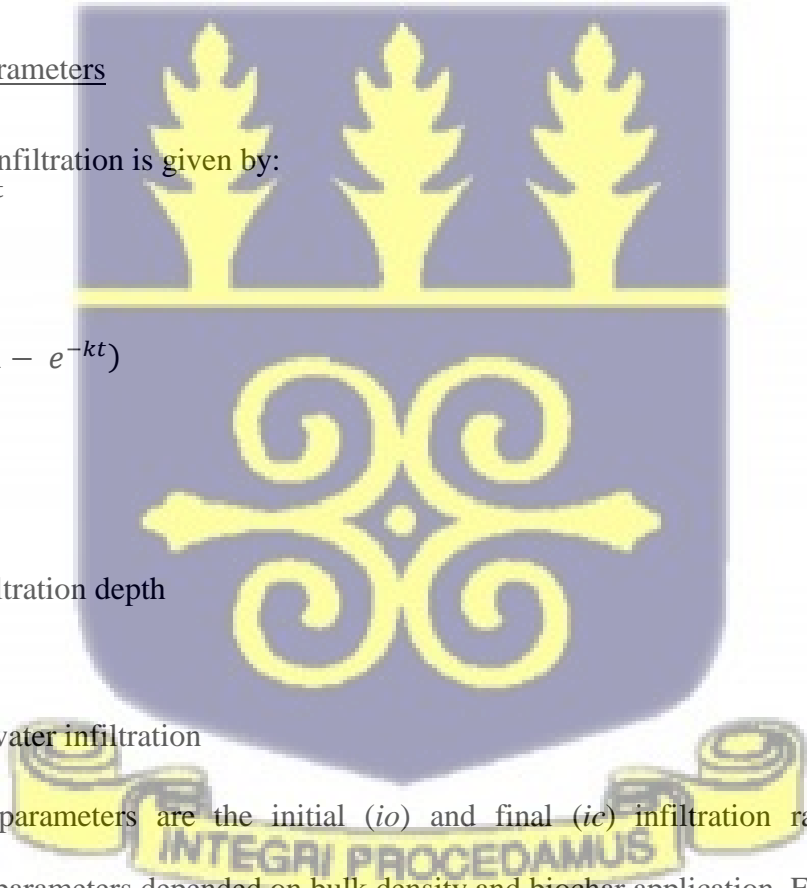
$i$  = infiltration rate

$I$  = cumulative infiltration depth

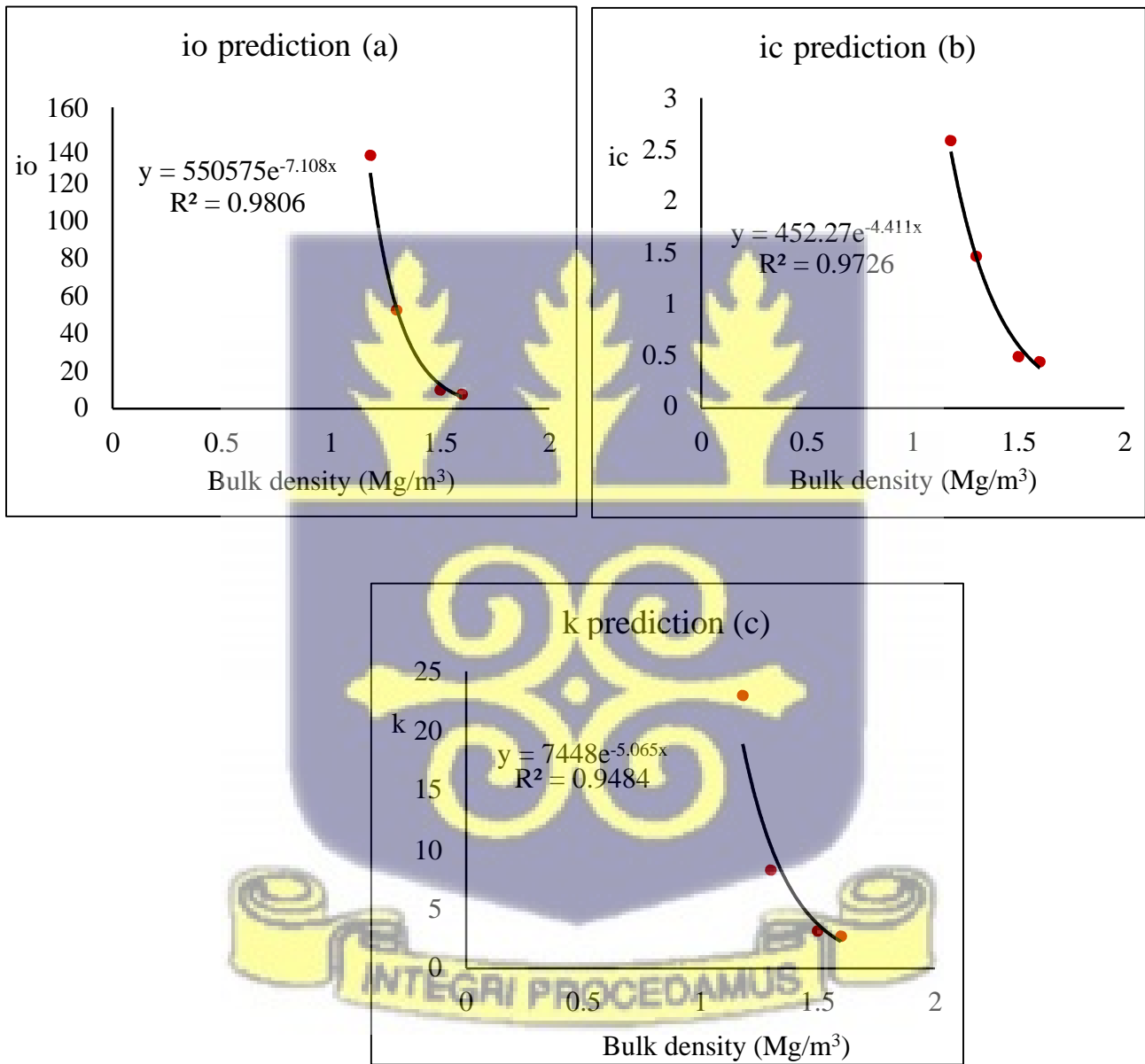
$k$  = decay constant

$t$  = time taken for water infiltration

The determining parameters are the initial ( $i_o$ ) and final ( $i_c$ ) infiltration rates and the decay constant,  $k$ . These parameters depended on bulk density and biochar application. From the trends (Fig 4.6a), it is clear from the regression equations that increasing density levels significantly ( $R^2 = 0.981, 0.973, 0.948; p < 0.01$ ) decreases the final, initial infiltration rate and decay constant respectively.



The final, initial infiltration rate and decay constant gave a higher correlation of determination of 97, 98 and 95% respectively. The initial infiltration rate and final infiltration rate changed significantly with bulk density which can also be seen in Table 4.4. Increasing density reduced the value of all the parameters. The highest compaction levels (D3) reduced significantly from the initial infiltration rate of 52.5 to 1.47 and the final infiltration rate from 7.7 to 0.45 (Table 4.4).



**Fig 4.6(a): The effect of bulk density on Horton parameters (a) initial infiltration rate (b) final infiltration rate, and (c) decay constant (k)**

Curve fitting the experimental data obtained for  $i_0$ ,  $i_c$  and  $k$  for treatments B0D1, B20D1, B0D2, and B0D3 (Table 4.4) resulted in the derivation of the following equations:

$$i_c = 550575 \times \exp^{-7.108*BD} \quad 4.3$$

$$i_0 = 452.27 \times \exp^{-4.411*BD} \quad 4.4$$

$$k = 7448 \times \exp^{-5.065*BD} \quad 4.5$$

Thus, for the sandy loam soil used in this study, the effect of increasing bulk density on the Horton infiltration parameters can be described.

Given that the major effect of biochar application was to change the bulk density. The relationship between bulk density and biochar application, which was previously derived (equation 4.1) and discussed in section 4.1.1 of this chapter was invoked. Thus, for any biochar application rate, the corresponding bulk density was determined and used in the determination of  $i_0$ ,  $i_c$  and  $k$ .



**Table 4.3: Effects of bulk density on infiltration parameters.**

Treatments	io	ic	k	S (cm/hr <sup>-0.5</sup> )	K <sub>sat</sub> (cm/hr)
	Horton's model			Philip's model	
<b>BOD1</b>	52.5	1.47	8.29	6.00	5.078
<b>BOD2</b>	10	0.5	3.15	2.85	0.781
<b>BOD3</b>	7.7	0.45	2.73	2.06	0.777
<b>B10D1</b>	51.5	2.37	13.91	8.18	7.549
<b>B10D2</b>	56.5	0.5	10.25	6.73	1.658
<b>B10D3</b>	58.2	1.43	13.1	6.18	0.943
<b>B20D1</b>	134.7	2.59	22.98	12.06	9.24
<b>B20D2</b>	98.28	1.92	16.64	7.78	2.575
<b>B20D3</b>	55.95	1.45	14.56	4.82	1.382
<b>P value (0.05)</b>	0.00215	0.000761	0.000610	0.000226	0.8923
<b>CV (%)</b>					15.5

Wong *et al.*, (2018) studied the effect of biochar on the K<sub>sat</sub> of a compacted Kaolin clay loam soil. At the end of his experiment, he found out that 5 and 20% dry weight biochar increased the K<sub>sat</sub> while a less significant increase was reported for 10% biochar application. The literature on the effect of biochar on some hydraulic parameters such as the saturated hydraulic conductivity is somewhat inconclusive. In some studies, decreased K<sub>sat</sub> was reported because the biochar in-filled soil pores and clogged them (Yang *et al.*, 2016; Ren *et al.*, 2018; Rabbi *et al.*, 2021). This effect would depend on biochar fraction size and soil type. Presumably fine powdered biochar applied to coarse-textured soils

could lead to  $K_{sat}$  reduction. With regard to this, the review made us understand the relationship between different soil textures and biochar sizes on hydraulic parameters, particularly the  $K_{sat}$ . Biochar application effect on hydrological properties was examined by Głąb *et al.*, (2016) using sandy soil, and stated its effect was not limited to biochar rates only but also the biochar's size. He concluded based on his result that a smaller fraction of biochar decreases the diameter of the pores volume below  $0.5 \mu m$ . The number of macropores in sandy soil is reduced when amended with coarse biochar thereby reducing the  $K_{sat}$  (Dokoohaki *et al.*, 2017). Ibrahim *et al.* (2013) also noted the decrease in the  $K_{sat}$  of sandy loam soil amended with *Conocarpus* biochar. On the other hand, when fluffy coarse biochar is added to soils of fine texture, the overall bulk density would decrease, increasing porosity and  $K_{sat}$ . Thus, some studies reported increased  $K_{sat}$  with decreasing bulk density (Yazdanpanah *et al.*, 2016). The results in this study showed that for the Toje soil, biochar application increased the  $K_{sat}$  (Table 4.4).

#### Philip's model parameters

The infiltration model by Philip (1957) can be stated as:

$$i = 0.5 S t^{-0.5} + K \quad 4.6$$

And.

$$I = S\sqrt{t} + Kt \quad 4.7$$

where

$S$  = Sorptivity ( $cm/hr^{-0.5}$ )

$K_{sat}$  = Saturated hydraulic conductivity ( $cm/hr$ )

As can be observed in Fig. 4.7 both the sorptivity and the hydraulic conductivity depended on the bulk density. The sorptivity of the highest compaction levels (D3) was significantly low ( $2.06 cm/hr^{-0.5}$ ) compared with that of the non-compacted soil ( $0.6 cm/hr^{-0.5}$ ). Similarly, the  $K_{sat}$  for D3 was  $0.78 cm/hr$

compared with that of 5.07 for the non-compacted soil.

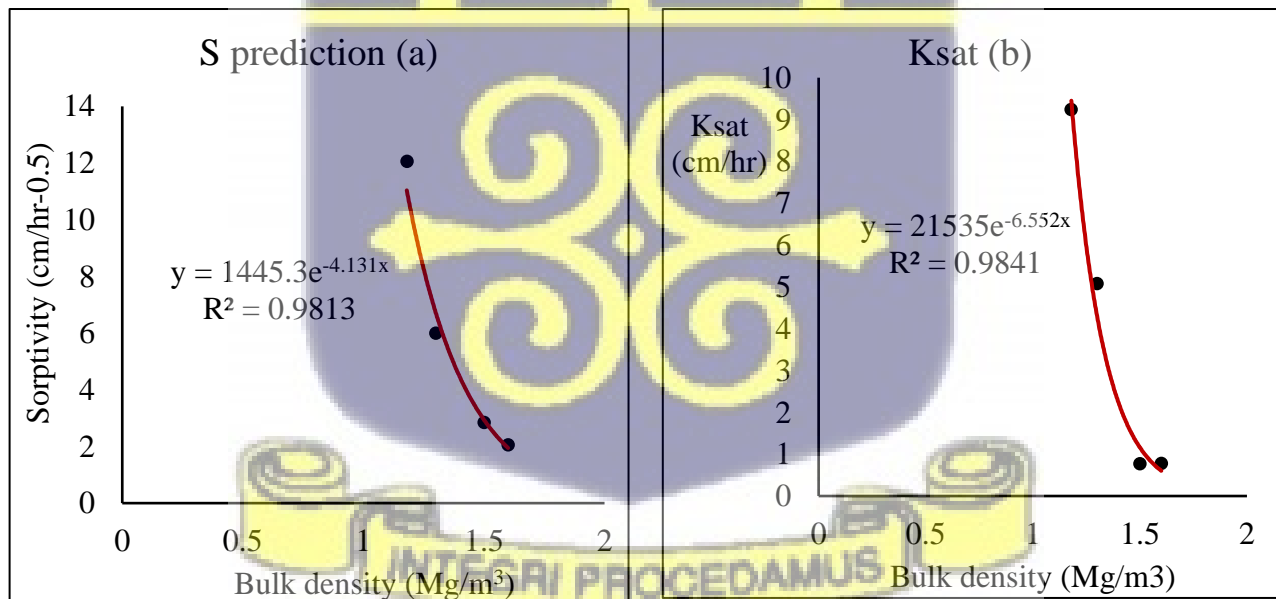
Biochar application affected the sorptivity and the  $K_{sat}$  of all density levels. Biochar ameliorated the compaction effect and increased the Philip parameters to influence the infiltration.

From the trends (Fig 4.7), it was clear from the regression equations that increasing bulk density levels significantly ( $R^2 = 0.987, 0.948; p < 0.01$ ) decreased the sorptivity and saturated hydraulic conductivity. An exponential model was used for the data set as it gave the best fit which also aligned with the result of Shafiq *et al.* (1994). Using the data points for treatments B0D1, B20D1, B0D2, and B0D3 (Table 4.4) and non-linear regression analysis, bulk density was related to the sorptivity and  $K_{sat}$  by the following equations:

$$S = 1445.3 * \exp^{-4.131*BD} \quad 4.8$$

$$K_{sat} = 21535 * \exp^{-6.552*BD} \quad 4.9$$

The values of  $S$  and  $K_{sat}$  for each treatment are summarized in Table 4.4.



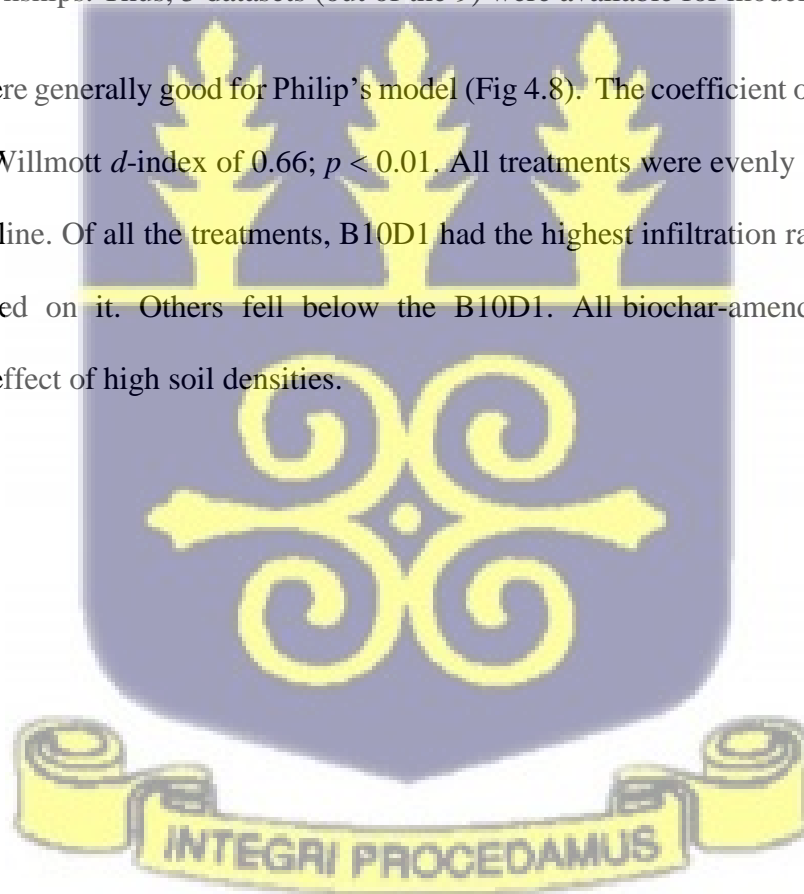
**Fig 4.7(a): Relationship between bulk density and (a) sorptivity, and (b) saturated hydraulic conductivity ( $K_{sat}$ )**

Given that the bulk density has the main impact on the soil hydraulic properties. It is necessary to explicitly describe the biochar modification on hydraulic properties, since biochar application affected the bulk density, as indicated in equation (4.1). Therefore, no separate biochar related equations were derived in this study.

#### 4.3 Prediction of the interactive effects of density and biochar on infiltration.

Having derived the relationships between the infiltration parameters and bulk density and that between bulk density and biochar application, it is now possible to predict the interactive effect of biochar and density impacts on infiltration. The test data were those which were not used in deriving the relationships. Thus, 5 datasets (out of the 9) were available for model testing.

The predictions were generally good for Philip's model (Fig 4.8). The coefficient of determination ( $R^2$ ) was 0.75 and the Willmott  $d$ -index of 0.66;  $p < 0.01$ . All treatments were evenly scattered in between the 1:1 regression line. Of all the treatments, B10D1 had the highest infiltration rate as a result of no compaction induced on it. Others fell below the B10D1. All biochar-amended treatments at 20 tons/ha offset the effect of high soil densities.



