



# Interactive effects of soil compaction, biochar application, and soil water regime on the growth, yield, and water use efficiency of upland rice



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## ABSTRACT

The mechanization of tropical agriculture by conventional tillage has enhanced production and contributed to soil compaction, which has long term adverse effects on soil and crop productivity. Application of biochar is among the several remedial measures proposed to offset the compaction problem. Yet, it is unclear how biochar interacts with varying soil water that occurs under variable weather to mitigate the compaction problem. In this study, a screen house experiment was conducted to investigate the growth, yield, and water use efficiency (WUE) of upland rice (*Nerica 14*) grown under a range of biochar-amended compacted soils and soil water conditions. The experimental design was a completely randomized design (CRD) in a factorial arrangement with three bulk density (D) levels (D1 = 1.30 Mg m<sup>-3</sup>, D2 = 1.50 Mg m<sup>-3</sup>, and D3 = 1.75 Mg m<sup>-3</sup>), two rates of rice husk biochar (RHB) application: (B) = 0 ton ha<sup>-1</sup>, and B10 = 10 ton ha<sup>-1</sup>, and three levels of seasonal irrigation (W1 = 391 mm, W2 = 419 mm, and W3 = 569 mm). Grain yield was influenced by biochar, bulk density and water regime. When averaged across irrigation levels, the B0 grain yields were 1336 kg ha<sup>-1</sup>, 947 kg ha<sup>-1</sup> and 636 kg ha<sup>-1</sup> for D1, D2 and D3, respectively. Biochar application reduced both the runoff, drainage, and improved the crop water use efficiency. In terms of WUE, the treatment combination of B10D1W1 and B10D3W3 recorded the highest (14.27 kg ha<sup>-1</sup> mm<sup>-1</sup>), and least (9.28 kg ha<sup>-1</sup> mm<sup>-1</sup>) values, respectively. Though biochar application improved the WUE under all density levels, high irrigation (W2, W3) could not compensate for the adverse effect of increasing soil density. It is concluded that the adverse impact of tillage-induced soil compaction on upland rice yield can be effectively alleviated by biochar application under varied soil water conditions.

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**Abbreviations:** B, biochar; RHB, rice husk biochar; CRD, completely randomized design; DAP, days after planting; D, density; ET<sub>a</sub>, actual evapotranspiration; PVC, polyvinyl chloride; W, water regime; WUE, water use efficiency; P, precipitation; Q, runoff; D<sub>r</sub>, drainage; ΔW, change in soil water storage.

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## Introduction

The mechanization of agriculture is a measure adopted by developing countries to achieve rapid growth in food production to meet the increasing demands of the growing population. Between 2000 and 2010, about 3000 large tractors were imported into Ghana and the trend continues to increase [1]. Though most farmers cannot acquire tractors, the Government's arrangement of tractor services enables farmers to access mechanization services. Survey reports by Cossar [2] indicated that by 2009, 31% of farmers in Ghana benefited from tractors services on their farms. A number of benefits are associated with mechanized agriculture compared to small-holder manual agriculture. These include increased farmed acreage, benefits of economies of scale, timely land clearing within a narrow planting window [2], increased labour productivity and the reduction in farm drudgery.

However, the long-term use of heavy machinery for conventional tillage also leads to several adverse impacts on soil and crop productivity. For many tropical soils with low structural stability, the sheer weight of the large machinery often leads to compaction depth far below the soil surface [3], even if there are no clear manifestations on the soil surface [4]. Arthur and Asamoah [5] observed that the severity of soil compaction due to heavy machinery also varied with land use and management in the semi-deciduous zone in Ghana. They showed that the bulk density of the subsoil reached 1.80 and 1.76 Mg m<sup>-3</sup> for conventionally tilled croplands and grasslands, respectively, compared with 1.44 Mg m<sup>-3</sup> for natural forest lands.

The consequences of soil compaction on soil processes and plant growth and development are numerous. Compaction depths of up to 50 cm as a result of tractor passes have been observed to inhibit seedling emergence [6]. Bawa et al. [7] observed that subsoil compaction decreased maize and soybean root growth. Many studies have documented soil compaction-induced adverse effects such as reduced soil pore space and water infiltration rate, increased potential for surface ponding, runoff and soil erosion, reduction in water holding capacity, and limitation of the soil volume explored by roots for water and nutrient uptake [8–10]. These effects generally reduce crop yield [11,12]. De Moraes et al. [13] observed a significant decline in maize root growth and yield with increasing soil compaction following varying numbers of tractor passes in Brazil. A review by Shaheb et al [14] indicated significant reduction in yield with increased tractor traffic, in some cases up to 50%.

The agronomic alleviation of the soil compaction problem has received scientific attention. Amendments shown to reduce the compaction problem include the application of poultry manure [7], or other organic wastes, all of which increased macro-porosity and decreased the bulk density significantly [15,16]. However, the challenge to alleviate the soil compaction, especially with fresh organic matter lies in the need to apply not only large quantities, but also frequently, due to their high decomposition rates. Biochar, as a light-weight organic material with a more stable carbon, has therefore attracted scientific attention for soil compaction amendment. Several studies have shown that biochar application to soils significantly improved soil physical [17–19], chemical [16,20,21], biological [21–23], and hydraulic [17], pollutants [24–26], greenhouse gas emissions [27], water use efficiency [28], and root growth and chemical composition [23,24] of plants. The improvement of soil physical properties by biochar [29], has been attributed to its large surface area, and the presence of internal micropores which increased the overall soil porosity [30–32]. Apart from biochar properties, the effectiveness of biochar application is also determined by the application rates and also by soil properties such as texture [33–35]. Some studies found improvement in physical properties only at high application rates (>15 ton ha<sup>-1</sup>) [36]. Others found no effects on soil water retention capacity for clayey soils, even at very high application rates [37,38]. Despite the apparent inconsistencies found in the literature with regard to biochar performance, Blanco-Canqui [36], following an extensive review, concluded that biochar generally has the potential to [28] reduce soil compaction effect.

The manner in which biochar interacts with factors such as soil water to affect agricultural productivity, especially under compacted soil conditions, has only received limited attention. Zhang et al. [39] investigated the interaction between irrigation and biochar application on the growth and yield of tomatoes and observed that biochar application under full irrigation and water deficit conditions increased tomato yield. By contrast, biochar application under moderate soil water resulted in a reduced yield. There is also some evidence suggesting that biochar application increased the water use efficiency of crops under drought conditions [40]. Though the study by Mannan et al. [41] also reported an increase in soybean growth when biochar was applied under drought conditions, the increase in growth was attributed to fertility enhancement. The lingering question is what role biochar application plays in water use by crops under varying soil water conditions, especially on compacted soils.

Conceivably, biochar application would reduce the mechanical impedance and strength of compacted soils [42,43], thereby enhancing root growth and possibly increasing the soil volume for exploration of water by the roots. High soil water regime resulting from high rainfall or irrigation would also decrease soil strength [44], and hence enhance root growth and water exploration to support plant growth. Therefore, both biochar application and high soil water regime would lead to the same effect on soil compaction, presumably in a synergistic manner to enhance crop productivity. Under low soil water regime, however, biochar application to a compacted soil would reduce the compaction effect but the extent to which the drought effect can be compensated for remains unclear. In effect, the soil water conditions under which biochar application should be recommended for compacted soils remains a research question.

This study aimed to investigate the response of an upland rainfed rice variety (*Nerica 14*), which is commonly grown under conventional tillage in Ghana, under different levels of soil compaction, irrigation, and biochar application rates, under greenhouse conditions.

## Materials and methods

### Soils and experimental treatment

Soil samples were collected from the University of Ghana farm, situated within the Coastal Savannah zone of Ghana's Greater Accra Region. The sampled soil belongs to the Toje series, which is classified as an Alfisol according to the USDA Soil Taxonomy. The study area is located approximately between latitudes  $0^{\circ} 8' 0''$  and  $0^{\circ} 12' 0''$  west, and  $05^{\circ} 38' 0''$  and  $05^{\circ} 42' 0''$  north.

Characterized by a mean annual temperature of  $27^{\circ}\text{C}$ , the study area receives an average annual rainfall of about 800 mm. The rainfall pattern follows a bimodal distribution, with the primary rainy season occurring from April to July, and a minor rainy season observed from September to November.

The soil samples were collected at a depth of 0-20 cm and subsequently sieved through a 4 mm mesh to remove any coarse materials.

Columns constructed from polyvinyl chloride (PVC) pipes of 35.0 cm height, 16.0 cm internal diameter and cross-sectional area of  $201\text{ cm}^2$  were used in the study. The PVC columns had runoff holes drilled at 5.0 cm below the upper end, whereas the lower end was closed with an end cap with drilled holes to allow drainage. The depths from 10 to 35 cm were packed with the soils to a bulk density, D1 ( $1.34\text{ Mg m}^{-3}$ ). The 5 to 10 cm section was packed with soils that were amended with biochar at two rates: B0 (0-ton  $\text{ha}^{-1}$ ) and B10 (10-ton  $\text{ha}^{-1}$ ) and three bulk densities: D1 ( $1.34\text{ Mg m}^{-3}$ ), D2 ( $1.50\text{ Mg m}^{-3}$ ), and D3 ( $1.75\text{ Mg m}^{-3}$ ) (Table 1). The top 0 - 5 cm section was also packed with biochar-amended soils. The packing of the soils in the PVC columns was to achieve the maximum compaction within the 5 - 10 cm depth.

The soil compaction was achieved by applying varying number of blows of a 5- kg rammer. The biochar was produced from rice husk pyrolysed at  $350^{\circ}\text{C}$ . Apart from the biochar and soil compaction treatments, an additional factor that was investigated was irrigation level, introduced at 3 levels: W1 (391 mm), W2 (419 mm), and W3 (569 mm). The irrigation levels were chosen to mimic typical poor, normal and good seasonal rainfall conditions at the location of soil sampling. The poor, normal and good seasons corresponded to the years 1984, 1970 and 2003. The irrigation was applied using a rainfall simulator mounted above the columns. All the treatments were replicated 3 times giving a total of 54 units.

### Planting and data collection

The soil columns were arranged in a screenhouse in a completely randomized design (CRD). Rice (*Nerica 14*) was planted in the PVC soil columns and the equivalent of  $60\text{ kg N ha}^{-1}$ ,  $45\text{ kg P}_2\text{O}_5\text{ ha}^{-1}$ , and  $45\text{ kg K}_2\text{O ha}^{-1}$  were applied using Ammonium sulphate (split application), Triple Superphosphate and Muriate of potash, respectively. The phosphorus and potassium fertilizers and half of the nitrogen fertilizers were applied, 7 days after planting (DAP). The remaining half of the nitrogen was applied 35 DAP. All the treatments were watered for the first 2 weeks and thereafter, the different water regimes were imposed. The irrigation regimes followed strictly the daily rainfall distribution for the years 1984, (poor rain-

**Table 1**  
Description of the combination of factor in each treatment.

Treatment name	Biochar rate -B (ton $\text{ha}^{-1}$ )	Bulk density -D ( $\text{Mg m}^{-3}$ )	Irrigation Level-W (mm)
B0D1W1	0	1.33	391
B0D2W1	0	1.51	391
B0D3W1	0	1.79	391
B0D1W2	0	1.33	419
B0D2W2	0	1.51	419
B0D3W2	0	1.79	419
B0D1W3	0	1.33	569
B0D2W3	0	1.51	569
B0D3W3	0	1.79	569
B10D1W1	10	1.33	391
B10D2W1	10	1.51	391
B10D3W1	10	1.79	391
B10D1W2	10	1.33	419
B10D2W2	10	1.51	419
B10D3W2	10	1.79	419
B10D1W3	10	1.33	569
B10D2W3	10	1.51	569
B10D3W3	10	1.79	569

(levels of soil compaction (bulk densities; D1- $1.33\text{ Mg m}^{-3}$ , D2- $1.51\text{ Mg m}^{-3}$  & D3-  $1.75\text{ Mg m}^{-3}$ ), biochar rates (B0 - 0 biochar & B10 - 10 tons  $\text{ha}^{-1}$ ), and levels of irrigation (W1- 391 mm, W2 - 419 mm & W3- 569 mm)).

fall), 1970 (normal rainfall) and 2003 (good rainfall). All the PVC-packed soil columns were weighed at the onset and at the end of the experiment.

Plant development data include days to emergence, 50% flowering and maturity. For above-ground growth, the rice plant was harvested at maturity and separated into grains and straw. The straws were dried at 70°C for three days and the dry weight was determined. For grain yield determination, the separated panicles were air-dried after which the grains were removed, and the unfilled grains were separated from the filled ones. The filled grains were then weighed.

The below-ground growth was determined by carefully removing the soil monoliths from the PVC columns and cutting them into 3 sections: top 5 cm, 5-10 cm, and 10 - 35 cm. The sectioned soils were separately washed in bowls and the roots in each section separated. The roots were dried at 70°C for three days and weighed on a sensitive Mettler balance. The soils in the bowls were oven-dried at 105°C for four days and the dried weight was determined. The dry weight of soil and volume of each section was used to determine the actual bulk densities of the different depths along the soil column.

#### Water balance and crop water use

Daily values of the water balance components (irrigation,  $P$ , runoff,  $Q$ , and drainage  $D_R$ ) were determined for all 54 experimental units. At the end of the experiment, the daily values were cumulated to obtain the seasonal values. The seasonal change in water storage,  $\Delta W$ , was determined from the difference in column weight at the beginning and end of the growing period, and used to determine the actual seasonal total water use, or actual evapotranspiration,  $ET_a$  (mm) for each treatment as:

$$ET_a = P - Q - D_R \pm \Delta W \quad (1)$$

with all the terms of Eq. (1) having units of mm.

The Water Use Efficiency (WUE) was determined as:

$$WUE = \frac{\text{Grain weight (kg ha}^{-1}\text{)}}{ET_a \text{ (mm)}} \quad (2)$$

#### Statistical analysis

Microsoft Excel (Version 2016) was used for data entry and graphical representation. A comprehensive Two-way Analysis of Variance (ANOVA) was conducted using the GenStat statistical software (12th edition, 2009) to assess the significance of treatment effects. This analysis considered the specific experimental design with varying combinations of treatments, allowing for the examination of main and interactive effects of biochar, water regime, and density levels on the response variables.