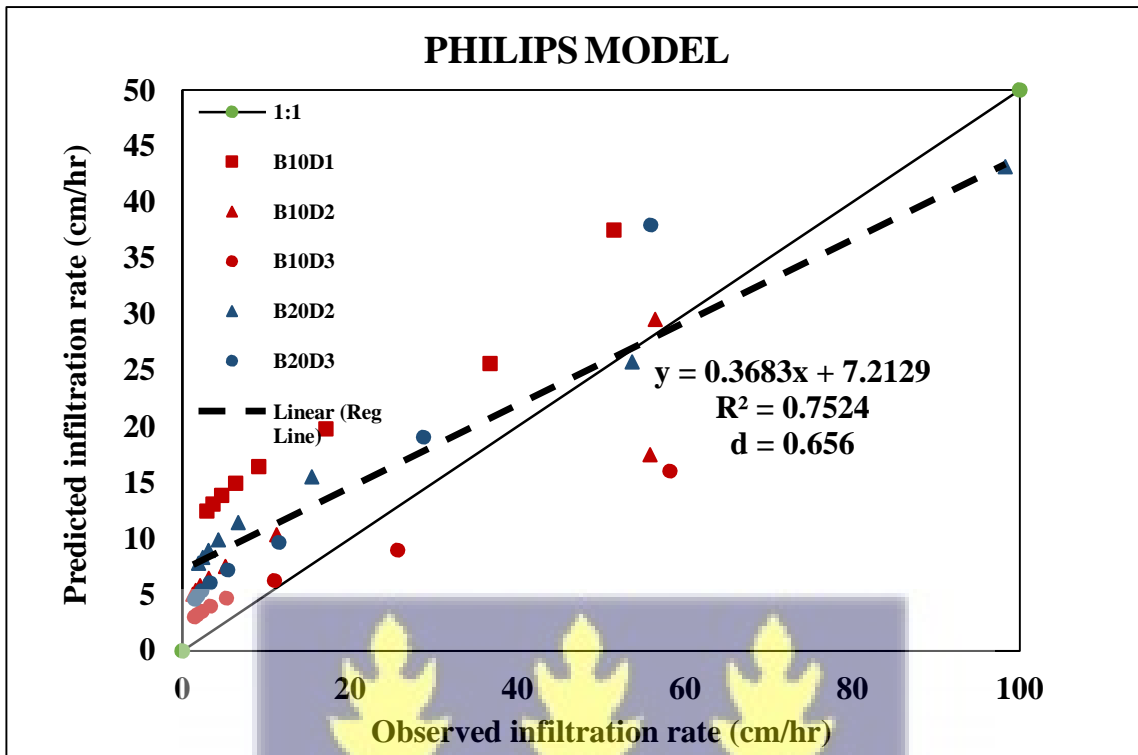
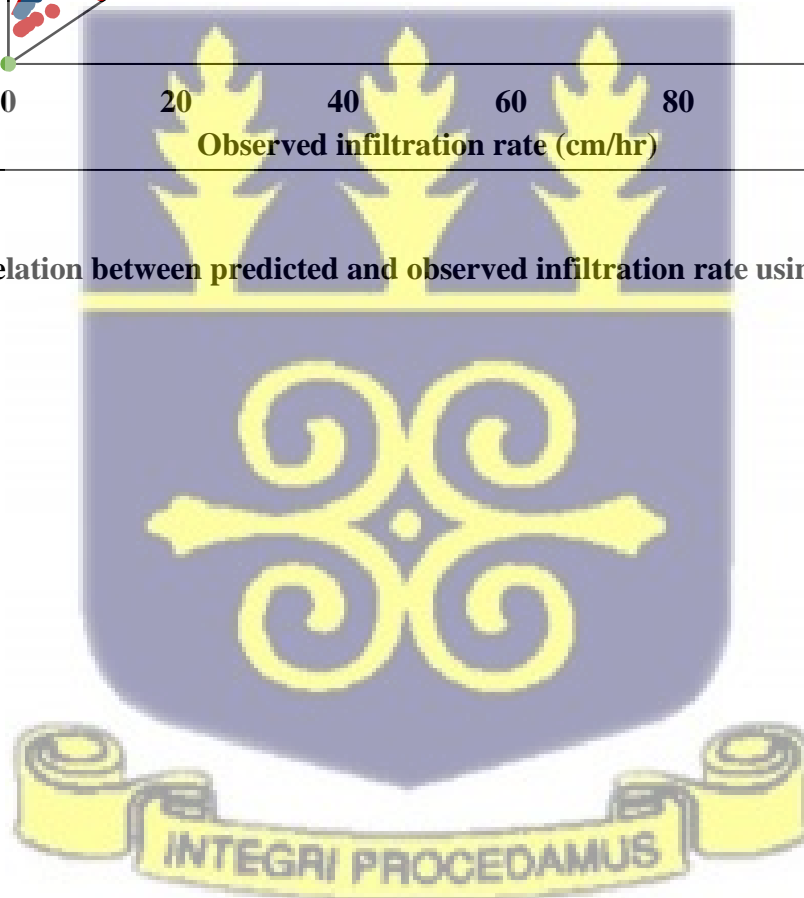


Fig 4.8: Correlation between predicted and observed infiltration rate using Philips model.



For Horton’s model, most of the data points were concentrated at lower infiltration ranges (Fig 4.9). The regression equation revealed a weaker agreement ( $R^2 = 0.46$ ;  $p < 0.01$ ) but the regression was significant. The Willmott  $d$ -index was, however, fairly high ( $d = 0.75$ ;  $p < 0.01$ ). The low value of  $R^2$  obtained for Horton’s model may be due to variability in parameters such as soil water measurement during the experiment.

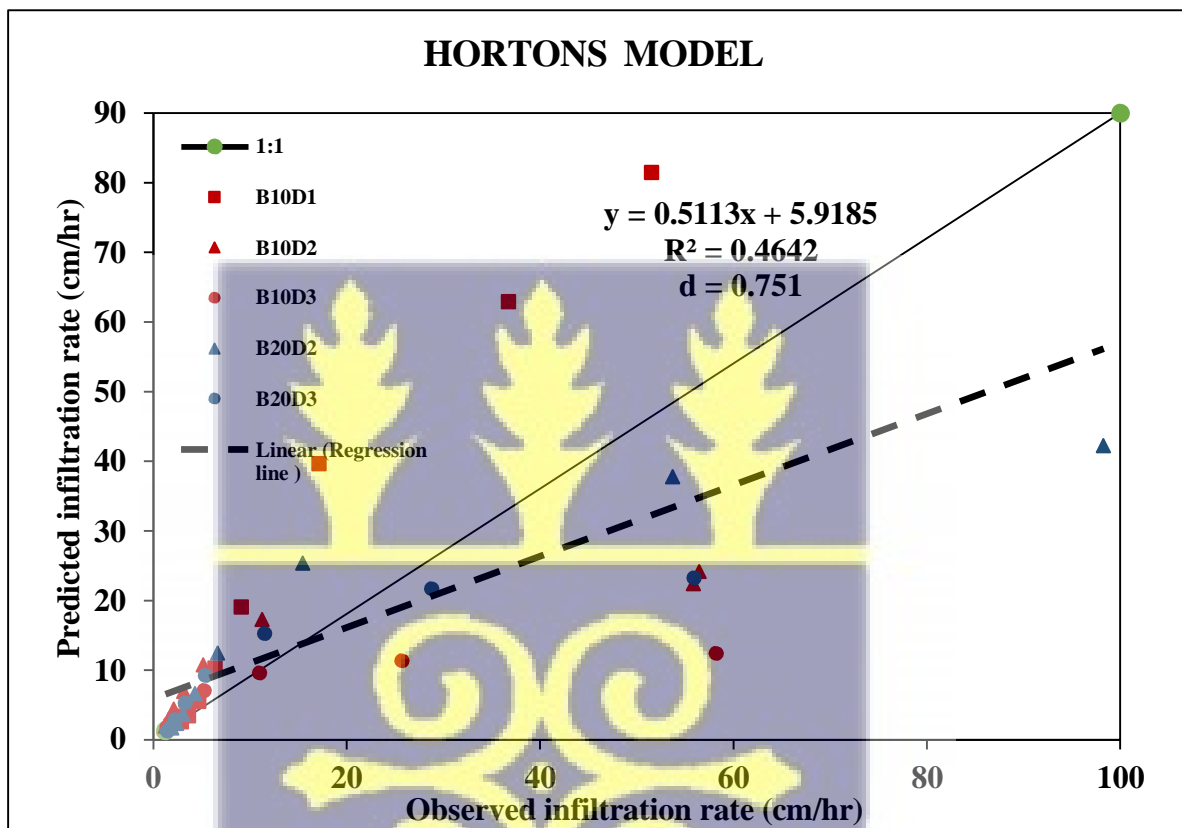


Fig 4.9: Correlation between predicted and observed infiltration rate using Horton’s model.

Therefore, it can be concluded that both the modified Philips and Horton’s models gave reasonable predictions of the interactive effects of bulk density and biochar on infiltration. These equations, simple as they are, could provide useful tools for assessing the impact of biochar application on the hydraulic properties (infiltration) and hence runoff from compacted soils.

## CHAPTER FIVE

### 5 RESULTS AND DISCUSSION: II

#### THE GROWTH, YIELD AND WATER USE EFFICIENCY OF UPLAND RICE GROWN ON BIOCHAR-AMENDED COMPACTED TOJE SOIL

##### 5.1 Characterization of soil and biochar used

The greenhouse experiment conducted to investigate the growth, yield and water use efficiency of upland rice grown on biochar-amended compacted soils was described in Chapter 3 (Section 3.2). Table 5.1 summarizes the physical and chemical properties of the soil and biochar used for the study. The soil can be classified as sandy clay loam containing sand, silt and clay composition of 51.7%, 30.8% and 17.5 %, respectively. The amount of sand in the soil is fairly high but silt and clay contents are also appreciable. The field bulk density of the soil is  $1.31 \text{ Mg/m}^3$  which is in the normal range of agricultural fields for productive farming (Chaudhari P.R. *et al.*, 2013). The pH of the soil in water was 4.36 while in KCl measured at 3.97. The soil can be described as acidic. The total carbon was 0.65%, which can be considered moderate. Other elements such as total nitrogen and sulphur were 0.0976% and 0.0005%, respectively.

The rice husk biochar had a pH of 6.8 which can be termed neutral as the charred pyrolyzed temperature is low ( $350^\circ\text{C}$ ), low total N of 0.0710%. However, organic carbon was fairly high (53%) and the CEC of  $19.77 \text{ cmolc kg}^{-1}$  Indicates a good value for nutrient availability. It has a bulk density of  $0.21 \text{ Mg/m}^3$  which is far lower than the soil bulk density. Research has proven that lower bulk density of biochar reduces the soil bulk density (Periera *et al.*, 2012; Abel *et al.*, 2013; Hardie *et al.*, 2014). The result is also similar to the result of MacCarthy *et al.* (2020) who reported the same rice husk biochar bulk density to be  $0.22 \text{ Mg/m}^3$ .

**Table 5.1: Soil and rice husk biochar physical and chemical properties.**

Soil Parameters	Soil properties
pH (H <sub>2</sub> O)	4.36
pH (KCl)	3.97
Total carbon (%)	0.65
Total nitrogen (%)	0.097
Total sulphur (%)	0.0005
Bulk density (Mg/m <sup>3</sup> )	1.31
Sand (%)	51.72
Clay (%)	30.78
Silt (%)	17.5
Textural class	Sandy Clay Loam
<b>Biochar parameters</b>	<b>Properties</b>
pH (H <sub>2</sub> O)	6.80
Total N (%)	0.071
CEC (cmolc kg <sup>-1</sup> )	19.77
Bulk density (Mg/m <sup>3</sup> )	0.21



## 5.2 Environmental conditions during the greenhouse experiments

### 5.2.1 Temperature

Temperature varied during the experimental period. The average minimum and maximum temperatures were 38.2 °C and 45.9 °C, respectively. In absolute terms, the lowest temperature recorded was 26 °C whereas the highest temperature was 50 °C (Fig. 5.1a). In general, the variability of the minimum temperature was higher than the maximum temperature and temperatures were lower at the beginning of the experiment (August) than towards the end of the experiment (October – November).

The temperature variations coincided with different phenological stages of the plant (Fig 5.1b). In general, the temperature increased from emergence to maturity except at the tillering stage where the temperature dropped from 40 to 37.6 °C before rising later up to the end of the growing cycle. The minimum average temperature was recorded at the tillering stage while the highest temperature was recorded at the dough-forming stage, the stage at which the rice grains are filled up and become hardened.



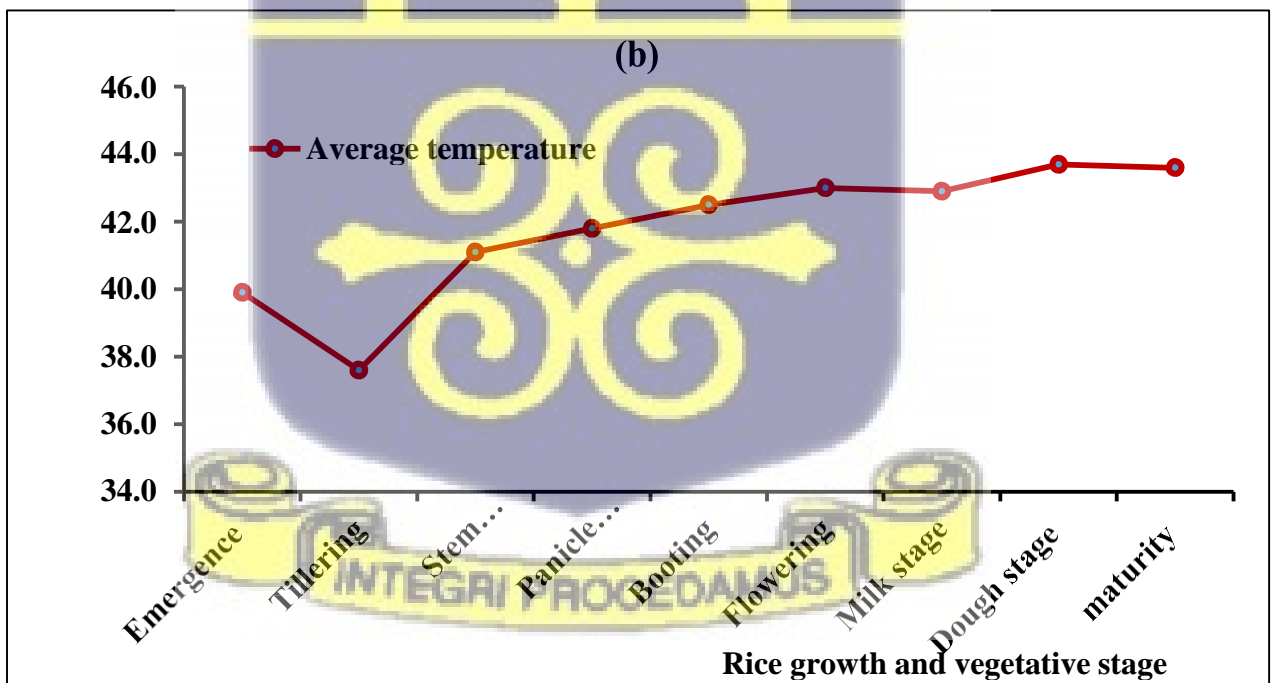
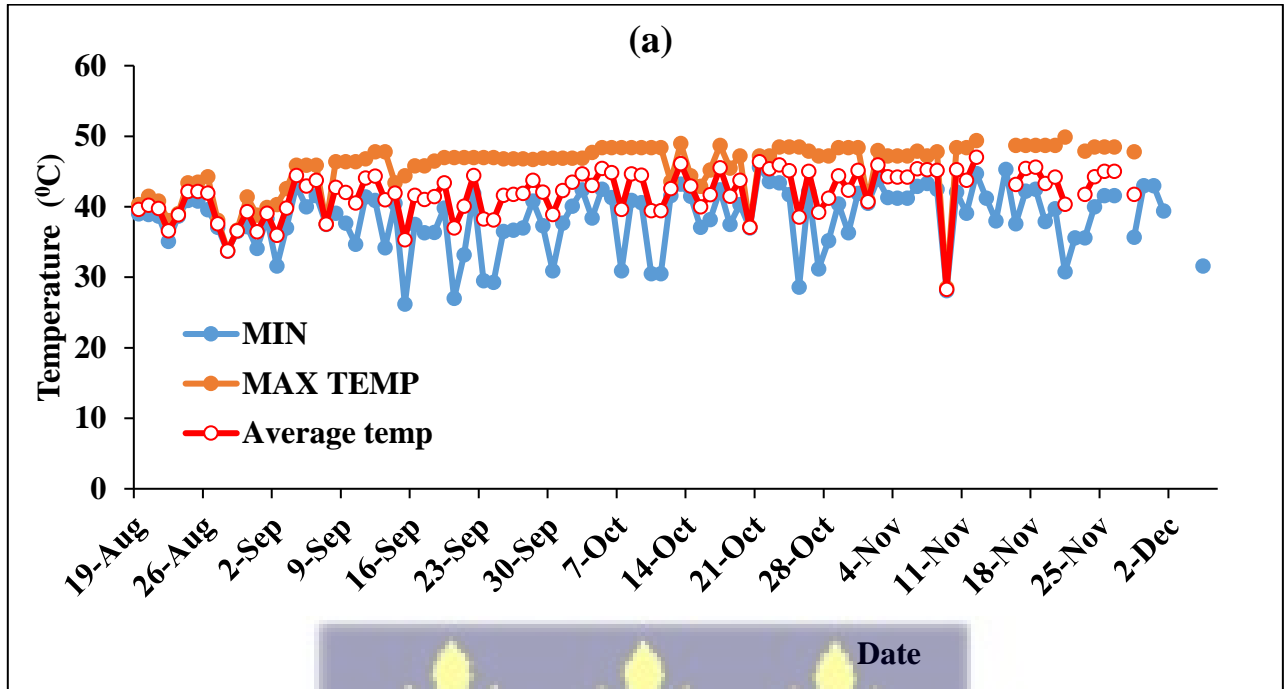
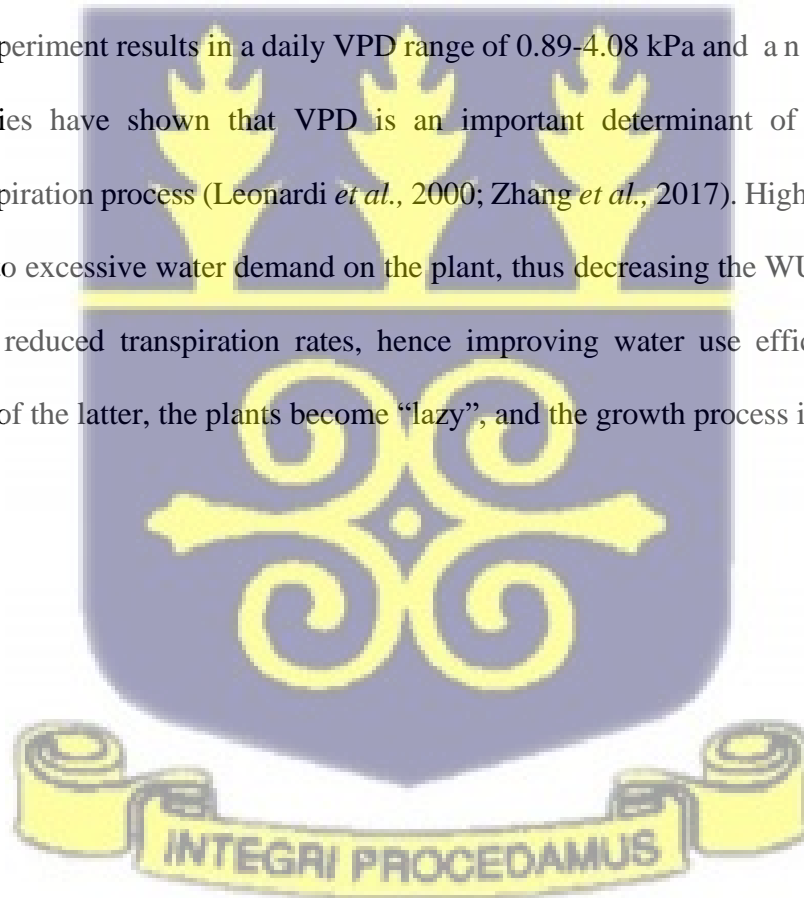
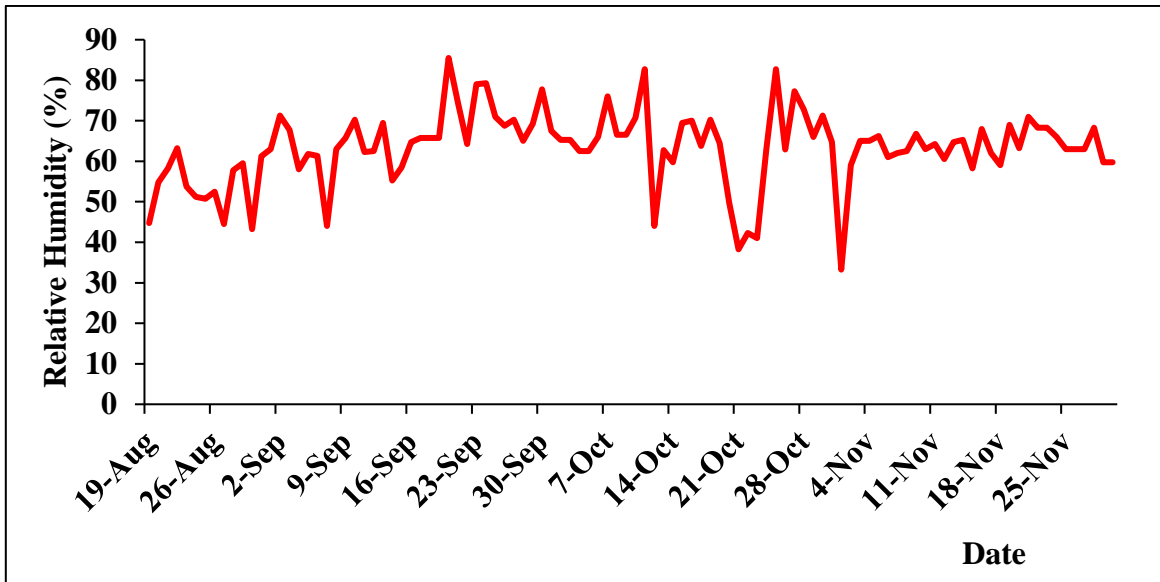