To compare treatment means and identify significant differences, the Duncan Multiple Range Test was employed as a post hoc analysis. This test enabled the determination of statistically significant variations among treatment groups at a 5% confidence level. Through these data management and statistical analyses, we ensured a robust evaluation of the effects of treatments and obtained valuable insights into the experimental outcomes, facilitating accurate interpretations of the research findings.

## Results and discussion

### Effects of treatment on plant development

Plant development under the different treatments is summarized in Table 2. Given that all treatments were well watered during the first 14 days after planting, emergence for all treatments was between 5 to 6 days and there was no significant difference among treatments. Though there is evidence that soil compaction can delay seed emergence [8], our findings did not support this because of the initial ample irrigation (irrigation will reduce soil strength so compaction effect is offset as the soil becomes soft). Three compounding treatments affected the speed of development of the rice plant to flowering (Table 2).

At first, under no biochar application, the low irrigation (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 W2 (normal rainfall) and W3 (good rainfall) reached 50% flowering at 71 DAP. Within a given irrigation level, days to 50% flowering varied with bulk density treatment. The rice plant under densities D1 and D2 reached 50% flowering at 72 DAP, but the development under D3 was faster, attaining 50% flowering 3 days earlier, which was statistically significant ( $p \leq 0.05$ ). When biochar was applied at 10 ton ha<sup>-1</sup>, the W1 delayed the development of flowering (71 DAP), followed by W2 (68) and W3 (65 DAP). With regard to the density effect, D1 delayed development of flowering whereas the higher densities D2 and D3 somewhat accelerated the development of flowering.

Plant development response to environmental stresses has been the focus of study for many years. McMaster et al. [45] reviewed the literature and summarized the determinants as air temperature, photoperiod, water and nutrient stresses.

**Table 2**  
Treatment effects on plant development (Days After Planting: DAP).

Treatment name	Bulk density -D (Mg m <sup>-3</sup> )	Biochar rate -B (ton ha <sup>-1</sup> )	Irrigation Level-W (mm)	Emergence DAP	Flowering DAP	Maturity DAP
B0D1W1	1.33	0	391	5	74	104
B0D2W1	1.51	0	391	6	73	103
B0D3W1	1.79	0	391	6	69	98
B0D1W2	1.33	0	419	5	72	102
B0D2W2	1.51	0	419	6	72	102
B0D3W2	1.79	0	419	6	68	96
B0D1W3	1.33	0	569	5	72	99
B0D2W3	1.51	0	569	6	72	97
B0D3W3	1.79	0	569	6	69	98
B10D1W1	1.33	10	391	5	73	103
B10D2W1	1.51	10	391	5	73	103
B10D3W1	1.79	10	391	5	69	98
B10D1W2	1.33	10	419	5	68	99
B10D2W2	1.51	10	419	5	60	99
B10D3W2	1.79	10	419	5	61	97
B10D1W3	1.33	10	569	5	71	99
B10D2W3	1.51	10	569	5	72	99
B10D3W3	1.79	10	569	5	65	97
LSD (0.05)				1.07	1.47	1.34
CV (%)				11.9	1.8	1.1

Bulk density (D1 - 1.3 Mg m<sup>-3</sup>; D2 - 1.5 Mg m<sup>-3</sup>; D3 - 1.7 Mg m<sup>-3</sup>), irrigation levels (W1 - 391 mm; W2 - 419mm; W3 - 569 mm) and Biochar (B0 - 0 ton ha<sup>-1</sup>; B10 - 10 ton ha<sup>-1</sup>). LSD and CV are bulk density, biochar rate, least significant difference, and coefficient of variation, respectively. Any two treatment combination in each column with mean differences above the LSD values are significantly different from each other.

Given that the air temperature was uniform in the greenhouse, differences in the observations cannot be attributed to temperature effects. With regard to water stress, Sah et al [46] and Campos et al. [47] observed a delay in maize development under severe water stress conditions imposed at flowering and graining stage of the crop. Observations in this study con-forms to other studies where water stress delayed flowering. Yet, there are also observations indicating that generally, water stress or low water availability promoted early flowering, a strategy for survival by the plant Shavrukov et al [48]. Mott and McComb [49] discussed the apparent inconsistencies with regard to water stress effect on plant development. With regard to soil compaction, Hoque and Kobata [50] attributed delayed heading in rice to soil compaction.

The days to maturity were prolonged under a low irrigation (W1) and increasing bulk density. Under optimum conditions of low density D1 and high irrigation W3 under B0, the days to maturity was 99 DAP. For the extreme situation of high soil density (D3) and low irrigation (W1), the days to maturity under B0 was 98. Biochar application to the low density (D1) and high irrigation (W3) did not alter the development to maturity (97 DAP). However, the combination of biochar application, (B10), high density (D3), and low irrigation (W1) delayed the development to maturity (103 DAP). In summary, our findings generally indicated that under extreme stress conditions of low irrigation and high bulk density, the development to both flowering and maturity were delayed, irrespective of biochar application.

#### Effect of treatment on above-ground growth

The shoot dry weight of rice was significantly influenced by bulk density, and the interaction between biochar and bulk density (Fig. 1). Generally, shoot dry weight declined with increasing soil compaction (bulk density) especially when no biochar was applied. The highest average shoot dry weight of 2500 ±100 kg ha<sup>-1</sup> was recorded under D1 and declined to 2000 kg ha<sup>-1</sup> under D3. The effect of biochar on shoot dry weight was clearly significant under the highest bulk density (D3). This suggests an interaction between biochar and soil density. When biochar was applied at D3 and low irrigation level (W1), a substantial increase of 24% in shoot dry weight was observed. Overall, these findings suggest that biochar application on compacted soil conditions can significantly influence the shoot dry weight of rice. At low soil density biochar effect was not clear-cut. Even though it may be expected that biochar application will increase porosity and enhance water storage thereby increasing growth, our data show that biochar application at 10 ton ha<sup>-1</sup> did not influence the shoot biomass at the lower soil compaction levels.

Unlike shoot growth, there were significant differences ( $p \leq 0.05$ ) in grain weight for the different irrigation levels and biochar application rates (Fig. 2). Grain yield decreased with compaction, irrespective of the irrigation level. Under no biochar application condition, the average yield of rice for D1 across all irrigation levels was 1336 kg ha<sup>-1</sup>, reducing to 947 kg ha<sup>-1</sup> under D2 and 636 kg ha<sup>-1</sup> under D3. Previous studies have also confirmed the impact of soil compaction on grain yield [50]. Irrigation level also had a significant effect on grain yield. Under no biochar application, the yield (averaged over density treatments) was 591 kg ha<sup>-1</sup>, 1042 kg ha<sup>-1</sup> and 1282 kg ha<sup>-1</sup> for W1, W2 and W3, respectively. It may be inferred that soil compaction under low irrigation (W1), reduced the yield by 41% and 68% for D2 and D3 respectively. In

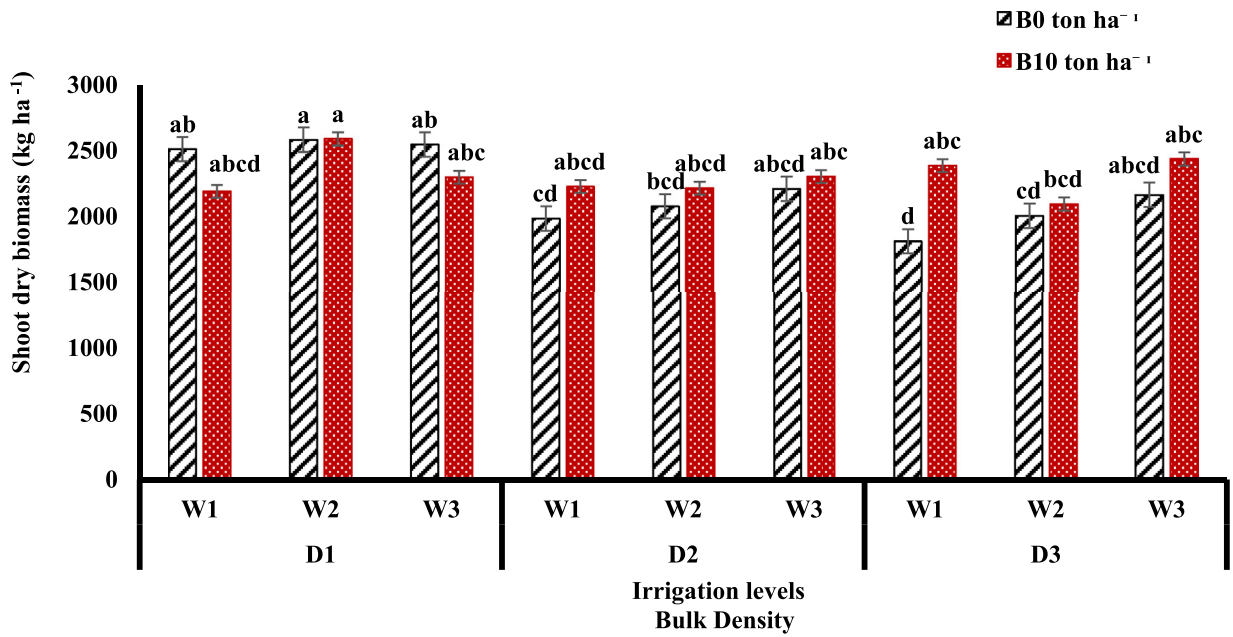


Fig. 1. Effect of biochar on shoot dry biomass as affected by varying bulk density (D1 - 1.3 Mg m<sup>-3</sup>; D2 - 1.5 Mg m<sup>-3</sup>; D3 - 1.7 Mg m<sup>-3</sup>), irrigation levels (W1 - 391 mm; W2 - 419mm; W3 - 569 mm), and biochar levels (B0 - No biochar applied and B10 - biochar at 10 tons ha<sup>-1</sup>). Treatments with common mean separation letters are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

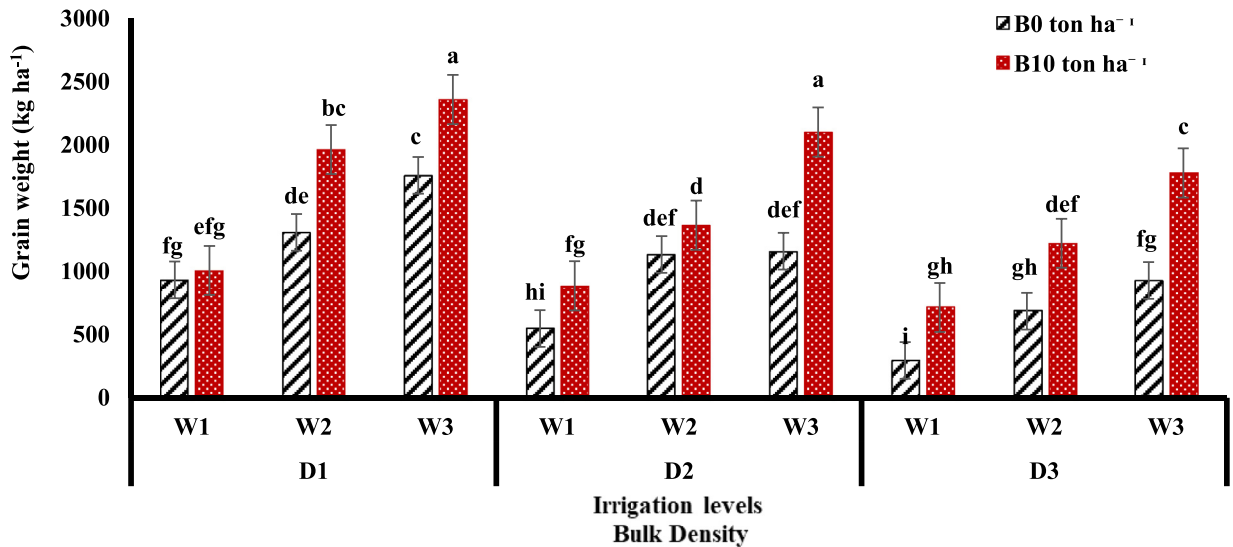
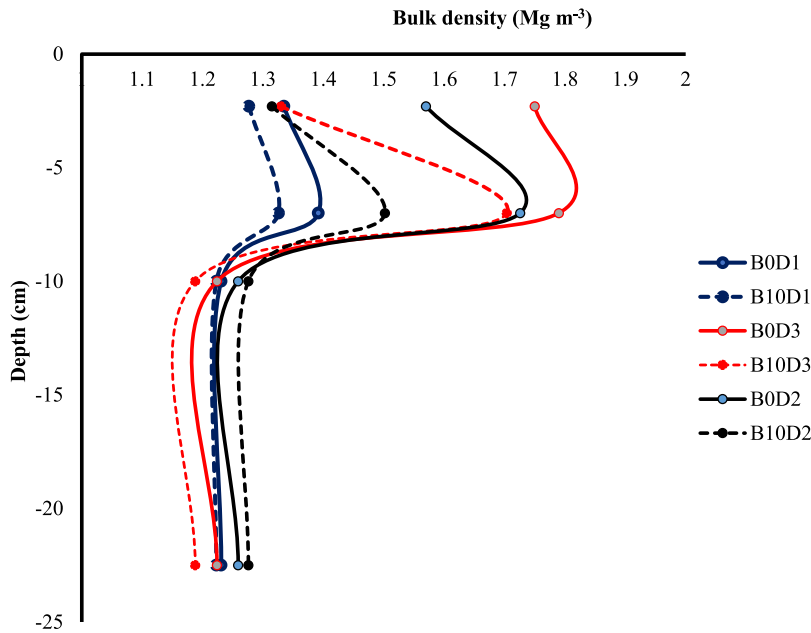


Fig. 2. Effect of biochar on grain weight for varying density (D1 - 1.3 Mg m<sup>-3</sup>; D2 - 1.5 Mg m<sup>-3</sup>; D3 - 1.7 Mg m<sup>-3</sup>) and irrigation levels (W1 - 391 mm; W2 - 419mm; W3 - 569 mm), and biochar levels (B0 - No biochar applied and B10 - biochar at 10 tons ha<sup>-1</sup>). Treatments with common mean separation letters are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

the case of high irrigation (W3), the yield reductions were 34% and 47% for bulk densities D2 and D3, respectively. Thus, the yield reduction effect of soil compaction could only be offset at the high-water level, especially when biochar is applied, but not under the drought conditions. It is generally known that biochar application to compacted soils decreased bulk density and hence, soil strength [42,43], by enhancing permeability of the soil for roots to explore for resources.