Fig 5.1(a) Daily maximum, average and minimum temperatures in the screen house during the experiment and (b) Average temperature during the development stages.

### 5.2.2 Relative humidity

As for temperature, the relative humidity also varied with time during the study. Figure 5.2 shows the average relative humidity in the screen-house reached as high as 85% during the initial vegetative stages of the plant when the average temperatures were low. Towards the end of the experiment when the average temperatures increased, the RH decreased to lower values of about 60%. The combination of temperature and humidity is the Vapour Pressure Deficit (VPD). In the study conducted by Tacarindua *et al.*, 2013 on increased temperature's effect on the growth and yield of soybean in temperate gradient chambers in Japan, they reported VPD increment with increasing temperature and low humidity which aligned with our result. Using average temperature and humidity values obtained in this experiment results in a daily VPD range of 0.89-4.08 kPa and an average VPD of 2.2 kPa. Several studies have shown that VPD is an important determinant of plant growth, as it controls the transpiration process (Leonardi *et al.*, 2000; Zhang *et al.*, 2017). High VPD values of more than 2.0 kPa lead to excessive water demand on the plant, thus decreasing the WUE whereas very low values (< 2 kPa) reduced transpiration rates, hence improving water use efficiency (Roby *et al.*, 2020). In the case of the latter, the plants become "lazy", and the growth process is halted.





**Fig 5.2: Average relative humidity in the screen-house for the duration of the study.**

It is concluded that the VPD values observed in this study of between 1.9 and 2.2 kPa did not hinder the growth of the rice plants.

### 5.2.3 Potential evapotranspiration

The daily potential evapotranspiration, as determined by changes in water level in a 250 ml (evaporimeter) placed in the screen house (Fig. 5.3) showed values between 2.05 to 6.5 mm/day with an average of 4.3 mm/day. These observations generally correspond to those measured for tropical conditions by (Qiu *et al.*, 2017) who reported maximum evapotranspiration to be 6.28 mm/day. Though the high-temperature conditions observed in the screen house would imply high evaporation, the high RH would also minimize evaporation. Thus, in an enclosure such as a screen house where wind movement is reduced, the lower potential evapotranspiration values are not out of range. The total potential evapotranspiration at the end of the experiment was 462.8 mm.

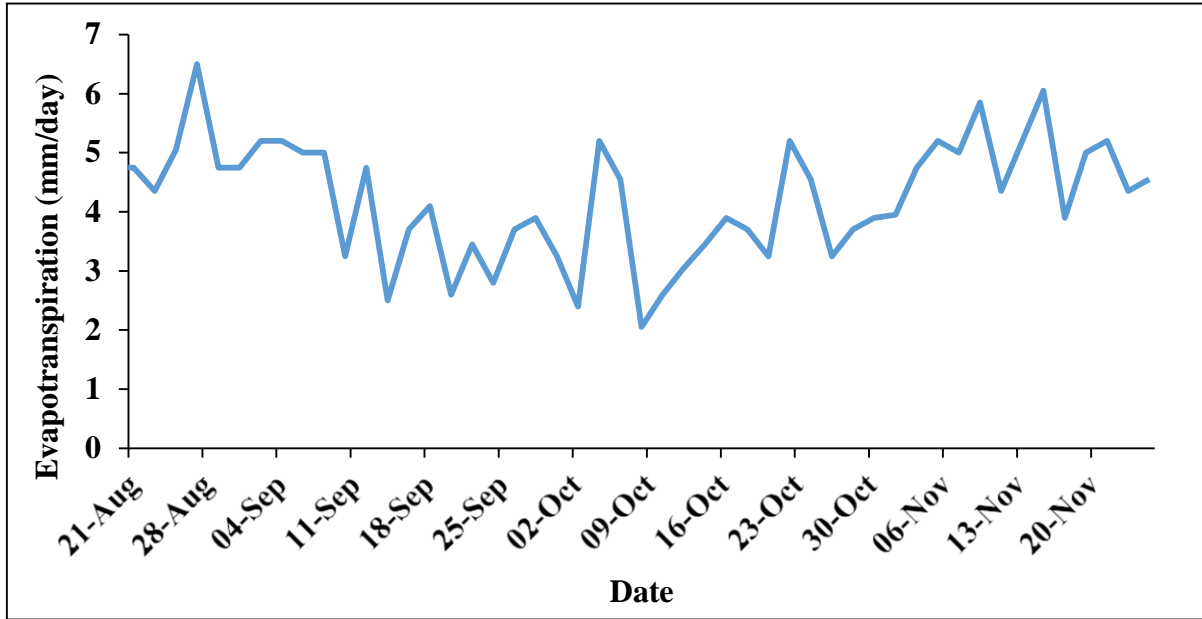


Fig 5.3: Daily evapotranspiration from a free water surface.

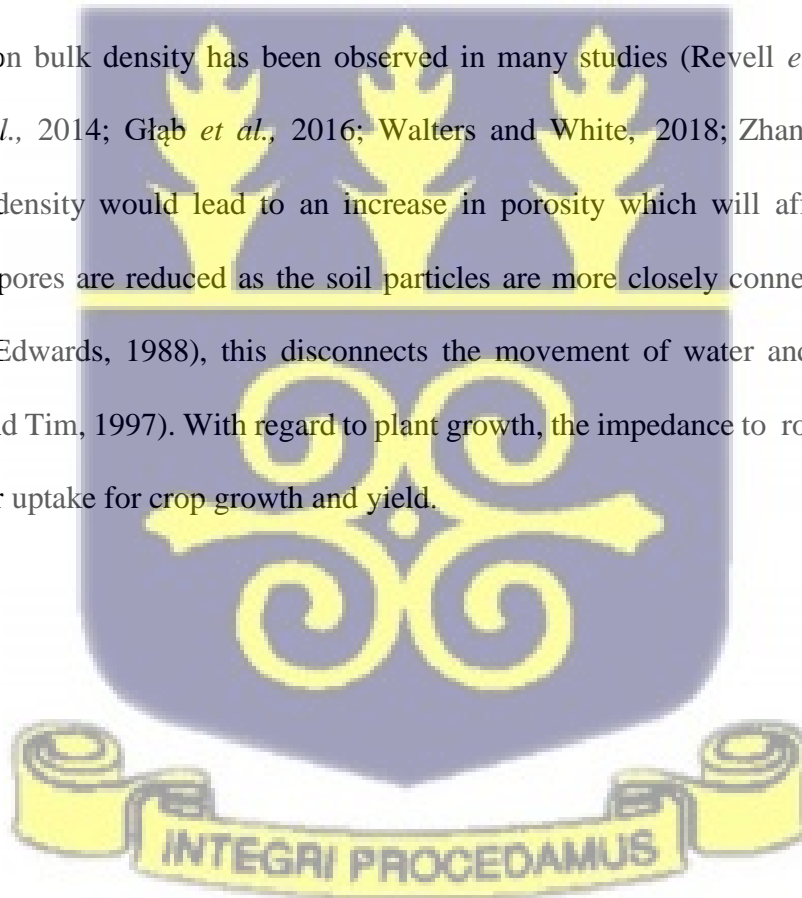
### 5.3 Soil and water conditions

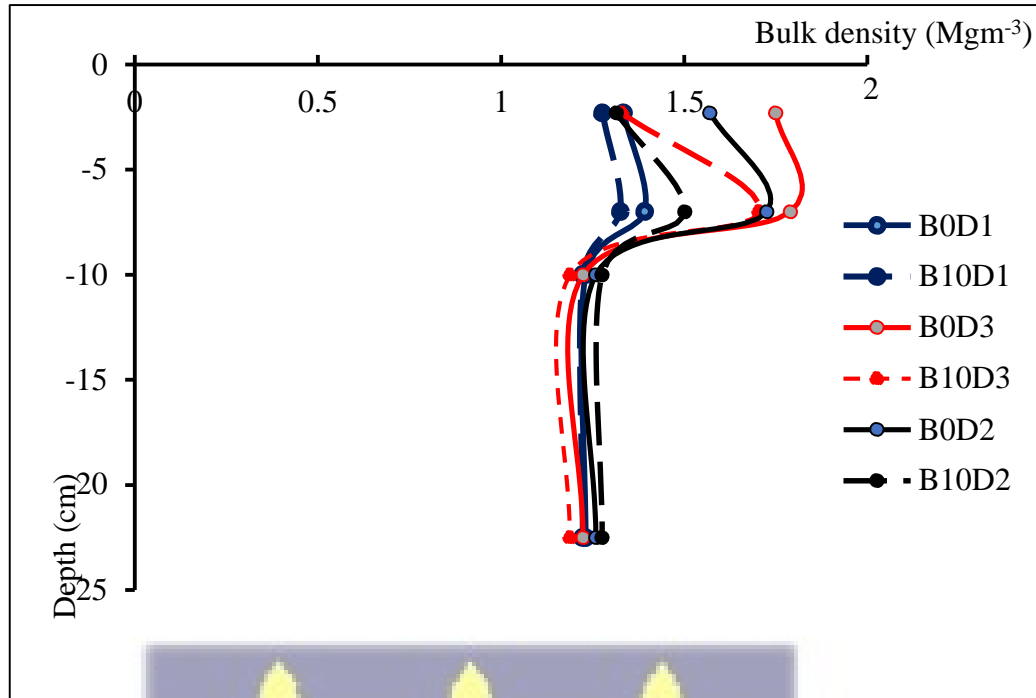
#### 5.3.1 Variations in soil bulk density with depth

The bulk density of the soil layers down the depth of the soil columns are shown in Fig. 5.4. The bulk density variations represent the various packing densities as well as the biochar application treatments. The treatment B0D1, for example, targeted the field bulk density ( $1.30 \text{ Mg/m}^3$ ) at any depth of the column with no biochar application. However, the measured values after soil packing were  $1.33 \text{ Mg/m}^3$  with some minimum variation with depth. Thus, on average, the top 10 cm of the soil had a bulk density of  $1.36 \text{ Mg/m}^3$ . The application of 10 tons/ha of biochar to the top 4.5 cm of the soil in the column (designated as B10D1), resulted in a slight reduction in the bulk density there to about  $1.28 \text{ Mg/m}^3$ . Thus, on average, the top 10 cm of the soil had a bulk density of  $1.32 \text{ Mg/m}^3$ . For D2, the resultant soil bulk density at the top was  $1.5 \text{ Mg/m}^3$ , increasing to a peak of  $1.73 \text{ Mg/m}^3$  at about 7 cm depth when no biochar was applied (i.e., B0D2), giving an average density of  $1.61 \text{ Mg/m}^3$  within the top 10 cm of the soil. The application of 10 ton/ha biochar to the top 4.5 cm of D2 (i.e., B10D2) reduced the

bulk density of the top to  $1.32 \text{ Mg/m}^3$  and at 7 cm depth to  $1.5 \text{ Mg/m}^3$  resulting in an average bulk density of  $1.41 \text{ Mg/m}^3$ . The highest bulk densities were observed for D3 treatments. Without biochar application (B0D3), the bulk density at the top was  $1.72 \text{ Mg/m}^3$ , increasing to  $1.79 \text{ Mg/m}^3$  at 7 cm depth, giving an average of  $1.76 \text{ Mg/m}^3$  within the top 10 cm of the soil. When 10 ton/ha of biochar was applied to the top 4.5 cm in B10D3, the bulk density reduced from  $1.32 \text{ Mg/m}^3$  at the top to  $1.72 \text{ Mg/m}^3$  at 7 cm depth, resulting in an average density of  $1.52 \text{ Mg/m}^3$  for the top 10 cm of the soil. Since the soil compaction was limited to the top 4.5 to 10 cm sections of all treatments, the bulk density of all the treatments below the depth of 10 cm returned to the field value of approximately  $1.33 \text{ Mg/m}^3$ .

In general, the addition of biochar reduced the bulk density at the depths to which it was applied. This effect of biochar on bulk density has been observed in many studies (Revell *et al.*, 2012; Githinji, 2014; Hardie *et al.*, 2014; Głab *et al.*, 2016; Walters and White, 2018; Zhang *et al.*, 2021). The decrease in bulk density would lead to an increase in porosity which will affect other hydraulic properties. Macro pores are reduced as the soil particles are more closely connected, causing lower air permeability (Edwards, 1988), this disconnects the movement of water and nutrient to the root of crops (Seixas and Tim, 1997). With regard to plant growth, the impedance to root penetration would likely reduce water uptake for crop growth and yield.



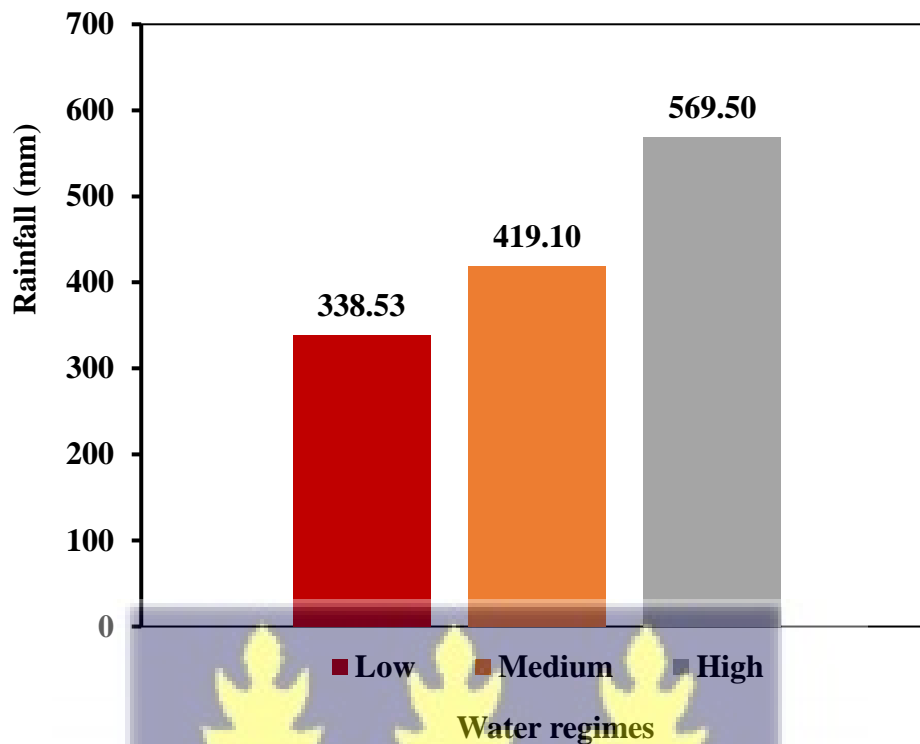


**Fig. 5.4: Variation of soil bulk density with depth.**  
 (Note: biochar applied to topsoil only).

### 5.3.2 Water regimes and water balance components

Soil water regimes of the experiment followed closely the application rates. As shown in Fig. 5.5, the total water applied under three (3) regimes varied significantly. The lowest application W1 of 338.5 mm was 59% of the highest (W3 = 569 mm) and the medium regime W2 of 419 mm was about 74% of W3. These water regimes affected the components of the water balance differently.