**Fig. 3.** Variation of the bulk density with depth among treatments with varied compaction and biochar application rates. D1 ( $1.3 \text{ Mg m}^{-3}$ ), D2 ( $1.5 \text{ Mg m}^{-3}$ ), D3 ( $1.7 \text{ Mg m}^{-3}$ ), B0 ( $0 \text{ ton ha}^{-1}$ ), B10 ( $10 \text{ ton ha}^{-1}$ )

**Table 3**  
Root mass at different depths of the biochar-amended soil columns.

Treatment ID	Soil bulk density ( $\text{Mg m}^{-3}$ )	Biochar rate ( $\text{ton ha}^{-1}$ )	Root mass (g) _____ Soil depth		
			0-5 cm	5-10 cm	10-22.5 cm
B0D1	1.33	0	2.90 (43)	0.93 (14)	2.84 (43)
B10D1	1.33	10	3.89 (51)	1.10(15)	2.61 (34)
B0D2	1.51	0	2.31 (43)	0.71 (13)	2.36 (44)
B10D2	1.51	10	2.83 (49)	0.86 (15)	2.12 (36)
B0D3	1.79	0	2.15 (48)	0.68 (15)	1.62 (37)
B10D3	1.79	10	2.45 (43)	0.83 (15)	2.39 (42)
	LSD ( $p < 0.05$ )		0.558	0.042	1.08
	CV (%)		21.1	5.1	39.6

Biochar (B0 -  $0 \text{ ton ha}^{-1}$ ; B10 -  $10 \text{ ton ha}^{-1}$ ). Numbers in parentheses represent % root mass. LSD and CV are the least significant difference and coefficient of variation, respectively.

#### Variation of bulk density with depth and below-ground growth

The variation of the bulk densities with depth is shown in Fig. 3. Treatments receiving biochar application tended to have lower bulk densities than those without biochar application. The lowest bulk density within the compacted zone was for treatment combination B10D1 whereas the highest density was for B0D3.

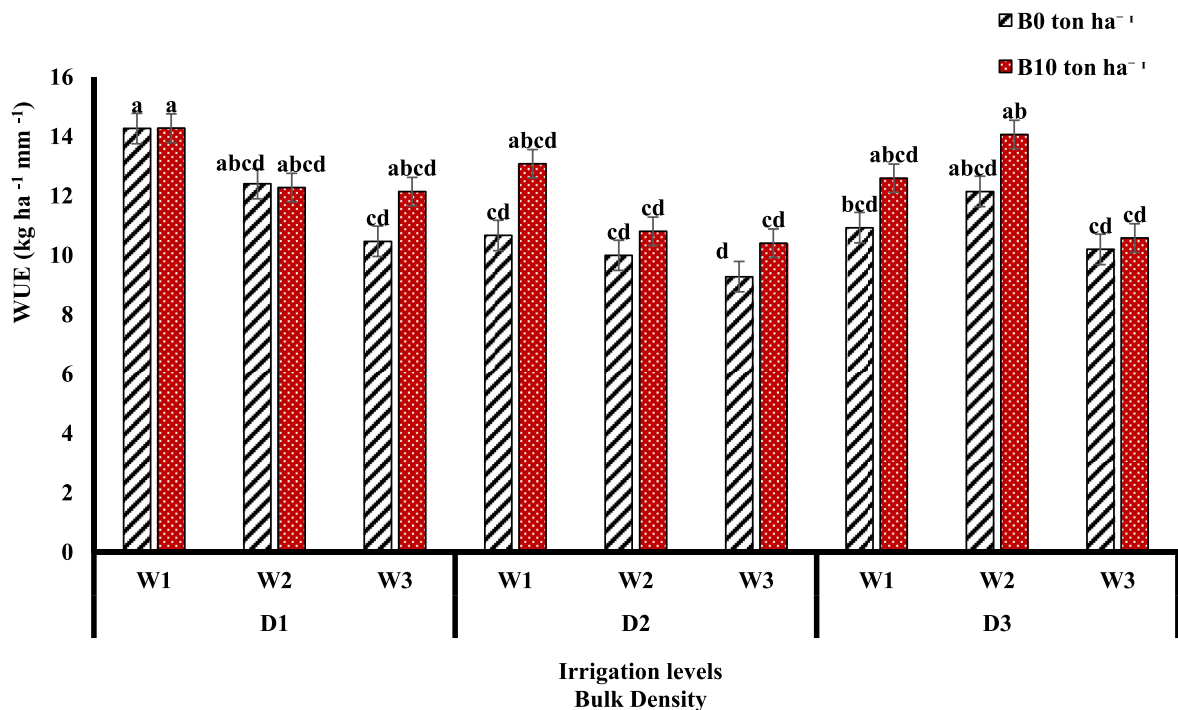
Plant root mass distribution followed the variation of the bulk density with depth (Table 3). Under the control treatment (B0D1), the total root mass was 6.67 g with about 43% of the total mass in the top 5 cm of the soil (Table 3) and 14% in the middle-compacted layer. Biochar application increased the total root mass to 7.60 g with 51% of the total root mass concentrated in the top 5 cm. Under B0D2 conditions, total root mass decreased to 5.38 g with about 43% in the top layer. Again, biochar application (B10D2) increased the total root mass to 5.81 g with 49% in topsoil. Root growth in the compacted layer (5 - 10 cm) was restricted and constituted 13 and 15% of total root weight for without and with biochar application, respectively. For the high-density treatments (B0D3 and B10D3) total root mass with and without biochar application were 4.45 and 5.67 g, respectively with about 48% and 43%, respectively in the top 5 cm and about 15% in each of the two biochar levels in the compacted layer (5 - 10 cm). Root elongation reduced as it experienced soil hardening in the compacted subsoil layer.