**Fig 5.5: The three water regimes used for irrigation throughout the rice growth experiment**

Table 5.2 presents the interactive effect of water regimes, soil bulk density levels and rice husk biochar on water balance components of the upland rice. When no biochar was applied, runoff and drainage were observed mainly for the higher water regimes (W2 and W3), especially under D2 and D3. Drainage was however more pronounced under D1. About 23% of total water applied under B0W3D3 was lost as seasonal runoff + drainage compared to 14% under B0D1W3. The high seasonal runoff under D2 and D3 can be attributed to the reduced infiltration of water and possibly low water conductivity in D2 and D3 (caused by soil compaction) and the high rainfall intensity. Khan *et al.* (2016) also observed that an increase in rainfall intensity causes lower water infiltration. Furthermore, Adekalu *et al.* (2006) observed compaction significantly increased runoff. The result of this study aligns with that of Grace *et al.* (2006) who reported that lower infiltration and saturated hydraulic conductivity contributed to increased water logging and runoff. The treatment B0D1W3 did not show

any significant runoff. The total runoff + drainage for this treatment constituted 13% of the applied water. The application of biochar to the top sections of the soil altered the runoff and drainage relations. For the high-water regime, the per cent loss of water as runoff + drainage was 4%, 6% and 18% for B10D1W3, B10D2W3 and B10D3W3 treatments, respectively. In particular, runoff is reduced with biochar application.



**Table 5.2: Interactive effect of biochar, water regime and bulk density levels on water balance components**

Components	D1	D2	D3	D1	D2	D3	D1	D2	D3
(mm)	Low water regime			Medium water regime			High water regime		
	Biochar 0 ton/ha								
<b>Total runoff</b>	0.27 a	6.09 b	41.72 e	0.30 a	44.31 e	68.82 g	2.22 a	100.51 h	101.53 h
<b>Total</b>	0.00 a	0.00a	0.00 a	7.73 a	0.00 a	0.00a	59.37 c	36.13 b	27.80b
<b>Drainage</b>									
<b>ETa</b>	242.10 b	242.90 b	206.40a	314.10de	285.20cd	279.00 c	423.30h	349.90 f	353.10 f
<b>Δ±W</b>	96.19 abc	89.55abc	90.38abc	97.01abc	89.55abc	71.31 a	84.58ab	82.92 ab	87.06 abc
	Biochar 10 ton/ha								
<b>Total runoff</b>	0.00 a	1.79 a	15.19 c	0.00 a	6.65 b	26.92 d	1.08 a	13.83 c	63.70 f
<b>Total</b>	0.00 a	0.00 a	0.00a	0.00 a	0.00 a	0.00 a	67.90c	60.27 c	27.33 b
<b>Drainage</b>									
<b>ETa</b>	229.90ab	237.20b	233.00ab	327.90ef	294.70cd	308.40cde	417.60gh	398.40gh	388.90 g
<b>Δ±W</b>	108.62 bc	99.50abc	90.38abc	91.21abc	117.74 c	83.75ab	82.92ab	97.01abc	89.55 abc

Common letters are not significantly different ( $p < 0.05$ ) according to Duncan multiple range test. D1: Field bulk density ( $1.31 \text{ Mg/m}^3$ ), D2: Medium bulk density ( $1.5 \text{ Mg/m}^3$ ), D3: High bulk density ( $1.75 \text{ Mg/m}^3$ )

The impacts of the treatments were also reflected in the plant water use (actual evapotranspiration  $ET_a$ ). The actual evapotranspiration ( $ET_a$ ) was reduced with increasing soil bulk density for each water regime. Under the low water regime, W1 the seasonal  $ET_a$  varied from 206 to 242 mm, for D3 and D1, respectively, when no biochar was applied. For the same biochar application rate, the  $ET_a$  varied from 279 to 314 mm for D3 and D1 under the medium water regime (W2). For the high-water regime (W3) and 0 ton/ha biochar application, the  $ET_a$  was 351 and 423 mm, for D3 and D1, respectively. When biochar application increased to 10 tons/ha, The  $ET_a$  values were 229 and 233 for W1D1 and W1D3, respectively. For W2, the  $ET_a$  was 327 and 308 mm for D1 and D3, respectively, and for W3, the  $ET_a$  was 417 and 389 mm, respectively.

Using some of the selected replicate data collected in this study, a general relationship could be derived for the determination of the runoff  $R$  plus drainage  $D_r$  from the knowledge of bulk density, rainfall and biochar application as:

$$(R + D_r) = -225 + 97.8BD + 0.37W - 2.35BC \quad R^2 = 0.86 \quad 5.1$$

where  $BD$  is bulk density ( $\text{g/cm}^3$ ),  $W$  = water application or rainfall,  $P$ , (mm), and  $BC$  is biochar application rate (ton/ha). With equation 5.1, the  $ET_a$  for any water ( $W$ ) or precipitation ( $P$ ) event can be determined as:

$$ET_a = P - (R + D_r) \pm \Delta S \quad 5.2$$



#### 5.4 Effect of soil compaction and biochar application on rice development and growth

##### 5.4.1 Plant development

For all biochar amended soils, planted seeds emerged after 5 days (Table 5.3). In the case of no biochar treated soils, emergence was between 5 and 6 days. All treatments, irrespective of their bulk density levels and biochar rates received the same adequate amount of water during the first week of planting. Hence, there were no expected differences in soil desiccation, which, could affect germination and emergence. However, the delay of one day in emergence observed for the non-biochar applied compacted treatments could be attributed to slight water logging conditions. This could possibly affect aeration or the increased impedance to shoot and radicle of the emerging seed due to compaction thereby delay the emergence. There is evidence that soil compaction can delay seed emergence (Gemtos and Lellis, 1997).

**Table 5.3 Treatment effects on plant development days after planting.**

Treatment name	BD	BC	WR	Emergence	Flowering	Maturity
B0D1	1.33	0	W1	5	74	104
B0D2	1.51	0	W1	6	73	103
B0D3	1.79	0	W1	6	69	98
B0D1	1.33	0	W2	5	72	102
B0D2	1.51	0	W2	6	72	102
B0D3	1.79	0	W2	6	68	96
B0D1	1.33	0	W3	5	72	99
B0D2	1.51	0	W3	6	72	97
B0D3	1.79	0	W3	6	69	98
B10D1	1.33	10	W1	5	73	103
B10D2	1.51	10	W1	5	73	103
B10D3	1.79	10	W1	5	69	98
B10D1	1.33	10	W2	5	68	99
B10D2	1.51	10	W2	5	60	99
B10D3	1.79	10	W2	5	61	97
B10D1	1.33	10	W3	5	71	99
B10D2	1.51	10	W3	5	72	99
B10D3	1.79	10	W3	5	65	97
LSD (0.05)				1.07	1.47	1.34
CV (%)				11.9	1.8	1.1

BD: bulk density, BC: Biochar; W1, W2 and W3 are low, medium and high-water regimes

#### 5.4.2 Days to 50% flowering

Three compounding treatments affected the speed of development of the rice plant to flowering (Table 5.3). First, under no biochar application, the low water regime (W1) treatment tended to delay the time to flowering slightly, irrespective of soil compaction level, with an average of 72 DAP. The rice plant under the water regimes W2 and W3 (high water) reached 50% flowering at 71 DAP. Within a given water regime, days to 50% flowering varied with bulk density treatment. The rice plant under bulk densities D1 and D2 reached 50% flowering at 72 DAP, but the development under D3 was faster, attaining 50% flowering at 69 DAP, which was significant. When biochar was applied at 10 tons/ha, the lower water regime (W1) again delayed the development to flowering (71 DAP) followed by the medium water regime W2 (68) and finally the high-water regime W3 (65 DAP). With the density effect, low-density B10D1 delayed development to flowering whereas D2 and D3 somewhat accelerated the development to flowering.

Plant development response to environmental stresses has been the focus of study for many years. McMaster *et al.* (2005) reviewed the literature and summarized the determinants as air temperature, photoperiod, and water and nutrient stresses. Given that the air temperature was uniform in the screen house, differences in the observations cannot be attributed to temperature effects. With water stress, Abrecht and Carberry (1993) and Campos *et al.* (2004) observed a delay in maize development under severe water stress conditions imposed at silking and tasseling stage of the crop. Observation in this study conforms to these reports where water stress delayed flowering. Yet, there are also general observations or opinions that water stress or low water availability promoted early flowering, a strategy for survival by the plant. Mott and McComb (1973) have discussed the apparent contradictions to the water-stress effect on plant development.

There is a paucity of data on the impact of soil compaction on plant development. The effect may

be indirect. It would be expected that since runoff was highest under the high bulk density treatments (D3) and the overall water use was lowest for the highest bulk density treatments, the combination of W1 and D3, irrespective of biochar treatment would decrease water availability and hence increase soil water stress. The result would be a generally accelerated development of the plant, as observed in this study.

#### 5.4.3 Days to maturity

Figure 5.6 presents the maturity of rice plants under different density levels, biochar rates for different water regimes. The days to maturity were prolonged under the low water regime and decreasing bulk density. Under optimum soil conditions (D1) and high-water regime (W3) the days to maturity irrespective of biochar application was 99 DAP, though there was no difference

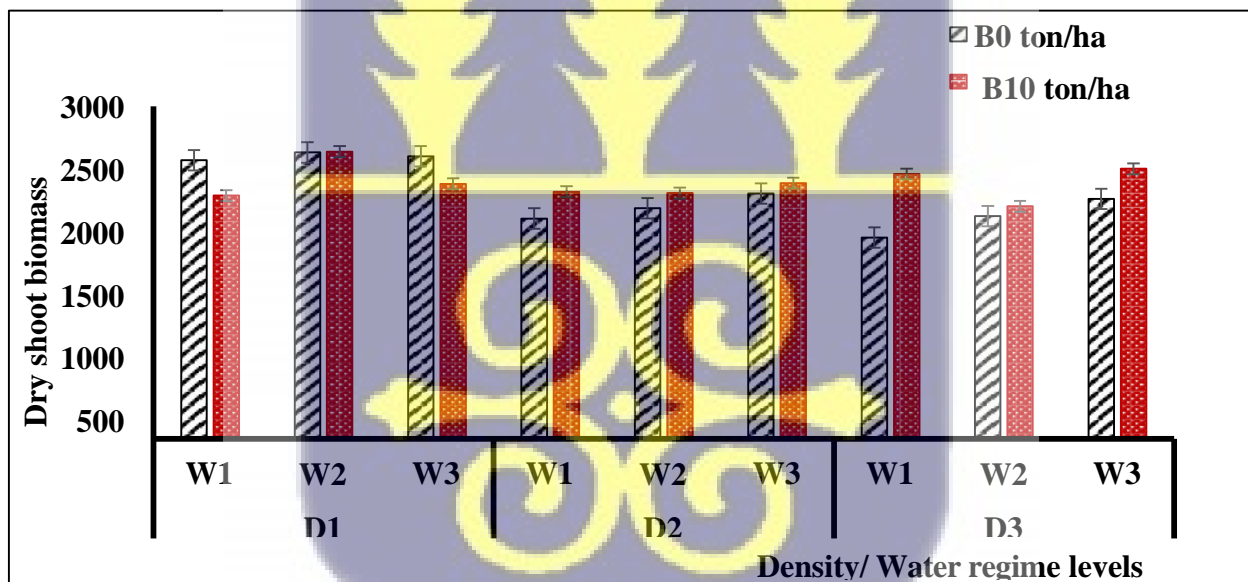


Fig 5.6: Effect of biochar on dry shoot biomass as affected by density levels and water regimes.

in days to maturity, however, the changes were seen in the yield produced. From days to 50% flowering, it took  $30 \pm 2$  days for all treatments to reach maturity. As the water amount applied increased, it took lesser days for the plants to reach maturity. At both biochar rates, with a low water

regime, the plants took longer days before reaching maturity. This could probably be due to the slow developmental phases of the crop caused by prolonged water stress days. With the bulk density effect, the days to maturity reduced as the density increased. The plant's development was delayed due to the inability to transmit the required nutrient from the source (due to root suppression) to the sink (root and shoot). Hoque and Kobata, (2000) also noted delayed heading and a reduced number of spikelets caused by soil compaction.

**Table 5.4: The effect of different biochar rates, density on days to emergence of upland rice.**

Treatment names	Density	Biochar	Days to emergence
<b>B0D1</b>	1.33	0	5
<b>B0D2</b>	1.51	0	6
<b>B0D3</b>	1.79	0	6
<b>B10D1</b>	1.33	10	5
<b>B10D2</b>	1.51	10	5
<b>B10D3</b>	1.79	10	5
<b>LSD (&lt; 0.05)</b>			0.6164

## 5.5 Effect of soil compaction and biochar application on the growth and yield of upland rice.

### 5.5.1 Total dry shoot biomass

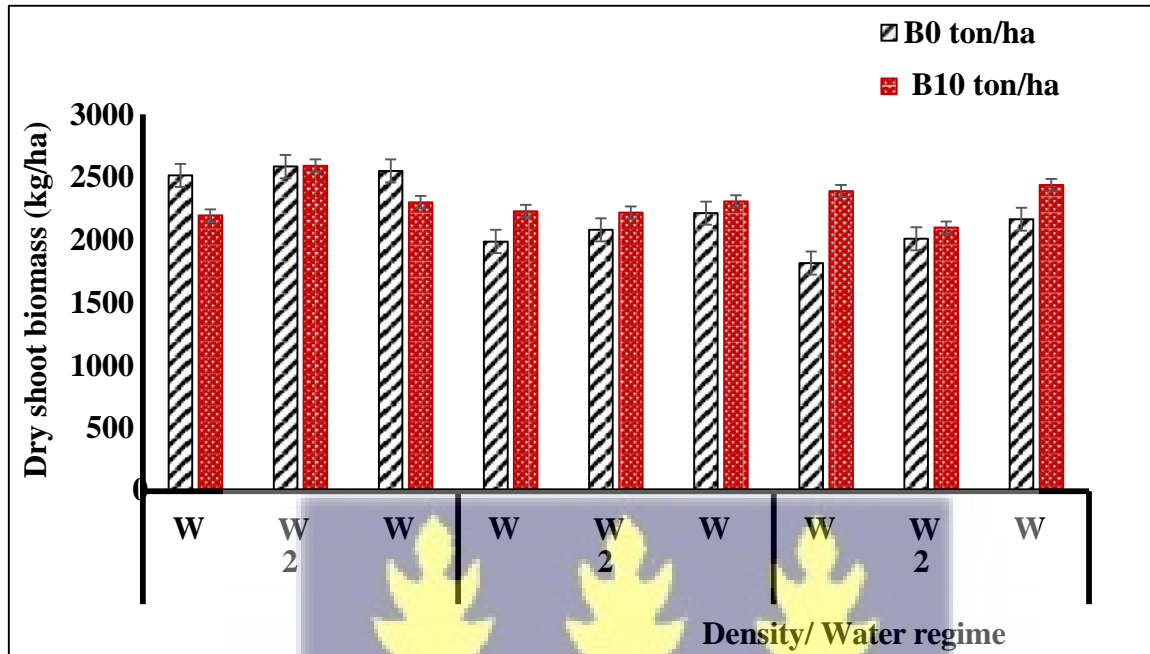
The shoot dry weight of rice did not show drastic variations with water treatments (Fig. 5.7). For density D1, with no biochar application, the average shoot dry weight was 2500±100 kg/ha. For D2, dry shoot biomass decreased to 2117 kg/ha, even though there were also slight increases with water application from 2000 kg/ha under W1 to 2250 kg/ha under W3. In the case of the highest density level (D3), the average shoot dry weight was 2000 kg/ha with an increasing trend of 1900, 2000 and

2100 kg/ha for W1, W2 and W3, respectively. Generally, the dry shoot biomass reduced with increasing soil bulk density, with D1 having the highest shoot biomass. In other words, as the soil bulk density increases, there is a reduction in the production of rice shoot, apparently caused by the restriction of root elongation to only the compaction cracks and tilled topsoil layers, thereby reducing the uptake of water and nutrient by the root system. Similar results were observed by Ocloo *et al.* (2014) where bulk densities of 1.7 and 1.9 Mg/m<sup>3</sup> reduced the dry matter yield. The actual mechanisms of plant response to compaction are not clear but appear to involve the induction of hormonal signals that slow shoot growth (Passioura, 1991; 2002).

To some extent, higher water application appeared to offset somewhat the effect of soil compaction on shoot growth. For example, shoot biomass was greater under W2 and W3 in un-compacted soils (D1) and D2. Therefore, the adverse effect of soil compaction on yield response could be mitigated with increasing rainfall amount or irrigation applied (Batey, 2009).

The application of biochar also offsets the soil compaction effect on shoot growth. Shoot growth in the compacted soils (D2 and D3) increased under biochar application (Fig. 5.7), even under a low water regime (W1). Without biochar application to the highly compacted D3, the average shoot growth was 1996 kg/ha which was lower than that obtained (2,307 kg/ha) when 10 ton/ha biochar was applied. This was contrary to the observations under the normal field density (D1). Therefore, the effectiveness of biochar may vary depending on soil conditions. Indeed, some studies have indicated that biochar (eucalyptus biochar) had no significant effect on dry matter accumulation of upland rice in the first year of incorporation (Petter *et al.*, 2012) but claimed positive results with the addition of fertilizer. However, biomass application of  $\leq 22.4$  Mg/ha increases the shoot biomass of wheat in silt loam soil (Bista *et al.*, 2019). A 12% increase in shoot biomass was reported in wheat after the application of biochar applied to compacted soil (Liu *et al.*, 2017). Further research is

required to ascertain when biochar application is required for soil improvement.



**Fig 5.7: Effect of biochar on dry shoot biomass as affected by density levels and water regimes.**

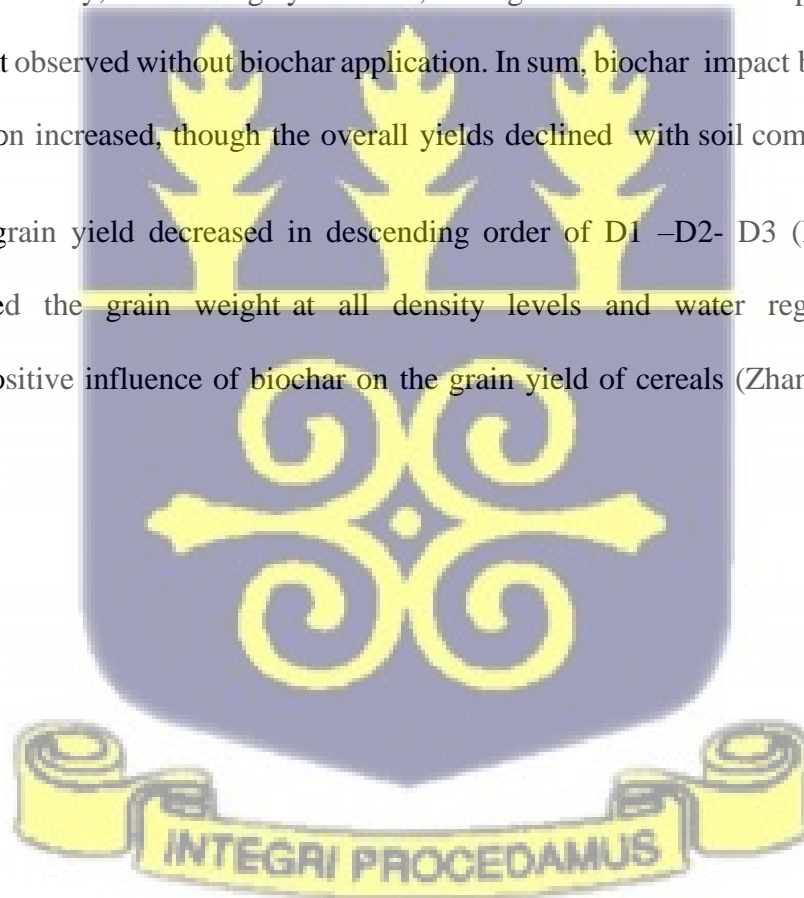
### 5.5.2 Grain weight

Unlike shoot growth, there were drastic differences in grain weight for the different water regimes and biochar application rates (Fig. 5.8a). Grain yield is reduced with compaction, irrespective of the water regime. When no biochar was applied, the average yield of rice for D1 across all water regimes was 1336 kg/ha but reduced to 947 kg/ha under D2 and 636 kg/ha under D3. Previous studies have also confirmed the impact of soil compaction on grain yield (Seixas and Tim, 1997). Water regime also had a significant effect on grain yield. Under no biochar application, the yield for W1 (averaged over bulk density treatments) was 591 kg/ha, 1042 kg/ha and 1282 kg/ha for W1, W2 and W3, respectively. It may be inferred that though soil compaction reduced the yield by 41.1%, and 68% for D2 and D3, respectively, at low water regime and 34% and 47% at D2 and D3

for high water regime, the yield responses to water regime appeared to be dominant. In effect, the reduction of rice yield due to soil compaction could still be offset by an increased supply of water. The interaction between biochar and water regime was highly significant ( $p < 0.001$ ).

The application of biochar also significantly affected rice yield. The highest yield of approximately 2500 kg/ha was observed for biochar application of 10 tons/ha under density D1 and water regime W3. For D1, the average rice yield for biochar application averaged over all water regimes was 1778 kg/ha, which was 33% higher than that without biochar application. In the case of D2, the average yield under biochar application was 1451 kg/ha which was 53% higher than that without biochar application. For the highest bulk density, the average yield of 1,238 kg/ha under biochar application was almost double (94%) that observed without biochar application. In sum, biochar impact became more evident as soil compaction increased, though the overall yields declined with soil compaction.

In general, the grain yield decreased in descending order of D1 –D2- D3 (Fig 5.8b). However, biochar increased the grain weight at all density levels and water regimes. Other studies confirmed the positive influence of biochar on the grain yield of cereals (Zhang *et al.*, 2012; Ocloo *et. al.*, 2014).



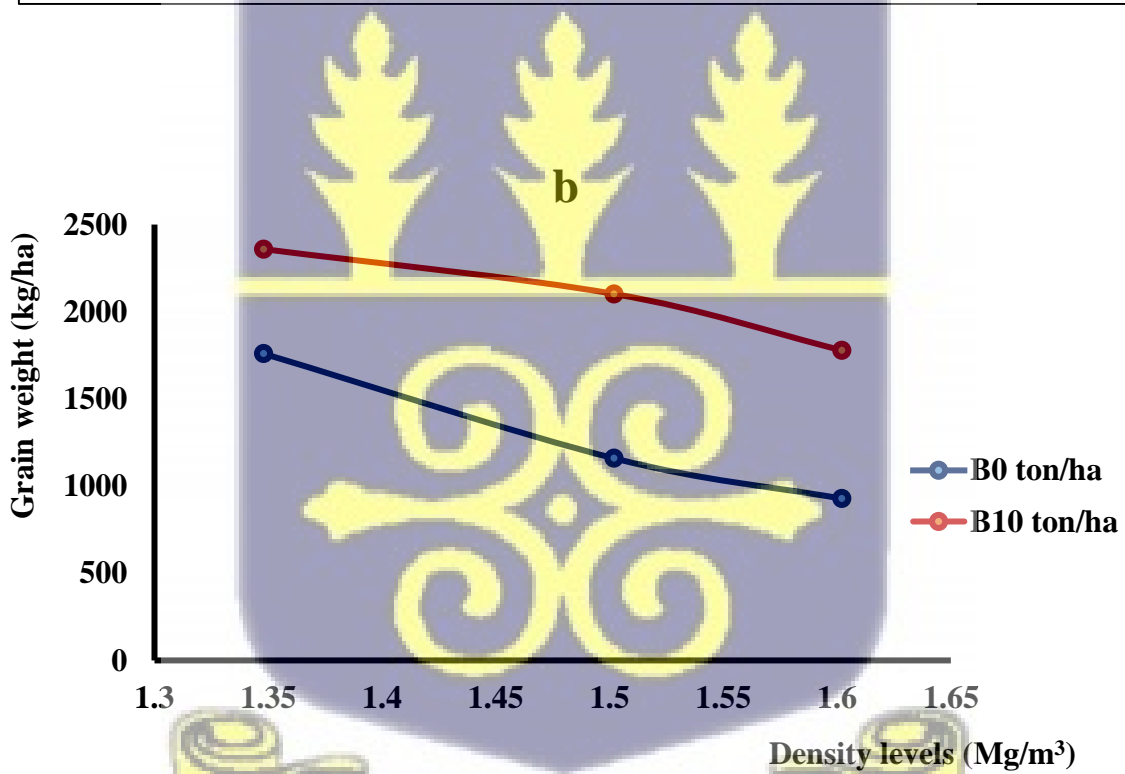
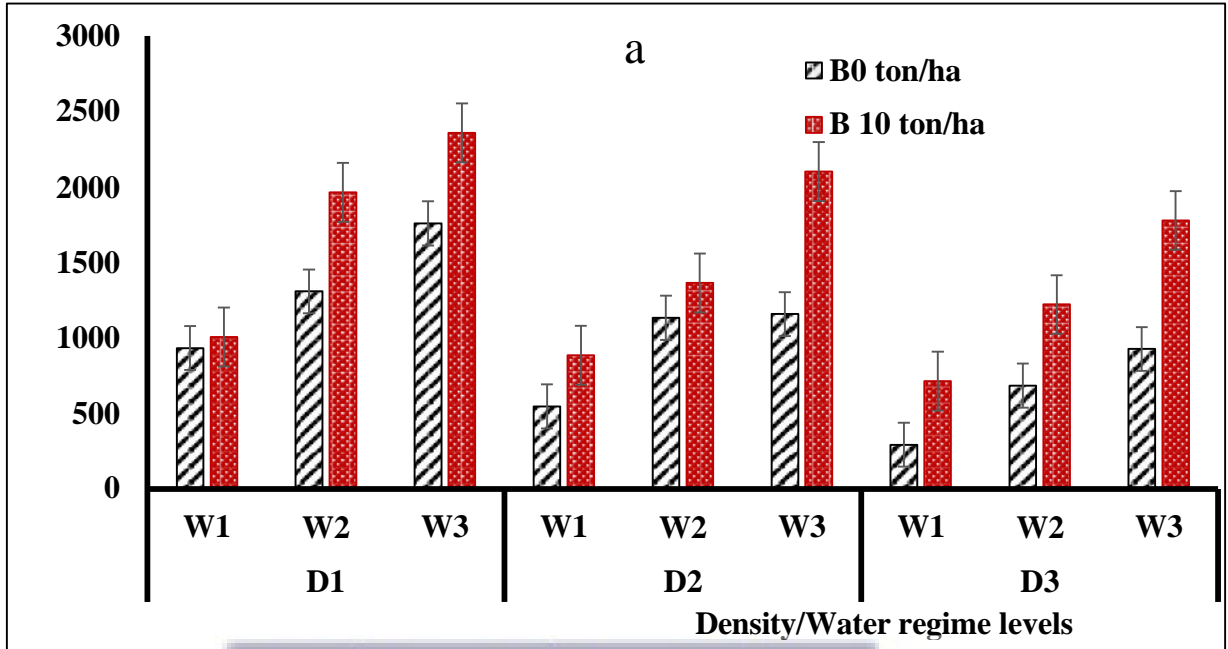


Fig 5.8 (a) Effect of biochar on grain weight for varying density levels and water regimes, and (b) trends of grain weight with density and biochar application.

## 5.6 Root growth and distribution

The root masses at three different depths of the soil columns are presented in Table 5.5. Under field bulk density condition ( $1.33 \text{ Mg/m}^3$ ), total root mass in the non-biochar amended soil column was 6.67 g with about 44% of the root mass in the top 5 cm of the soil (Table 5.6) and 14% in the middle layer. Biochar application increased the total root mass to 7.61 g with 51% of the total root mass concentrated in the top 5 cm. Under D2 conditions, total root mass decreased to

5.38 g with about 43% in the top layer while biochar application increased it to 5.81 g with 43% in the topsoil. Root growth in the compacted layer (4.5 – 10 cm) was restricted and constituted not more than 13-15%. For the high-density treatment (D3) total root mass with and without biochar application were 4.45 and 5.68 g, respectively, with more than 48% in the top 5 cm and less than 16% in the compacted layer (4.5 – 10 cm). Root elongation reduced as it experienced soil hardening at the subsoil layer.

The impact of soil compaction on root development and growth had been the focus of many studies. The observations of this study aligned with the report by Seixas and Tim (1997) who studied compaction effects on crop growth and yield. Others such as Ocloo *et al.* (2014) observed a decline of maize and soybean root mass with soil compaction (increasing bulk density) in some Ghanaian soils but pointed out that there are varietal differences in response. Likewise, Håkansson and Lipiec (2000) also stated decreasing dry root mass with increasing bulk density. Ozpinar and Cay (2006) reported the inhibition of upland rice root elongation beyond 0-10 cm at a density of  $1.5 \text{ Mg/m}^3$ . Because the root developed a maximum pressure above which they are unable to expand in the soil layer.

**Table 5.5: Root mass (g) at different depths (cm) of the soil column as influenced by biochar amendment.**

Bulk density (g/cm <sup>3</sup> )	Biochar (ton/ha)	Root mass (g)			
		0-4.5	4.5-10	10-22.5	Total
1.33	0	2.899	0.929	2.843	6.671
1.33	10	3.892	1.101	2.612	7.605
1.51	0	2.309	0.71	2.363	5.382
1.51	10	2.829	0.864	2.119	5.812
1.79	0	2.153	0.68	1.618	4.451
1.79	10	2.454	0.833	2.39	5.677
<b>LSD (p&lt;0.05)</b>		0.558	0.042	1.08	1.68
<b>CV (%)</b>		21.1	5.1	39.6	

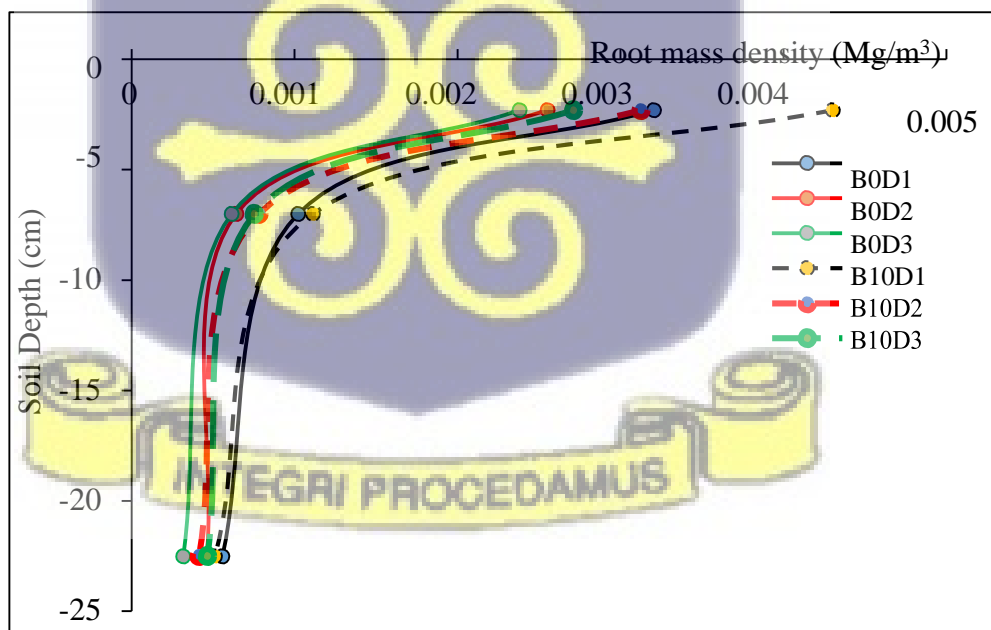
0-4.5, 4.5-10 and 10-30 cm depth represent top, middle and bottom soil layer, respectively.

**Table 5.6: Root mass percentage (%) at different depths (cm) as influenced by biochar amendment.**

Bulk Density (Mg/m <sup>3</sup> )	Biochar (ton/ha)	Root mass percentage (%)		
		Top	Middle	Bottom
1.33	0	43.5	13.9	42.6
1.33	10	51.2	14.5	34.3
1.51	0	42.9	13.2	43.9
1.51	10	48.7	14.9	36.5
1.79	0	48.4	15.3	36.4
1.79	10	43.2	14.7	42.1

### 5.6.1 Root mass density distribution

The vertical distribution of root mass density of upland rice is described in Fig. 5.9. Generally, the root mass density was highest at the topsoil and rapidly declined with depth. For the compaction effect, the root density was in increasing order of B0D3 < B0D2 < B0D1 and for the biochar effect, the same trend was observed. The highest root mass was recorded for treatment D1 and the lowest for D3. Below the depth of 10 cm, the root mass density was uniform (average of 0.0004 Mg/m<sup>3</sup>) since the soils at those depths were packed to the field bulk density (D1). The compacted zone (4.5 to 10 cm) resulted in a drastic reduction in root mass. The root penetration into the deeper zone was restricted as they developed a maximum pressure above which they are unable to expand in the subsoil layer (Seixas and Tim, 1997). In the experiment of soil aggregation and root growth of perennial grasses carried out in Brazil, it was observed that the root development of all species decreased at the subsoil layer which was attributed to the compression of aggregated soil, high bulk density and low macro-porosity (Stumpf *et al.*, 2016).



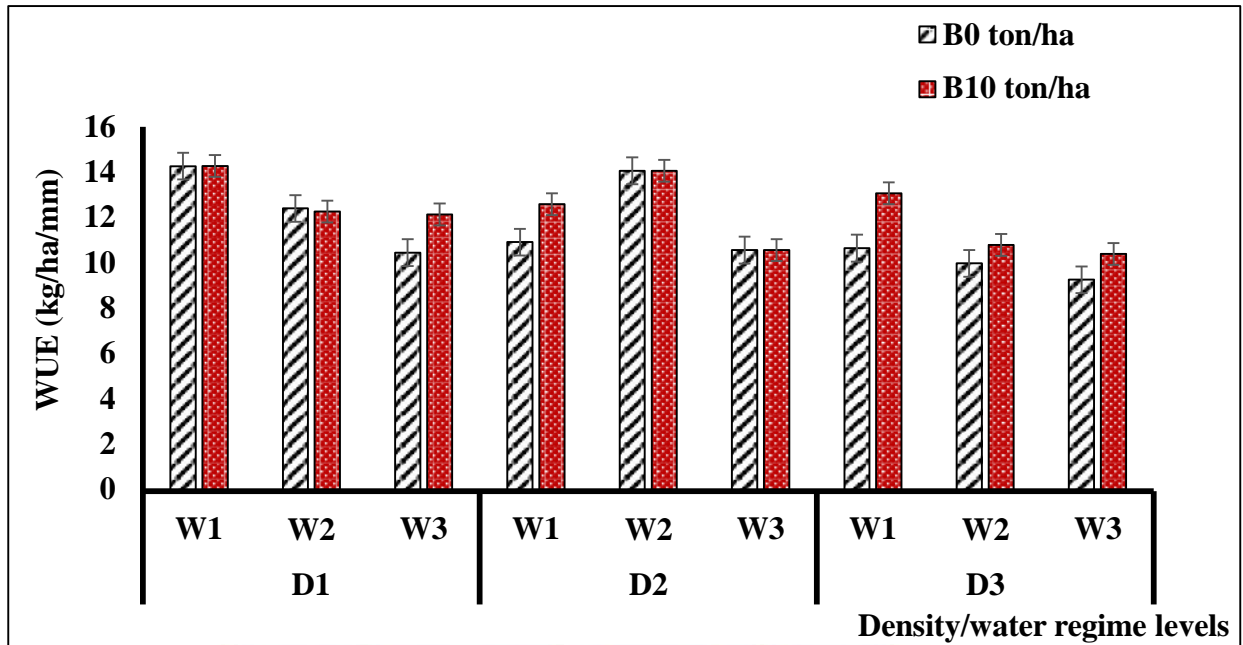
**Fig 5.9: Root mass density distribution along the soil profile of biochar-amended and un-amended soil.**

### 5.7 Effects of biochar on water use efficiency of upland rice on a compacted soil.

Figure 5.10 shows the impact of biochar application on the water use efficiency (WUE) of rice grown on soil with varying degrees of compaction. The WUE decreased with increasing bulk density levels and water regimes except in the case of medium water regimes at medium density levels (D2). The lowest density (D1) had a significantly higher WUE of 14 kg/ha/mm, whereas the highest density D3 had the lowest WUE (9.28 kg/ha/mm under W3 conditions). Biochar had only a small significant effect on the WUE of the compacted soils.

The reduction in the WUE with increasing water regime could perchance be attributed to higher losses as runoff and drainage as well as lower grain yield.