The impact of soil compaction on root development and growth has also been the focus of many studies. The observations of this study aligned with reports by Seixas and Tim [51] who studied compaction effects on crop growth and yield. Others such as Ocloo et al. [52] observed a decline of maize and soybean root mass with soil compaction or increasing bulk density in some Ghanaian soils but pointed out that there were varietal differences in response. Likewise, Håkansson

**Table 4**  
Interactive effects of biochar, irrigation level and bulk density on water balance components.

Water balance components	D1	D2	D3	D1	D2	D3	D1	D2	D3
	Low irrigation level (W1)			Medium irrigation level (W2)			High irrigation level (W3)		
	Biochar 0-ton ha <sup>-1</sup>								
Total runoff (mm)	0.27 h	6.09 g	41.72 d	0.30 h	44.31 d	68.82 b	2.22 h	100.51 a	101.53 a
Total Drainage (mm)	0.00 h	0.00 h	0.00 h	7.73 h	0.00 h	0.00 h	59.37 f	36.13 g	27.80 g
ETa (mm)	242.10 h	242.90 g	206.40 h	314.10 de	285.20 ef	279.00 f	423.30 a	349.90 c	353.10 c
±ΔW (mm)	96.19 fgh	89.55 fgh	90.38 fgh	97.01 fgh	89.55 fgh	71.31 h	84.58 gh	82.92 gh	87.06 fgh
	Biochar 10-ton ha <sup>-1</sup>								
Total runoff (mm)	0.00 h	1.79 h	15.19 f	0.00 h	6.65 g	26.92 e	1.08 h	13.83 f	63.70 c
Total Drainage (mm)	0.00 h	0.00 h	0.00 h	0.00 h	0.00 h	0.00 h	67.90 f	60.27 f	27.33 g
ETa (mm)	229.90 gh	237.20 g	233.00 gh	327.90 cd	294.70 ef	308.40 def	417.60 ab	398.40 ab	388.90 b
±ΔW (mm)	108.62 fg	99.50 fgh	90.38 fgh	91.21 fgh	117.74 f	83.75 gh	82.92 gh	97.01 fgh	89.55 fgh

All values are in mm. Common letters are not significantly different ( $p < 0.05$ ) across rows for each components according to Duncan's 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 ( $1.75 \text{ Mg m}^{-3}$ ). ETa and  $\Delta W$  are evapotranspiration and change in water storage, respectively.



**Fig. 4.** Effect of biochar application rate on water use efficiency (WUE) as affected by bulk density (D1 -  $1.3 \text{ Mg m}^{-3}$ ; D2 -  $1.5 \text{ Mg m}^{-3}$ ; D3 -  $1.7 \text{ Mg m}^{-3}$ ), irrigation levels (W1 - 391 mm; W2 - 419mm; W3 - 569 mm), and biochar levels (B0 - No biochar applied and B10 - biochar at 10 tons ha<sup>-1</sup>). Treatments with common mean separation letters are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

and Lipiec [53] also observed a decreasing dry root mass with increasing bulk density. Ozpinar and Cay [54] reported the inhibition of upland rice root elongation beyond 0-10 cm at a density of  $1.5 \text{ Mg m}^{-3}$ .

Our findings indicated that the overall root growth reduced under high bulk density and low irrigation (W1) treatments. Also, though root growth was severely restricted in the compact zone, recovery was good in the deeper layers, which could improve water uptake if available. Biochar application tended to improve root mass in the topsoil sections of the columns.

#### Effect of treatments on water balance and water use efficiency

The water used by the plant varied with bulk density and biochar application (Table 4). The actual evapotranspiration (ETa) decreased with increasing soil bulk density at each irrigation level. Under the low irrigation level (W1), the seasonal ETa increased from 206 to 242 mm, for D3 and D1, when no biochar was applied. For the same B0 biochar application rate, the ETa increased from 279 to 314 mm for D3 and D1 under the medium irrigation level (W2). For the high irrigation

level (W3) and 0 ton ha<sup>-1</sup> biochar application, the *ETa* was 350 and 423 mm, for D3 and D1, respectively. When biochar application increased to 10 ton ha<sup>-1</sup>, the *ETa* was not significantly different under the various irrigation levels, except for the medium irrigation (W2). The effects of soil compaction on total drainage were only evident under high irrigation levels, irrespective of biochar application. In general, high irrigation resulted in high runoff + drainage, as density increased. This effect could be offset by biochar application.

Figure 4 shows that with the exception of D2, the WUE decreased with increasing bulk density and irrigation levels. The combination of low density (D1) and low irrigation (W1) had a significantly higher WUE of 14.27 kg ha<sup>-1</sup>mm<sup>-1</sup> than that (9.28 kg ha<sup>-1</sup>mm<sup>-1</sup>) observed for the treatment combination D3W3. Though biochar application significantly increased the WUE of the compacted soils, increased irrigation could not compensate for the increasing density effect.

The higher WUE of 14.27 kg ha<sup>-1</sup>mm<sup>-1</sup> observed for W1 (low irrigation) could be attributed to the reduction of transpiration and evaporation caused by inadequate availability of water for plant use. Even with biochar application, the relatively higher *ETa* of 350 mm for treatment combination D3W3 compared with 206 mm for D1W1, together with the significant reduction in yield (68%) under D3W3 resulted in a reduced WUE. In effect, increased irrigation could not offset the density effect. This may be attributed to the low root growth under the high-density conditions.

Researchers have related the changes in WUE to climatic conditions such as vapour pressure deficit (VPD), average relative humidity [55,56] and limitation to water supply which can be water stress conditions. Amongst the climatic conditions, VPD has a significant effect on the WUE under non-limiting soil water conditions [57]. However, high WUE under water-limiting conditions is 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 [58]. Also, Jin et al [59] reported increased WUE under water stress condition. Similar effects were reported by other researchers [60–62]. For the high bulk density treatments (D3), low irrigation (W1) under B0 would explain both the low yield and water use, resulting in an WUE of 10.67 kg ha<sup>-1</sup>mm<sup>-1</sup> (Fig. 4). The application of biochar (B10) under same water and bulk density conditions somewhat compensated for the compaction effect by improving the WUE to 13.08 kg ha<sup>-1</sup>mm<sup>-1</sup>. The general trend was that addition of biochar to compacted soils increased the WUE across different soil water regimes.

## Conclusions

Plants respond to multiple factors in an integrated way to either ensure survival or maximize production. Among the factors studied in this work are water, soil compaction and management and their interactions on the growth, yield and water use efficiency of upland rice (*Nerica* -14), given that these factors determine crop productivity under mechanized agriculture and climate variability. Our findings showed that the effect of biochar application on plant development was not clearcut, though there was an accelerated development to flowering at high biochar application rate. Though biochar application reduced bulk density, it could not offset the negative impact of water stress effects. Thus, for crop growth and yield, adequate water is also essential. Our study again, showed that when averaged across densities, irrigation level significantly increased grain yields in the order W3 > W2 > W1. However, the impact of soil compaction on the water use cannot be ignored, given that the overall water use of the plant did not only increase with decreasing bulk density, but is also depended on water regime. High biochar application resulting in decreased soil compaction did not lead to significant increase in crop water use efficiency under medium to high level water regime, suggesting limitations of biochar effect. This study suggests that the value of biochar application with regard to water balance can be attributed to the significant reduction in runoff, especially under high irrigation. Thus, an implementation of the biochar application technology to reduce soil compaction must be designed taking into consideration the soil water regime. With regard to below ground growth, the response of the roots to the interactive effects appeared to depend on how the plants re-distribute their roots with depth, especially the recovery in the lower soil sections beyond the compacted ones. Treatment combinations that improved root growth beyond the compacted zone enabled a better exploration of water stored at the lower soil depths, and showed better crop growth and yield. It is concluded that though biochar application reduced soil compaction effect on upland rice yield, a further understanding of the overall interactions between biochar and soil water regime is necessary to improve the biochar technology.