The higher water use efficiency observed (14.27 kg/ha/mm) for W1 (low water regime) could be attributed to reduced transpiration and evaporation caused by inadequate availability of water for plant use. Researchers have related the changes in WUE with climatic conditions such as vapour pressure deficit and average relative humidity (Arkely, 1963; Bierhuizen and Slatyer 1965) and limitation to water supply which can be water stress conditions. Amongst the climatic conditions, VPD has a greater effect on the WUE with water un-limiting conditions (Abbate *et al.*, 2004). Abbate *et al.* (2004) reported high WUE in water limiting conditions caused by the closure of stomata restricting the rate of transpiration in the day with high VPD. The literature confirms that plants growing under severe and moderate water stress at early and middle stages may exhibit increased WUE (Ge *et al.*, 2012). Also, Yin *et al.*, (2005) reported increased WUE under water stress conditions. Similar effects are reported by other researchers (Marron *et al.*, 2002; Siemens and Zwaizek 2003; Zhang *et al.*, 2004). In well-watered conditions, the shoot growth contributes mainly to the total biomass while for the stress condition, the root growth contributes to the total biomass. Similar effects are reported by other researchers (Marron *et al.*, 2002; Siemens and Zwaizek, 2003; Zhang *et al.*, 2004).



**Fig 5.10: Effect of biochar on Water use efficiency as affected by bulk density levels and water regimes.**

### 5.8 Rice yield prediction

It is one of the major aims of this study to derive a relationship between rice yield and soil compaction, biochar amendment and watering regime. For this, equations 5.1 and 5.2 were derived to predict the runoff plus drainage and subsequently, the *ETa* of rice under various soil compaction, biochar application rate and water application. This substitution of the *ETa* into the Doorenbos and Kassam (1979) equation is given by:

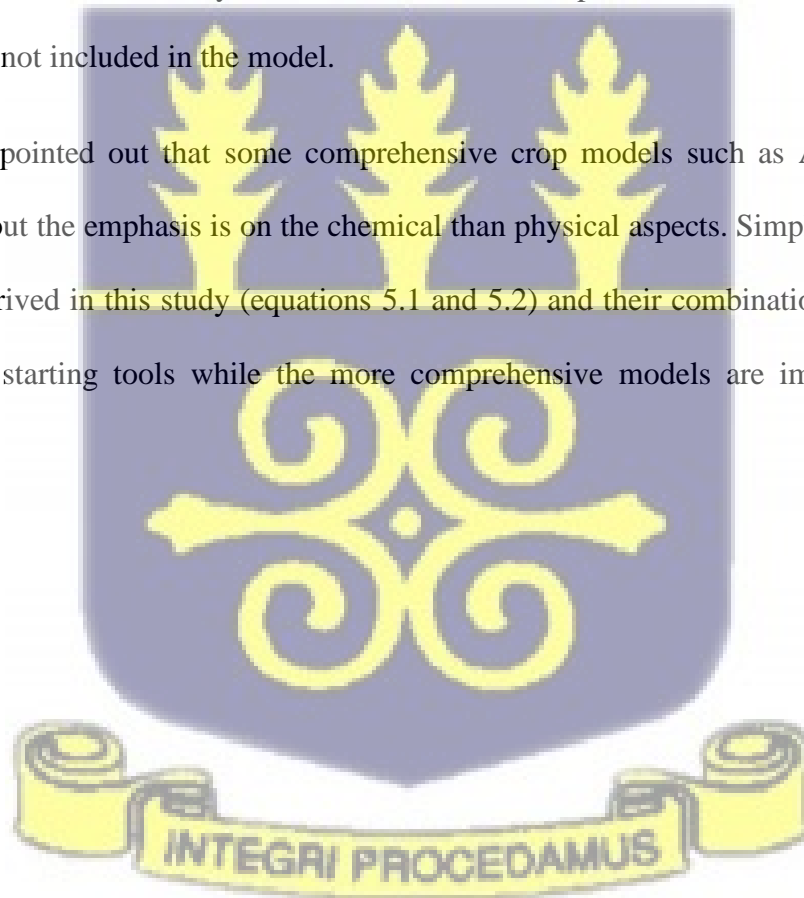
$$\left(1 - \frac{Y_a}{Y_p}\right) = Ky \left(1 - \frac{ET_a}{ET_p}\right) \quad 5.3$$

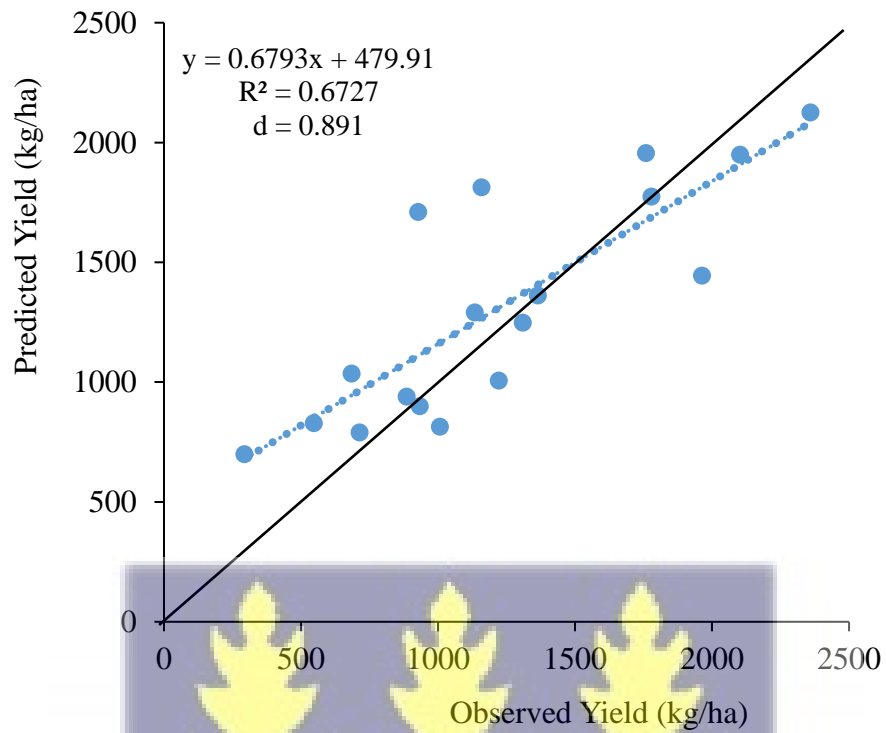
where, *Ky* is the yield response factor (= 1.3 for rice), *Ya* and *Yp* (kg/kg) are the actual and potential yield of rice, respectively, and *ETa* and *ETp* are the actual and potential evapotranspiration, which enables the determination of the actual yield, *Ya*. The *Yp* was taken as the highest observed rice yield of 2,359 kg/ha (see Fig. 5.8a), while the *ETp* was the measured seasonal

free water surface evaporation from beakers in the screen house, which was 462 mm (see Section 5.2.3 above).

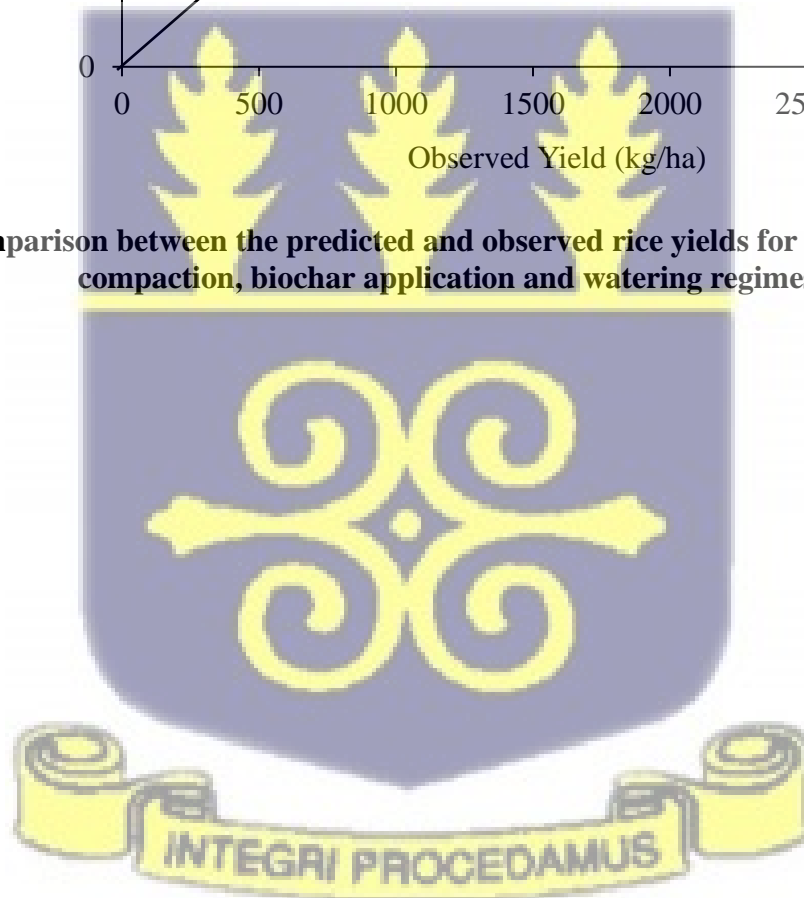
The prediction of rice yields using equation 5.3 is compared with the observed given in Fig. 5.8a, while the comparisons are shown in Fig. 5.11. The degree of association between the observed yield and the predicted yield is shown in fig 5.11. The coefficient of determination ( $R^2 = 0.67$ ) and a Willmott *d*-index of 0.891 indicates a generally good agreement between the predicted and observed. This implies that rice yield for different soil conditions under biochar application can be predicted, providing a tool for decision support and agricultural planning. It may be pointed out that the focus of soil factors in this study did not include chemical aspects of biochar and hence soil fertility parameters were not included in the model.

It must also be pointed out that some comprehensive crop models such as APSIM now include biochar effects, but the emphasis is on the chemical than physical aspects. Simple regression models such as those derived in this study (equations 5.1 and 5.2) and their combination with equation 5.3 can be used as starting tools while the more comprehensive models are improved further and validated.





**Fig 5.11: Comparison between the predicted and observed rice yields for the different soil compaction, biochar application and watering regimes.**



## CHAPTER SIX

### 6 RESULTS AND DISCUSSION: III

#### SIMULATION OF RUNOFF FROM BIOCHAR-AMENDED COMPACTED RHODIC KANDIUSTALF SOIL

##### Introduction

Runoff is a very important parameter in the water balance equation because it partitions rainfall into surface loss and what can infiltrate the soil to increase water storage for plant use. Runoff models abound in the literature, ranging from very physical approaches that require knowledge of soil hydraulic properties, to more empirical approaches. Runoff can be predicted using Philip's (1957) infiltration equation, which requires knowledge of the sorptivity and the saturated hydraulic conductivity, as discussed in Chapter 4. Alternatively, runoff can also be determined by the Horton (1940) infiltration equation. In both cases, if there is no surface storage then the difference between the total rainfall and total infiltration can be taken as the runoff.

The physically-based approach may be suitable for small-scale situations. For field landscape-scale runoff assessment, the variability of soil properties from one place to another presents complications, apart from the fact that the hydraulic properties of the soils may not be known at those scales. Furthermore, for many field landscape situations, rainfall intensity data are not available. Often, rainfall data are available at only a daily time scale. It is therefore desirable to be able to predict runoff from limited field to landscape information only.

Two models that are popularly applied for runoff modelling at the field to landscape scales are the Ives *et al.* (1976) model, which requires information on daily rainfall and the antecedent water content of the topsoil, and the United States Department of Agriculture (USDA) Natural Resource Conservation (NRCS) Curve Number Technique (Rallison, 1980). The Curve Number method is used

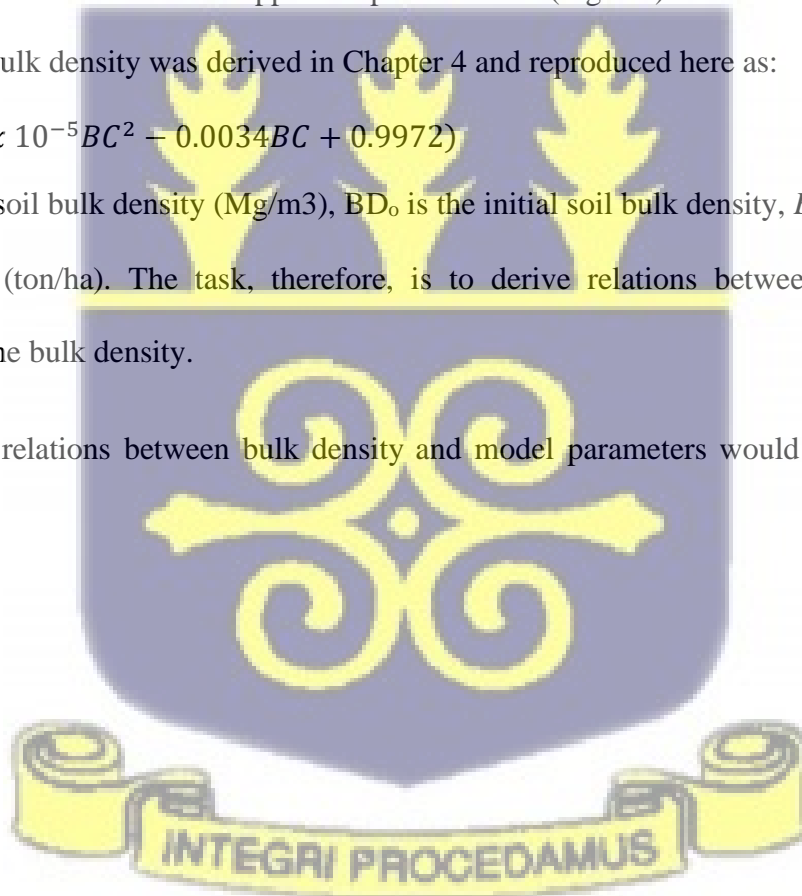
to estimate runoff (Q) from small to medium watersheds. The Curve Number Technique requires information on the daily rainfall and the soil conditions (e.g., soil type, land use, hydrologic class, etc.) Whereas these models have been used successfully in crop modelling, the impact of management practices such as biochar application has not been assessed.

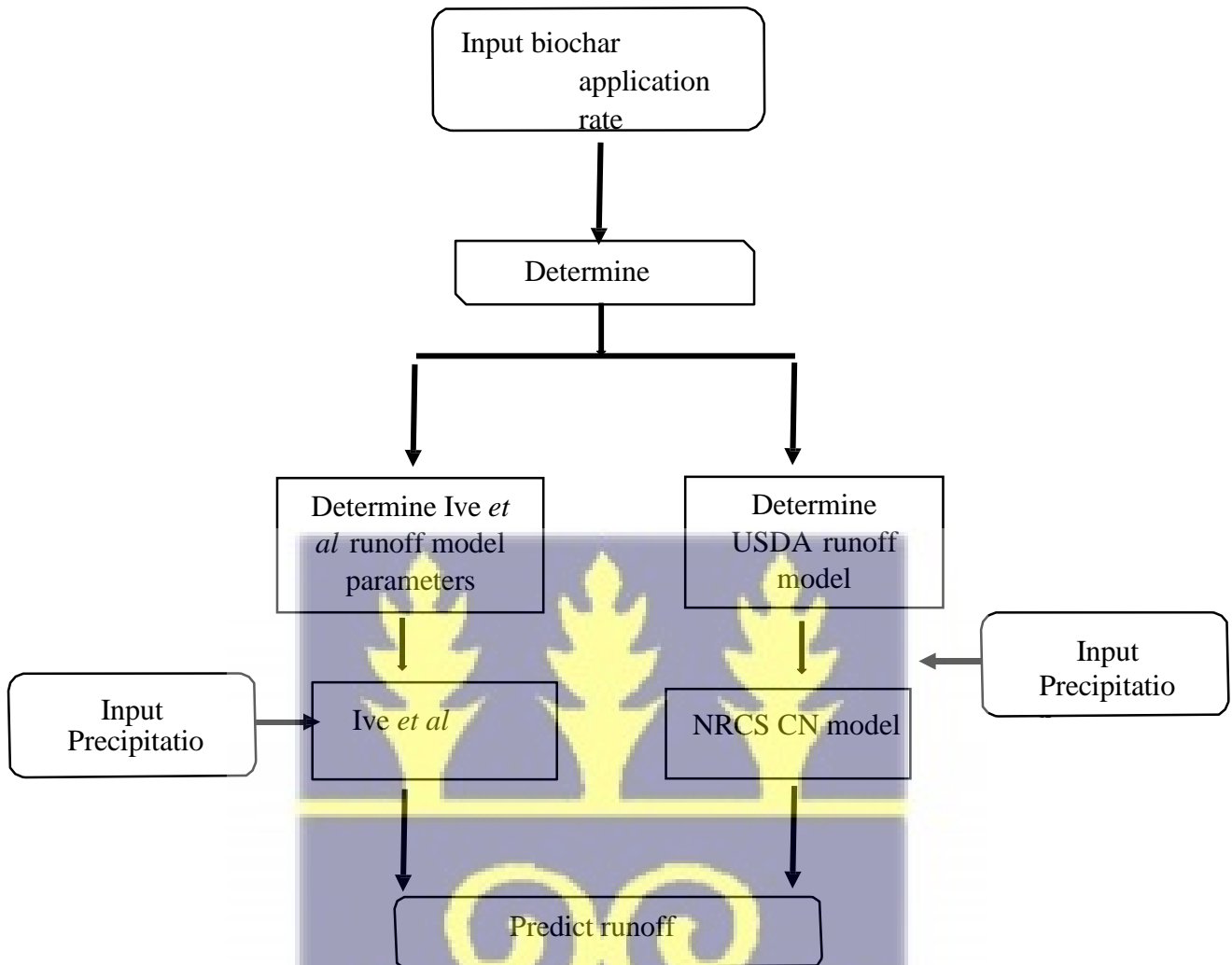
In this chapter, an attempt is made to test modified versions of the two models to account for the biochar effect. The hypothesis state that “biochar application to soils basically modified the bulk density and porosity of the soil”. Furthermore, it is hypothesized that runoff parameters of the Ives *et al.* (1976) and USDA Curve Number (1972) models are functions of bulk density. The bulk-density modified models can then be applied to predict runoff (Fig. 6.1). A relation between the biochar application and bulk density was derived in Chapter 4 and reproduced here as:

$$BD = BD_0 \times (2 \times 10^{-5} BC^2 + 0.0034 BC + 0.9972) \quad 6.1$$

where  $BD$  is the soil bulk density (Mg/m<sup>3</sup>),  $BD_0$  is the initial soil bulk density,  $BC$  is the biochar application rate (ton/ha). The task, therefore, is to derive relations between the runoff model parameters and the bulk density.

Hence, deriving relations between bulk density and model parameters would account for biochar impact.