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## CRediT authorship contribution statement

Conceptualization, S.G.K.A. and D.S.M. Methodology, A.E.A.; Formal analysis, A.E.A.; Investigation, A.E.A., SGKA, D.S.M.; Writing – original draft preparation, A.E.A.; Writing – review and editing, SGKA, D.S.M. All authors have read and agreed to the published version of the manuscript.

## Declaration of competing interest

The Authors hereby declare of having no competing interest.

## References

- [1] X. Diao, F. Cossar, N. Houssou, S. Kolavalli, Mechanization in Ghana: Emerging demand, and the search for alternative supply models, *Food Policy* 48 (2014) 168–181.
- [2] F.R. Cossar, Agricultural development, mechanization, and rental markets: theory and empirics from Ghana, University of Oxford, 2018.
- [3] A. Bot, J. Benites, The importance of soil organic matter: Key to drought-resistant soil and sustained food production, Food & Agriculture Org, 2005.
- [4] D.J.C.A.E. McGarry, in: farmers experiences, innovations, socio-economy, policy, Tillage and soil compaction, 2003, pp. 307–316.
- [5] M.D. Arthur, E.F. Asamoah, Soil compaction under three different land use systems within the semi-deciduous agroecological zone of Ghana, *Int. J. Plant Soil Sci* 13 (2016) 1–12.
- [6] S. Gürsoy, Soil compaction due to increased machinery intensity in agricultural production: its main causes, effects and management, *Technology in Agriculture* (2021) 1–18.
- [7] S. Bawa, C. Quansah, H. Tuffour, A. Abubakari, C. Melenya, Root Growth Responses of Maize (*Zea mays* L.) and Soybean (*Glycine max* L.) to Soil Compaction and Fertilization in a Ferric Acrisol, *Journal of Experimental Agriculture International* 35 (2019) 1–11.
- [8] T.F. Guerin, The effect of interactions between soil compaction and phenol contamination on plant growth characteristics: Implications for scaling bioremediation at industrial sites, *Journal of Environmental Management* 302 (2022) 114017.
- [9] P.B. Obour, C.M. Ugarte, A meta-analysis of the impact of traffic-induced compaction on soil physical properties and grain yield, *Soil Tillage Research* 211 (2021) 105019.
- [10] H. Mozaffari, A.A. Moosavi, A.R. Sepaskhah, Land use-dependent variation of near-saturated and saturated hydraulic properties in calcareous soils, *Environmental Earth Sciences* 80 (2021) 1–17.
- [11] M. Hamza, W.K. Anderson, Soil compaction in cropping systems: A review of the nature, causes and possible solutions, *Soil Tillage Research* 82 (2005) 121–145.
- [12] B. Radford, B. Bridge, R. Davis, D. McGarry, U. Pillai, J. Rickman, P. Walsh, D. Yule, Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic, *Soil Tillage Research* 54 (2000) 155–170.
- [13] M.T. De Moraes, H. Debiasi, J.C. Franchini, J.d.A. Bonetti, R. Levien, A. Schnepf, D. Leitner, Mechanical and hydric stress effects on maize root system development at different soil compaction levels, *Frontiers in Plant Science* 10 (2019) 1358.
- [14] M.R. Shaheb, R. Venkatesh, S.A.J.J.o.B.E. Shearer, A review on the effect of soil compaction and its management for sustainable crop production (2021) 1–23.
- [15] A. Rivenshield, N.L. Bassuk, Using organic amendments to decrease bulk density and increase macroporosity in compacted soils, *Arboriculture Urban Forestry* 33 (2007) 140.
- [16] D.S. MacCarthy, E. Darko, E.K. Nartey, S.G. Adiku, A. Tetey, Integrating biochar and inorganic fertilizer improves productivity and profitability of irrigated rice in Ghana, West Africa, *Agronomy* 10 (2020) 904.
- [17] L. Liang, F. Xi, W. Tan, X. Meng, B. Hu, X. Wang, Review of organic and inorganic pollutants removal by biochar and biochar-based composites, *Biochar* 3 (2021) 255–281.
- [18] E. Gavili, A.A. Moosavi, F. Moradi Choghamarani, Cattle manure biochar potential for ameliorating soil physical characteristics and spinach response under drought, *Archives of Agronomy and Soil Science* 64 (2018) 1714–1727.
- [19] Y. Zhang, J. Wang, Y. Feng, The effects of biochar addition on soil physicochemical properties: A review, *Catena* 202 (2021) 105284.
- [20] E. Gavili, A.A. Moosavi, M. Zahedifar, Integrated effects of cattle manure-derived biochar and soil moisture conditions on soil chemical characteristics and soybean yield, *Archives of Agronomy and Soil Science* (2019).
- [21] N. Ameloot, S. Sleutel, K. Das, J. Kanagaratnam, S. De Neve, Biochar amendment to soils with contrasting organic matter level: effects on N mineralization and biological soil properties, *Gcb Bioenergy* 7 (2015) 135–144.
- [22] D. Egamberdieva, B. Alaylar, A. Kistaubayeva, S. Wirth, S.D. Bellingrath-Kimura, Biochar for improving soil biological properties and mitigating salt stress in plants on salt-affected soils, *Communications in Soil Science and Plant Analysis* 53 (2022) 140–152.
- [23] J. Lehmann, M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday, D. Crowley, Biochar effects on soil biota—a review, *Soil biology and biochemistry* 43 (2011) 1812–1836.
- [24] M. Zahedifar, S. Najafian, *Ocimum basilicum* L. growth and nutrient status as influenced by biochar and potassium-nano chelate fertilizers, *Archives of Agronomy and Soil Science* 63 (2017) 638–650.
- [25] M. Zahedifar, Effect of biochar on cadmium fractions in some polluted saline and sodic soils, *Environmental Management* 66 (2020) 1133–1141.
- [26] M. Zahedifar, A.A. Moosavi, Assessing cadmium availability of contaminated saline-sodic soils as influenced by biochar using the adsorption isotherm models, *Archives of Agronomy and Soil Science* 66 (2020) 1735–1752.
- [27] Y. Li, S. Hu, J. Chen, K. Müller, Y. Li, W. Fu, Z. Lin, H. Wang, Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review, *Journal of Soils Sediments* 18 (2018) 546–563.
- [28] J. Nyasapoh, S. Adiku, D. MacCarthy, S. Yanore, Mode of Biochar Application to Vertisols Influences Water Balance Components and Water Use Efficiency of Maize (*Zea mays* L), *West African Journal of Applied Ecology* 30 (2022) 1–12.
- [29] G. Murtaza, Z. Ahmed, M. Usman, W. Tariq, Z. Ullah, M. Shareef, H. Iqbal, M. Waqas, A. Tariq, Y. Wu, Biochar induced modifications in soil properties and its impacts on crop growth and production, *Journal of Plant Nutrition* 44 (2021) 1677–1691.
- [30] E. Gavili, A.A. Moosavi, A.A.K. Haghighi, Does biochar mitigate the adverse effects of drought on the agronomic traits and yield components of soybean? *Industrial Crops Products* 128 (2019) 445–454.
- [31] T.H. Nguyen, R.A. Brown, W.P. Ball, An evaluation of thermal resistance as a measure of black carbon content in diesel soot, wood char, and sediment, *Organic Geochemistry* 35 (2004) 217–234.
- [32] A. Mukherjee, A. Zimmerman, W. Harris, Surface chemistry variations among a series of laboratory-produced biochars, *Geoderma* 163 (2011) 247–255.
- [33] E.H.J.E.M. Tryon, Effect of charcoal on certain physical, chemical, and biological properties of forest soils 18 (1948) 81–115.
- [34] F. Moradi-Choghamarani, A.A. Moosavi, A.R. Sepaskhah, M. Baghernejad, Physico-hydraulic properties of sugarcane bagasse-derived biochar: the role of pyrolysis temperature, *Cellulose* 26 (2019) 7125–7143.
- [35] Y. Gao, G. Shao, Z. Yang, K. Zhang, J. Lu, Z. Wang, S. Wu, D. Xu, Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of Maize in improving plant photosynthetic rate: A meta-analysis, *European Journal of Agronomy* 130 (2021) 126345.
- [36] H. Blanco-Canqui, Biochar and soil physical properties, *Soil Science Society of America Journal* 81 (2017) 687–711.
- [37] K. Kameyama, T. Miyamoto, Y. Iwata, T. Shiono, Influences of feedstock and pyrolysis temperature on the nitrate adsorption of biochar, *Soil Science and Plant Nutrition* 62 (2016) 180–184.
- [38] M. Hardie, B. Clothier, S. Bound, G. Oliver, D. Close, Does biochar influence soil physical properties and soil water availability? *Plant and soil* 376 (2014) 347–361.
- [39] C. Zhang, X. Li, H. Yan, I. Ullah, Z. Zuo, L. Li, J.J.A.W.M. Yu, Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and quality of greenhouse tomato 241 (2020) 106263.
- [40] Y. Zhang, J. Ding, H. Wang, L. Su, C. Zhao, Biochar addition alleviate the negative effects of drought and salinity stress on soybean productivity and water use efficiency, *Plant Biology* 20 (2020) 1–11.
- [41] M. Mannan, S. Mia, E. Halder, F.A. Dijkstra, Biochar application rate does not improve plant water availability in soybean under drought stress, *Agricultural Water Management* 253 (2021) 106940.
- [42] A. Ahmed, Y. Garipey, V. Raghavan, Influence of wood-derived biochar on the compactibility and strength of silt loam soil, *International Agrophysics* 31 (2017) 149–155.

- [43] I. Wani, V. Kushvaha, A. Garg, R. Kumar, S. Naik, P.J.B.C. Sharma, Biorefinery, Review on effect of biochar on soil strength: towards exploring usage of biochar in geo-engineering infrastructure (2022) 1–32.
- [44] A. Khaledi Darvishan, K. Banasik, S. Hamidreza Sadeghi, L. Gholami, L. Hejduk, Effects of rain intensity and initial soil moisture on hydrological responses in laboratory conditions, *International Agrophysics* (2015) 29.
- [45] G.S. McMaster, Phytomers, phyllochrons, phenology and temperate cereal development, *The Journal of Agricultural Science* 143 (2005) 137–150.
- [46] R. Sah, M. Chakraborty, K. Prasad, M. Pandit, V. Tudu, M. Chakravarty, S. Narayan, M. Rana, D. Moharana, Impact of water deficit stress in maize: Phenology and yield components, *Scientific reports* 10 (2020) 2944.
- [47] H. Campos, M. Cooper, J. Habben, G. Edmeades, J. Schussler, Improving drought tolerance in maize: a view from industry, *Field Crops Research* 90 (2004) 19–34.
- [48] Y. Shavrukov, A. Kurishbayev, S. Jatayev, V. Shvidchenko, L. Zotova, F. Koekemoer, S. De Groot, K. Soole, P.J.F.i.p.s. Langridge, Early flowering as a drought escape mechanism in plants: how can it aid wheat production? 8 (2017) 1950.
- [49] J. Mott, A. McComb, Effects of moisture stress on the growth and reproduction of three annual species from an arid region of Western Australia, *The Journal of Ecology* (1975) 825–834.
- [50] M.M. Hoque, T. Kobata, Effect of soil compaction on the grain yield of rice (*Oryza sativa* L.) under water-deficit stress during the reproductive stage, *Plant production science* 3 (2000) 316–322.
- [51] F. Seixas, T.J.F.P.J. McDonald, Soil compaction effects of forwarding and its relationship with 6-and 8-wheel drive machines 47 (1997) 46–52.
- [52] C. Ocloo, C. Quansah, V. Logah, B. Amegashie, The impact of different levels of soil compaction on soil physical properties and root growth of maize and soybean seedlings, *West African Journal of Applied Ecology* 22 (2014) 17–30.
- [53] I. Håkansson, J. Lipiec, A review of the usefulness of relative bulk density values in studies of soil structure and compaction, *Soil Tillage Research* 53 (2000) 71–85.
- [54] S. Ozpinar, A. Cay, Effect of different tillage systems on the quality and crop productivity of a clay-loam soil in semi-arid north-western Turkey, *Soil Tillage Research* 88 (2006) 95–106.
- [55] J. Bierhuizen, R. Slatyer, Effect of atmospheric concentration of water vapour and CO<sub>2</sub> in determining transpiration-photosynthesis relationships of cotton leaves, *Agricultural Meteorology* 2 (1965) 259–270.
- [56] R. Arkley, Relationships between plant growth and transpiration, *Hilgardia* 34 (1963) 559–584.
- [57] P.E. Abbate, J.L. Dardanelli, M.G. Cantarero, M. Maturano, R.J.M. Melchiori, E.E. Suero, Climatic and water availability effects on water-use efficiency in wheat, *Crop Science* 44 (2004) 474–483.
- [58] T. Ge, F. Sui, L. Bai, C. Tong, N. Sun, Effects of water stress on growth, biomass partitioning, and water-use efficiency in summer maize (*Zea mays* L.) throughout the growth cycle, *Acta Physiologiae Plantarum* 34 (2012) 1043–1053.
- [59] N. Jin, W. Ren, B. Tao, L. He, Q. Ren, S. Li, Q. Yu, Effects of water stress on water use efficiency of irrigated and rainfed wheat in the Loess Plateau, China, *Science of the total environment* 642 (2018) 1–11.
- [60] T. Hussain, N. Hussain, M. Tahir, A. Raina, S. Ikram, S. Maqbool, M. Fraz Ali, S. Duangpan, Impacts of Drought Stress on Water Use Efficiency and Grain Productivity of Rice and Utilization of Genotypic Variability to Combat Climate Change, *Agronomy* 12 (2022) 2518.
- [61] X. Zhang, R. Zang, C.J.P.S. Li, Population differences in physiological and morphological adaptations of *Populus davidiana* seedlings in response to progressive drought stress 166 (2004) 791–797.
- [62] W. Guo, B. Li, X. Zhang, R. Wang, Effects of water stress on water use efficiency and water balance components of *Hippophae rhamnoides* and *Caragana intermedia* in the soil-plant-atmosphere continuum, *Agroforestry systems* 80 (2010) 423–435.