**Fig 6.1: Ive et al 1976 and NRCS CN 1972 model flow chart representation.**



## 6.1 Datasets for parameter derivation and model testing

As detailed in Chapter 3, a total of five (5) irrigation events were carried out on repacked soils of varying biochar application and compaction levels. The runoff measurements from three (3) events, namely: events 1, (irrigation amount of 25 mm) event 2 (irrigation amount of 15 mm) and event 5 (irrigation amount of 50 mm) were used for parameter derivation. For each irrigation event, the treatments included B0D1 (zero biochar and soil at field bulk density), B20D1 (biochar application of 20 ton/ha at field bulk density) and B0D2 (zero biochar and soil at medium bulk density). Data for event 3 (50 mm irrigation) was used for model testing.

## 6.2 The Ive *et al* (1976) model

The model predicts the daily runoff,  $Q$  (mm), from the daily precipitation,  $P$  (mm), and the antecedent soil water content  $\theta$  ( $\text{cm}^3/\text{cm}^3$ ) of the top 20 cm of the soil. Hence, the model has two parts and is given as:

$$Q = (P - C)f_1(P) + Pf_2(\theta) \quad 6.2$$

where,  $C$  is a constant and  $f_1$  and  $f_2$  are two functions given by:

$$f_1(P) = a + bP \quad 6.3a$$

$$f_2(\theta) = d + e\theta \quad 6.3b$$

where  $a$ ,  $b$ ,  $d$ , and  $e$  are parameters. Hence, equation (6.2) can be rewritten as:

$$Q = (P - C)(a + bP) + P * (d + e\theta) \quad 6.4$$

For the sandy loam soil and field water balance collected by Ive *et al.* (1976) values of the parameters derived from curve fitting were  $C = 50$ ,  $a = 0.346$ ,  $b = 0.00691$ ,  $d = -1.19$  and  $e = 7.41$

In this study, however, each of the parameters was expressed as functions of BD, using data obtained from the runoff experiments described in Chapter 3 (Section 3.4.1.1). Curve fitting was carried out using the SigmaPlot version 14.0.

6.2.1 *C* as a function of Bulk density

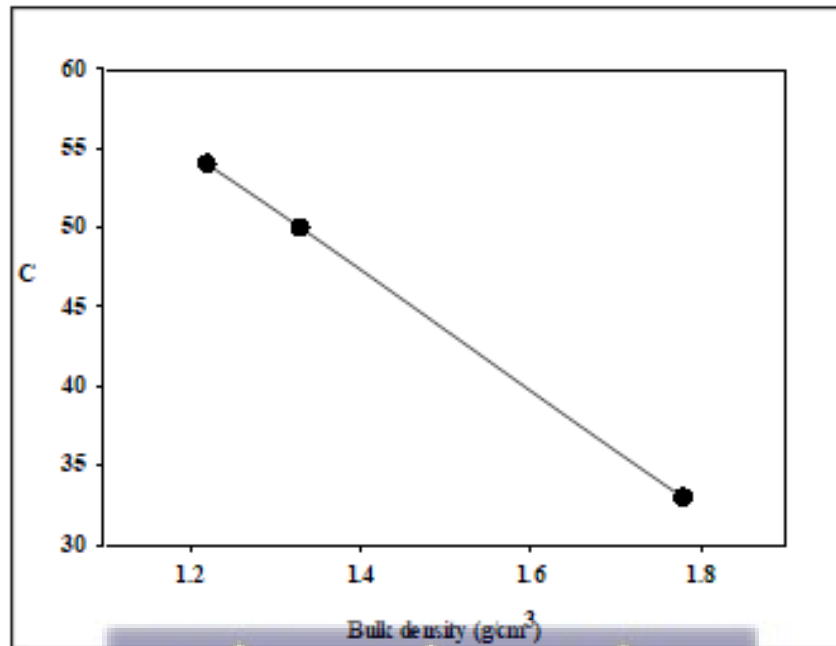
The general observation from the runoff experiments indicated that the *C* parameter was high for low bulk density treatments but decreased sharply with soil compaction. Though Ive *et al.* (1976) did not provide any interpretation for *C*, *C* likely is related to the quantity of water that would infiltrate the soils before runoff inception, if the antecedent soil water content was low. The relation between the *C* parameter and the bulk density is shown in Fig 6.2 giving a high value of about 78 mm for low BD ( $\leq 1.2 \text{ Mg/m}^3$ ) which decreased sharply to about 20 mm for high BD. The curve was non-linear and could be described by a sigmoidal equation of the form ( $R^2 = 1.0, p < 0.05$ ):

$$C = \frac{78}{1 + \exp\left[-\left(\frac{BD - 1.60}{-0.4792}\right)\right]} \quad 6.5$$

As indicated, it would be expected that the amount of water entering/infiltrating into the soil before the onset of runoff will drastically reduce as the soil bulk density increased. This is as a result of soil surface being clogged, mean pore sizes that hold water is reduced. If the bulk density of the soil can be managed properly using effective management practices, then, runoff loss, loss of soil sediments, and fertilizer and nutrient depletion would be reduced.

With regard to biochar application, equation 6.1 indicated that the application of every ton /ha of biochar to soil would reduce the initial bulk density by 15%. Therefore, *C* would be affected.





**Fig 6.2: Relationship between the parameter C and bulk density.**

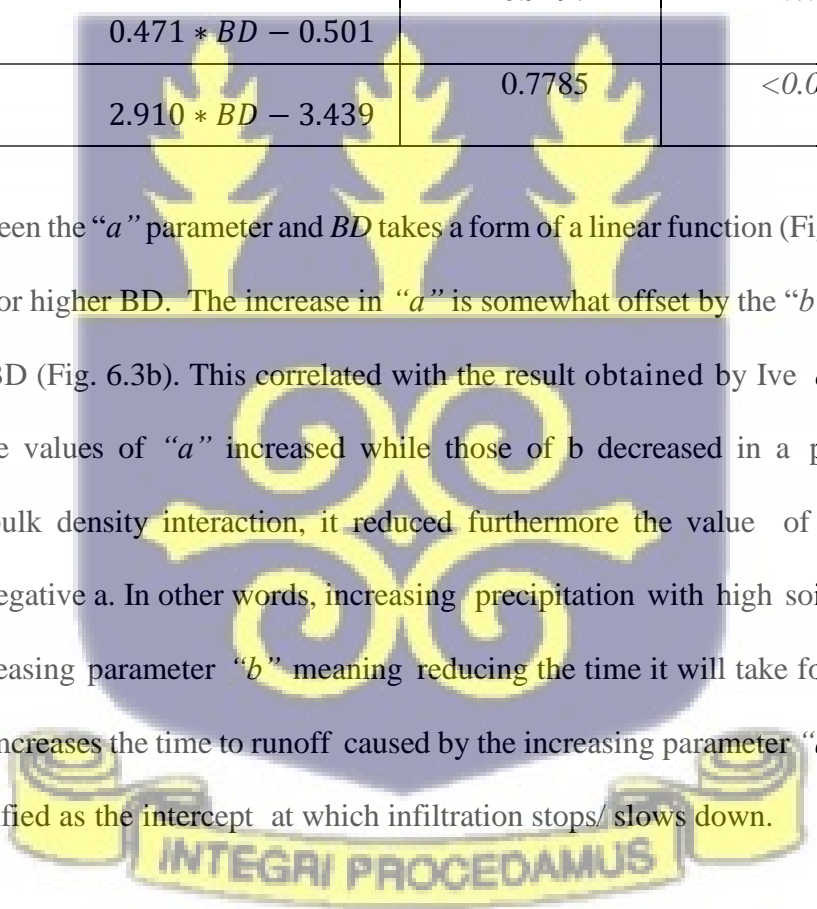
### 6.2.2 Other model Parameters as functions of Bulk density

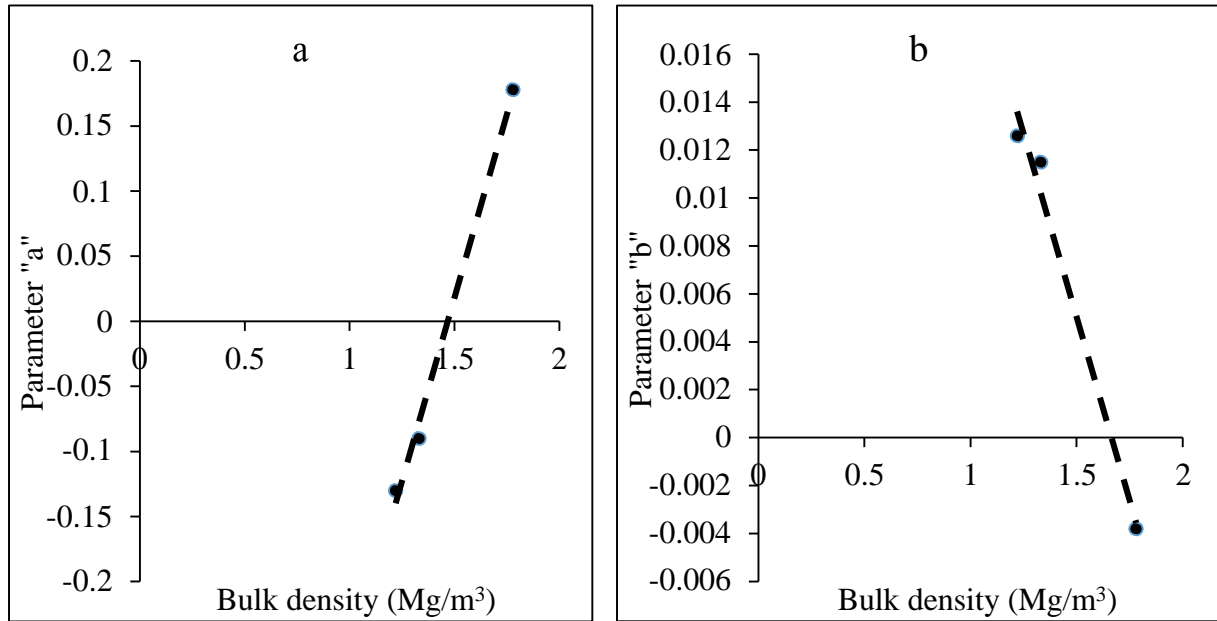
The relationships between the parameters *a*, *b*, *d* and *e* and the BD are summarized in Table 6.1. Coefficient of determination was used in testing the significant effect of bulk density on the parameters. All showed a good and positive degree of association. “*C*” and “*a*” have the perfect coefficient of determination with  $R^2$  of 1 and 0.9956 ( $p < 0.0005$ ;  $p < 0.001$ ), respectively, as compared to others. 100% of the variation in parameters “*c*” and “*a*” is caused by the changes in the soil bulk density which tells why bulk density is an important factor in predicting the parameter that affects runoff amount from the watershed. Others: “*b*” and “*d*” also gave a good and best association,  $R^2$  of 0.9841 and 0.9497, respectively ( $p < 0.05$ ). Though “*e*” gave the lowest coefficient of determination, however, it is still noteworthy to give a positive and good significance and coefficient of determination.

**Table 6.1: Relationship and test of significance between parameters and bulk density**

Parameter	Equation	R <sup>2</sup>	<i>p</i>
C	$\frac{78}{1 + \exp\left[-\left(\frac{BD - 1.60}{-0.4792}\right)\right]}$	1.00	<0.0005
a	$0.563 * BD - 0.827$	0.9956	<0.001
b	$-0.0307 * BD - 0.051$	0.9841	<0.05
d	$0.471 * BD - 0.501$	0.9497	<0.05
e	$2.910 * BD - 3.439$	0.7785	<0.05

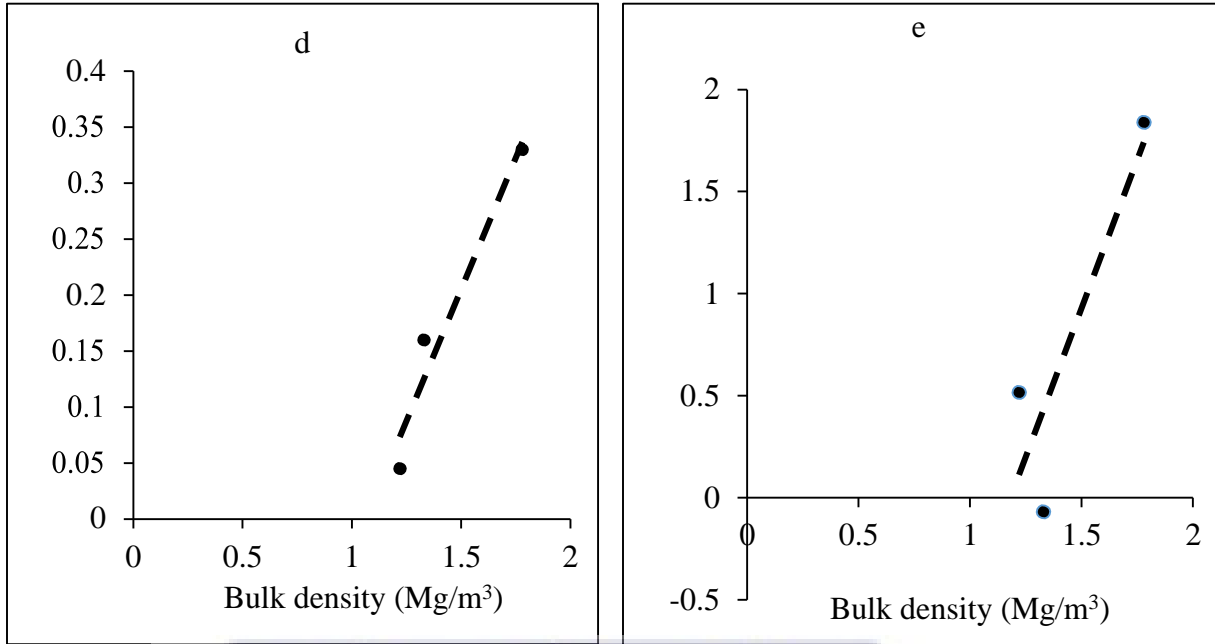
The relation between the “a” parameter and *BD* takes a form of a linear function (Fig. 6.3a) with higher values obtained for higher *BD*. The increase in “a” is somewhat offset by the “b”, which decreases with increasing *BD* (Fig. 6.3b). This correlated with the result obtained by Ive *et al.* (1976). It can be noted that the values of “a” increased while those of b decreased in a positive interaction. However, with bulk density interaction, it reduced furthermore the value of “b”- a function of precipitation to negative a. In other words, increasing precipitation with high soil bulk density will account for decreasing parameter “b” meaning reducing the time it will take for water to infiltrate into the soil and increases the time to runoff caused by the increasing parameter “a”. Also, parameter “a” can be classified as the intercept at which infiltration stops/ slows down.





**Fig 6.3: (a) Parameter ‘a’ and (b) parameter “b” as a function of bulk density.**

In the case of parameters *d* and *e*, the relationship with BD is also one of the linear equations (Fig. 6.4 a) with higher values obtained for higher BD. Both gave an increasing value with increasing BD (Fig. 6.4a and 6.4b). Parameter “*e*” gave the highest values with high bulk density, it is described as a function of the initial water content of the soil. As a result, when soil is initially wet, it reaches saturation quickly thereby any other excess water added especially with increasing rainfall amount or intensity, is regarded as surface water loss or runoff water. However, when soil is dry, infiltration increases geometrically and steadily decreases when almost at saturation. Therefore, with regards to the parameter “*e*”, a high soil initial water content will speed up the time to run off of the soil. With increasing bulk density, the parameter ‘*e*’ relating to initial water content will increase by 2.91 and thereby increase the runoff amount. Also, parameter “*e*” can be classified as the intercept at which infiltration stops/ slows down as in parameter “*b*”.



**Fig 6.4: (a) Parameters “d” and (b) parameter “e” as a function of BD**

### 6.3 The USDA NRCS CN method.

#### 6.3.1 CN (Curve number) as a function of bulk density (BD) and initial water content

The CN model predicts the daily runoff,  $Q$  (mm) from:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad 6.6$$

$$S = \frac{25400}{CN} - 254 \quad 6.7$$

where  $S$  is the maximum retention parameter, and  $CN$  is the Curve Number. The  $CN$  was considered to be the maximum infiltration penetration afterwards excess precipitation becomes runoff (Hawkins et al., 2009). The  $CN$  depends on soil texture, initial soil water content, land use type and hydrologic condition. Values of  $CN$  appropriate for a field condition are tabulated and available in the literature. However, in this study, a more rigorous relationship between the  $CN$  and bulk density were derived, given that the biochar application significantly affected the bulk density (equation 6.1). To arrive at the relation, pairs of runoff  $Q$  under varying irrigation,  $P$ , for varying soil

compaction levels as described in Chapter 3 (Section 3.4.1.1) were used to determine  $S$ , following Hawkins (1984) and Yoo *et al.* (1993) as:

$$S = 5P + 10Q - 10\sqrt{Q^2 - 1.25PQ} \quad 6.8$$

With  $S$  determined, the corresponding CN was then determined as:

$$CN = \frac{25400}{S+254} \quad 6.9$$

As the  $CN$  values correspond to different bulk densities, a relation between the  $CN$  and  $BD$  could be derived. Apart from the  $BD$  effect, the impact of the antecedent soil moisture content was also integrated into the modified  $CN$  value determination, to arrive at the overall equation:

$$CN = -14.4 + 45.3 * BD + 148 * \theta v \quad R^2 = 0.433 \quad 6.10$$

Other researchers also derived  $CN$  based on other soil factors, amongst which is the derivation of  $CN$  based on soil slope using 27 small rangeland, forest and agricultural watershed. They got a correlation of determination to be 0.49 which is statistically not different from our result (VerWeire *et al.*, 2005). Also, Simanton *et al.* (1996) noted that increasing drainage will cause decreasing  $CN$  value and got the statistic  $R^2$  relationship between  $CN$  and drainage in a linear equation to be 0.50.

### 6.3.2 Modification of bulk density effect on Curve Number and runoff

The calculated  $CN$  values using equation 6.10 corresponding to different bulk densities and initial soil water contents are summarized in Table 6.2. It can be observed that  $CN$  increased with  $BD$  and water content.

With regard to density effect, Treatment B20D1 (field bulk density 1.3 – 1.49 Mg/m<sup>3</sup> and 20 ton/ha biochar) gave the lowest  $CN$  value of 33.7 for the lowest initial soil water content.

Treatment D1 (1.3 – 1.49 Mg/m<sup>3</sup>) gave the average  $CN$  value of 75.9 under no biochar application.

Under D2 (1.63 – 1.89 Mg/m<sup>3</sup>) and D3 (1.54 – 1.74 Mg/m<sup>3</sup>), the average  $CN$  values increased to

82.6 and 86.3, respectively. These values are slightly higher than the tabulated CN of 81 reported for sandy clay loam with 0-2% slope in USDA SCS-CN (Ross *et al.*, 2018).

**Table 6.2: Measured bulk density and runoff for four rainfall events**

Event	Irrigation	BD	$\theta_v$	CN	Event	Irrigation	BD	$\theta_v$	CN
1	25	1.30	0.27	67.0	1	25	1.74	0.06	96.4
1	25	1.31	0.17	67.0	1	25	1.67	0.09	99.4
1	25	1.49	0.13	67.0	1	25	1.54	0.06	87.0
2	15	1.30	0.13	77.2	2	15	1.74	0.19	77.2
2	15	1.31	0.10	77.2	2	15	1.67	0.17	77.2
2	15	1.49	0.13	77.2	2	15	1.54	0.13	77.2
4	100	1.30	0.09	33.7	4	100	1.74	0.12	83.2
4	100	1.31	0.07	33.7	4	100	1.67	0.09	79.9
4	100	1.49	0.07	33.7	4	100	1.54	0.09	82.1
5	50	1.30	0.16	78.6	5	50	1.74	0.18	92.8
5	50	1.31	0.17	72.6	5	50	1.67	0.18	95.2
5	50	1.49	0.16	76.6	5	50	1.54	0.15	87.3
1	25	1.63	0.17	98.7	1	25	1.05	0.25	67.0
1	25	1.89	0.18	98.3	1	25	1.26	0.23	67.0
1	25	1.75	0.16	96.2	1	25	1.30	0.28	67.0
2	15	1.63	0.12	87.3	2	15	1.05	0.17	77.2
2	15	1.89	0.16	77.2	2	15	1.26	0.18	77.2
2	15	1.75	0.15	77.2	2	15	1.30	0.17	77.2
4	100	1.63	0.02	64.1	4	100	1.05	0.06	33.7
4	100	1.89	0.03	61.4	4	100	1.26	0.06	33.7
4	100	1.75	0.06	50.5	4	100	1.30	0.09	33.7
5	50	1.63	0.11	94.0	5	50	1.05	0.18	80.9
5	50	1.89	0.17	94.0	5	50	1.26	0.17	71.1
5	50	1.75	0.15	92.4	5	50	1.30	0.20	73.7

$\theta_v$ ; mean volumetric water content, BD; bulk density, CN; curve number

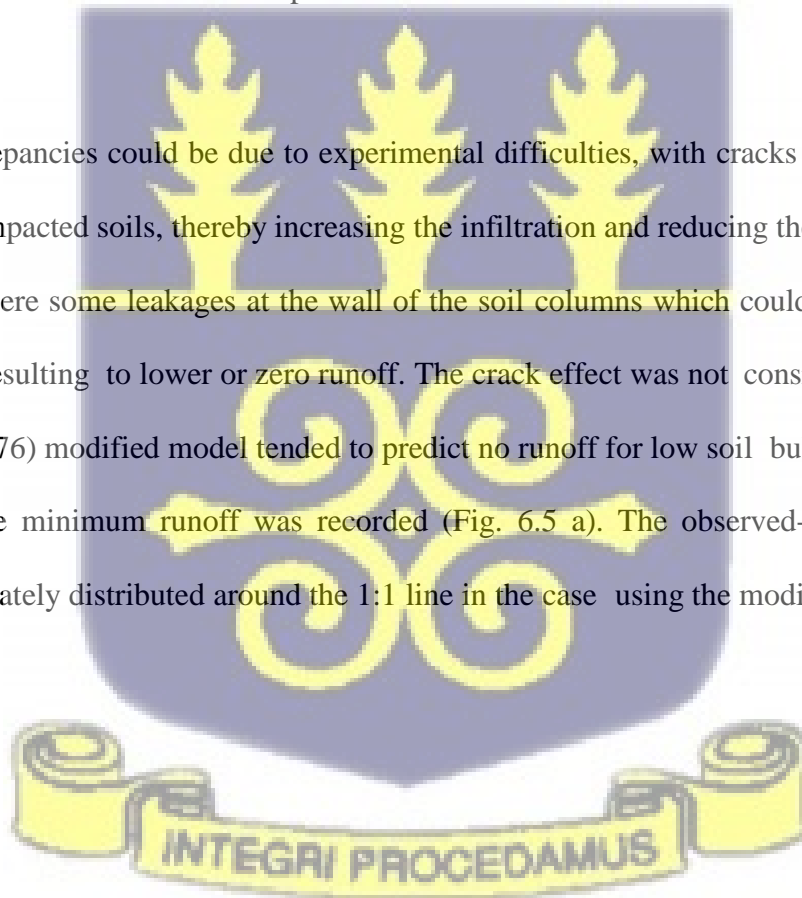
It is expected that biochar will improve the infiltration rate of the amended soil and reduce runoff. Increasing bulk density and antecedent water content increased the value of the curve number. The addition of biochar reduced the susceptibility of compacted soil to runoff. From Table 6.1, the CN for density D1 (field bulk density) reduced from  $\approx 76$  to 70 to 63.3 for biochar applications order of  $B0 > B10 > B20$ . Likewise, D2 and D3 reduced in the same descending order. In general, the biochar

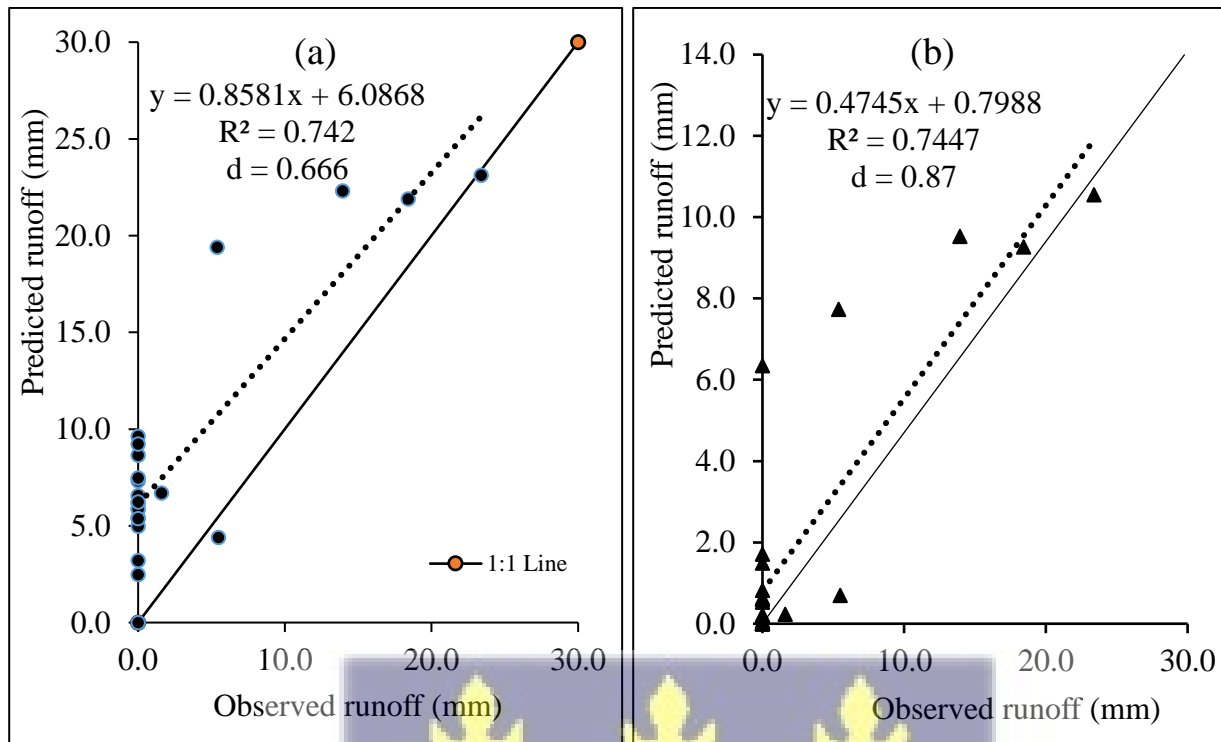
effect on the CN could be captured from the BD effect.

#### 6.4 Performance assessment of modified models on data sets.

Figure 6.5 presents the comparison of the predicted and observed runoff using the biochar/bulk density modified runoff models. In general, all the two models performed well with  $R^2$  of about 75% and Willmott index  $d > 0.6$ . Predictions using Ive *et al.* model matched almost the same ( $d = 0.666$  and  $R^2 = 0.742$ ) with that of SCS -CN model ( $d = 0.87$  and  $R^2 = 0.75$ ). The Ive *et al.* (1976) model slightly overestimated runoff for some of the treatments, especially the high soil bulk densities. Some of the observed-predicted pair's values were not well distributed around the 1:1 line basically because the models tended to predict some runoff values while none were observed (zero values).

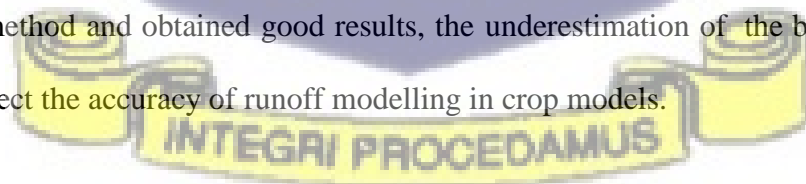
Part of the discrepancies could be due to experimental difficulties, with cracks developing in some of the highly compacted soils, thereby increasing the infiltration and reducing the runoff. In addition, probably there were some leakages at the wall of the soil columns which could have caused more water drainage resulting to lower or zero runoff. The crack effect was not considered in the models. The Ive *et al.* (1976) modified model tended to predict no runoff for low soil bulk density treatment (D1) while some minimum runoff was recorded (Fig. 6.5 a). The observed-predicted pair runoff values are moderately distributed around the 1:1 line in the case using the modified SCS-CN model.





**Fig 6.5: Comparison of measured and predicted runoff by the (a) Ive *et al.* (1976) and (b) NRCS SCS-Curve (1956) Number modified models.**

Efforts to derive the CN directly from bulk density are relatively few in the literature. In a recent study, Pugh (2020) derived CN values from soil bulk density and showed that the derived values were generally higher than those NRCS tabulated in the literature for similar soil conditions. This would imply that lower runoff would be predicted by the use of the tabulated than actual measured values. Though Hagen (2001) applied the water balance equation to predict runoff in a watershed based on the NRCS CN method and obtained good results, the underestimation of the bulk density effect on the CN could affect the accuracy of runoff modelling in crop models.



Modifications of the CN by the initial soil water content has also attracted research attention. Ali *et al.*, (2010) modified the CN by introducing a normalized initial rainfall index. Researchers have incorporated other factors that are supposed to modify the tabulated CN and obtained better model performance (Jain *et al.*, 2006). The effort to include the biochar effect via the bulk density could be seen as an additional effort to improve runoff modelling.

In general, while the two modified models performed well, the Ive *et al* model directly accounted for both the daily precipitation and the initial soil water content. The major challenge is the number of parameters that need to be evaluated. The NRCS CN model has relatively fewer parameters.



## 7 CHAPTER SEVEN

### SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This work investigated the effect of biochar application on crop growth and physical properties of compacted Toje soil (Rhodic Khandiustalf). The study was aimed at understanding how soil compaction affected crop and soil productivity and to what extent biochar application could be used as a remedial measure to offset the adverse impacts.

The study was divided into three parts: the first was to determine the biochar application effect on the physical properties of compacted soil, and the second was to study the growth, yield and water use efficiency of upland rice grown on biochar-amended compacted Toje soil under greenhouse conditions, and the third was to simulate the impact of biochar application on soils runoff, which is a major component of the water balance. Three compaction levels D1 (low: 1.33 Mg/m<sup>3</sup>), D2 (medium: 1.65 Mg/m<sup>3</sup>) and D3 (high: 1.78 Mg/m<sup>3</sup>) were considered in combination with three biochar application rates, B0 (0 ton/ha), B10 (10 ton/ha) and B20 (20 ton/ha). It was generally observed that the addition of biochar reduced the bulk density.

The first study investigated the relationship between biochar application and bulk density. The results showed that the bulk density decreased with increasing rice husk biochar application rates. The relation between the bulk density and biochar application gave a good coefficient of determination ( $R^2 = 0.9971$ ;  $p < 0.05$ ). The second part of the study, which examined the impact of soil compaction and biochar application on soil physical properties indicated that the porosity of all the biochar-applied treatments increased in consonance with the decline in bulk density. The observations showed that the lowest field capacity was observed for B0D3 (0 ton/ha, high bulk density) and the highest was for B0D1. However, the effect of biochar application on the field capacity ( $\theta_{FC}$ ) was not clear-cut. Both soil compaction and biochar application affected the moisture characteristics curve, in that soil

compaction, reduced the saturated water content  $\theta_s$  values from 0.25 g/g for B0D1 (non-compacted soil) to 0.20 g/g for the medium compacted soil (B0D2) and further to 0.17 g/g for the highly compacted soil (B0D3). Likewise, biochar application shifted the entire SMC curve to the right, indicating increased water content for the same tension. In general, biochar application to both compacted and non-compacted soil improved soil water retention. The saturated soil water content and residual soil water content ( $\theta_s$  and  $\theta_r$ ) increased with increasing biochar rates (Table 5.1) in the order of B0 < B10 < B20.

Biochar application significantly impacted the pore size distribution, such that the dominant pore radius increased from 0.0136 cm for the 0 ton/ha application to 0.015 cm for the 20 ton/ha biochar application. At 20 ton/ha biochar application rate, not only did the pore size increase but there appeared to be multiple “dominant” pores.

Both biochar and bulk density as well as their interactions showed a significant effect on the saturated hydraulic conductivity ( $K_{sat}$ ). Soil compaction had a greater impact on the  $K_{sat}$  with increasing compaction resulting in a significantly decreasing  $K_{sat}$ . The least  $K_{sat}$  of 0.78 cm/hr was observed for the highest bulk density (B0D3) with no biochar application. There were no significant differences between the medium and high bulk density at all biochar rates. Biochar application significantly increased the soil's hydraulic conductivity. The highest  $K_{sat}$  of 9.24 cm/hr was observed for D1 under 20 ton/ha biochar (B20D1) application. Therefore, it is concluded that biochar application can be a practice to offset soil compaction effects on soil water transport.

soil bulk density significantly affected the infiltration parameters. Increasing density reduced the value of all the parameters of infiltration for both Horton and Philips models ( $i_0$ ,  $i_c$ ,  $k$ ,  $S$  and  $K_{sat}$ ). The inclusion of biochar and bulk density effects in the Philips and Horton equations improved the predictions of infiltration. In the case of Philip's model, the agreement between the predicted and

observed cumulative infiltration was good ( $R^2 = 0.75$  and Willmott  $d$ -index of 0.66;  $p < 0.01$ ). The agreement was weaker in the case of Horton model ( $R^2 = 0.46$ ;  $d$ -index = 0.75;  $p < 0.01$ ) but the regression was significant. Therefore, it can be concluded that both the modified Philips and Horton's models gave reasonable predictions of the interactive effects of bulk density and biochar on infiltration. These equations, simple as they are, could provide useful tools for assessing the impact of biochar application on the hydraulic properties (infiltration) and hence runoff from compacted soils.

In the second study, rice growth and yield were investigated under 3 water application regimes: W1 (low), W2 (medium) and W3 (high). The results from greenhouse studies indicated that the rice plant under densities D1 and D2 reached 50% flowering at 72 DAP, but the development under D3 was faster, attaining 50% flowering at 69 DAP, which was significant. The application of biochar delayed development and increased the life cycle of the rice plant. Bulk density significantly affected rice growth. Regarding bulk density, the order of the yield was  $D1 > D2 > D3$ . There was a reduction in the production of rice shoots for treatments D2 and D3 compared to D1, caused by the restriction of root growth in compacted zones of the soil. The application of biochar offsets the soil compaction effect on shoot growth.

The application of biochar altered the runoff-and-drainage relations during the greenhouse studies. For the high-water regime, the per cent loss of water as runoff + drainage was 4%, 6% and 18% for B10D1W3, B10D2W3 and B10D3W3 treatments, respectively. Runoff reduced from 18% to 11% under D3W3 when biochar application increased from 0 to 10 tons/ha. The actual evapotranspiration ( $ET_a$ ) reduced with increasing soil bulk density for each water regime. Increasing bulk density didn't affect the emergence of the seeds as they all emerged within 5 to 6 days after sowing irrespective of the density levels.

Grain yield reduced with compaction, irrespective of the water regime. Water regime had a dominant

significant effect on grain yield. The application of biochar also significantly affected rice yield. The highest yield of 2,500 kg/ha was observed for biochar application of 10 tons/ha under density D1 and water regime W3. In general, the grain yield decreased in descending order of  $D1 > D2 > D3$ . However, biochar increased the grain weight at all density levels and water regimes. Root growth in the compacted layer (4.5 – 10 cm) was restricted and constituted not more than 13-15% of the total root mass. The highest root mass was recorded for treatment D1 and the lowest for D3. The Water Use Efficiency (WUE) decreased with increasing bulk density levels and water regimes except in the case of D2 for medium water regime. Biochar had only a small significant effect on the WUE of the compacted soils.

A multiple regression equation was derived to estimate the impact of biochar application, soil bulk density and water application on the combined runoff + drainage. Using the equation in the water balance enabled the estimation of the actual evapotranspiration,  $ET_a$  (mm). The application of the Doorembos and Kassam (1979) based on the estimated  $ET_a$  for the various treatments resulted in a satisfactory prediction of the rice yield with a coefficient of determination ( $R^2 = 0.67$ ) and a Willmott  $d$ -index of 0.89.

The third experiment which was also a laboratory study focused on the effect of soil compaction and biochar application on runoff. The data obtained were used to modify and assess the predictive ability of two widely used runoff models, namely the *Ive et al.* (1976) and NRCS-CN (1972) models. The modification of the models involved the derivation of functional relationships between runoff determinants and bulk density. Given that a significant relation was derived between bulk density and biochar application implied that biochar effects could be accounted for by bulk density. In general, the performance of the two modified models was acceptable with  $R^2$  close to 75% and Willmott index  $d > 0.60$ . Predictions using *Ive et al.* (1976) model matched almost the same ( $d = 0.666$  and  $R^2 = 0.742$ )

with that of SCS -CN model ( $d = 0.87$  and  $R^2 = 0.75$ ). Challenges of water running into cracks in the soil could be possible sources of experimental error and may diminish the agreement between the predicted and the observed runoff.

In general, it is concluded that soil compaction can be a major factor controlling the physical and hydrological properties of the soils. Increasing bulk density, which is becoming more common due to the adoption of conventional tillage involving the use of heavy machinery on poorly structured tropical soils, can increase runoff and adversely affect water availability and crop growth. Biochar application has been shown to offset this adverse impact. This study recommended the use of biochar as a soil amendment to offset the adverse effect of soil compaction.



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