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Can biochar improve soil physical properties of northern Ghana loamy sandy soils

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Abstract

Soils of the northern region of Ghana are largely coarse-texture and shallow as a consequence, their Water Holding Capacity (WHC) is low, with much of seasonal rainfall lost through drainage which is detrimental to crop growth. Given the poor state of the soil amendment application different experiments were carried in 2021 out to achieve two objectives, thus, the first experiment was a series of runoff and drainage (R+D) conducted in the laboratory to assess the effect of biochar application on (R+D). The second experiment was carried out to determine the effect of biochar applications on Available water capacity AWC, Field capacity (FC), Permanent wilting point (PWP) and bulk density BD. The relationship between biochar application rate and the physical properties was also derived as a function of clay ratio and Biochar application. Study soils used were sampled from 3 locations in the northern regions, namely Wa (Upper West), Tamale (Northern Region) and Navrongo (Upper East). The same soil was used for the two experiments. The results showed that biochar had significant effect on the FC but not on PWP. Biochar application increased the AWC of the soil such that AWC increased from 0.03 cm3/cm3 for BC0 for the soil from Tamale to 0.06 cm^3/cm^3 for B20. In general, BC10 and BC20 did not differ significantly. Biochar application also influenced the BD with the highest BC20 ton/ha decreasing the initial BD from 1.50 to 1.30 g/ cm3. Runoff + drainage decreased with biochar application in the farming area BC20 < BC10.The effectiveness of biochar on R+D, BD reduction, and AWC increased as the CR decreased (i.e., high CR = low clay).

Keyword: Biochar; Runoff; Drainage; Soil physical-properties; Northern-Ghana

1. Introduction

In the northern region of Ghana, much of the seasonal rainfall is lost through drainage due to their soil physical properties, resulting in reduced water availability for crop growth. Apart from this, climate change has increased the variability of rainfall, leading to an increase in extreme events such as drought and flood. The combination of low Water Holding Capacity (WHC) and climate change impact has increased the vulnerability of crop production in Northern Ghana. In recent times, research has shown that the application of biochar, (BC), a pyrolyzed form of organic matter to soils can improve soil physical properties such as the WHC and hence improve soil and crop productivity. There is evidence that application of biochar improves the available water capacity (AWC), [1] increases porosity [2] and, hence, reduce runoff and drainage (R+D) and therefore reduce agricultural drought impact on crop yields. It is the aim of this research to evaluate the effect of biochar application on soil physical properties (ie. AWC, bulk density) and some water balance components (runoff, drainage,).

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2. Material and Methods

2.1. Site description

The northern part of Ghana is predominantly characterized by the Guinea savanna agro-ecology with a small stretch constituting the Sudan savanna in the north-eastern section of Upper-East region. The mean annual rainfall of the Guinea savanna is about 900-1100 mm and 500 – 700 mm in the Sudan savanna zone [3]. The mean monthly temperatures are high throughout the year ranging from 25 ºC to more than 33 ºC.

The study soils were taken from three locations in the northern part of Ghana: Wa (Upper West: 10.060074 N and -2.509891 W, Tamale (Northern Region 9°24'2.84" N and 0°50'21.48" E), and Navrongo (Upper East; 10° 53' 44.05" N and -1° 05' 31.56" W).

2.2. Soil sampling and laboratory analyse

Three different soil series were sampled (cultivated soil) from the 2 Agro-ecological zones were transported to the University of Ghana for greenhouse and laboratory experiments.. The soil sampling was done at a depth of 20 cm and were air-dried for 24 hours and sieve through 2 mm-mesh and used for laboratory analyses. The core sampling method was used for soil bulk density determination and soil texture (percentage of sand, silt and clay) by Hydrometer method.

2.3. Laboratory experiments

2.3.1. Effect of biochar on runoff and drainage

A series of runoff and drainage experiments were conducted in the laboratory to assess the effect of biochar application on some water balance components . For this, PVC cylinders of internal diameter of 16 cm and height 20 cm were used. Runoff holes were drilled at 3 cm from the top. Also, drainage holes were drilled at the bottom of the columns in which the soils sampled from the 3 locations were potted with the biochar application at 0, 10, 20 ton/ha. The soils were irrigated 5 times, with a different intensity at each irrigation event. At each irrigation event, data collected included the total irrigation I, runoff R and drainage D. A relationship between (R+D) and biochar application rate, soil texture and rainfall was derived using regression methods.

$$(R+D)=Fi(B,I,CR) \qquad \text{(Eq 1)}$$

Where Fi is a function of relations, B = biochar rate, I = irrigation and CR= clay ratio

$$(Sand+silt)/clay \qquad \text{(Eq 2)}$$

2.3.2. Biochar effect on soil physical properties

The effect of biochar application on the AWC (i.e. FC, PWP) and BD was determined. The experiment was done such that biochar application rates were 0, 10, 20 and 30 ton/ha using the same 3 soils. The experimental design comprised factorial arrangement of 3 soils x 4 biochar application rates arranged in completely randomized design with 3 replications totalling 36 units. The sunflower (Genus helianthus) response procedure detailed in [4] was followed to estimate volumetric water content at PWP. For this, sunflowers were grown in the potted soils and irrigated until the flowering stage. Thereafter, water application was discontinued until the plant wilted. At this stage undisturbed (Core) soil cores were taken from each treatment, and the water content and the bulk density were determined. The volumetric water content was taken as the PWP.

As far as the field capacity (FC) determination is concerned, the same potted soils used were wetted to saturation and covered with polythene sheets to prevent evaporation, the wetted pots were allowed to drain for 2 days therefore the soil was sampled to determine the volumetric water content. The AWC was calculated as the difference between FC and PWP. The relationship between biochar application rate and the physical properties was also derived as:

- PWP = f2 (B,CR) (E3)
- FC = f3 (B,CR) (Eq 4)
- AWC = FC-PWP (Eq 5)

2.4. Statistical analysis

Data collected during the experiment was statistically analyzed using ANOVA with GenStat statistical software 12th version. The means were compared using the least significant difference test at $P < 0.05$ and the graphs were drawn using GraphPad software 10. The relationships were derived as multiple regressions, using SigmaPlot 4.0 edition.

3. Result and Discussion

3.1. Soil and biochar properties

Table 1 shows the physical characteristics of the soils used for the experiment (0-20 cm depth). The three soils were loamy Sand with a high sand content of about 80%. The bulk density was measured to be 1.49 g/cm3 for Navrongo soils and 1.50 g/cm3 for Tamale and Wa soil.

Table 1 Some physical properties of the study soils

Properties	Tamale (Lima)	Wa (Varempere)	Navrongo (Tenchera)
Clay (%)	10	5	7.5
Silt (%)	5	7.5	5.5
Sand (%)	85	87.5	87
Clay ratio	9	19	12.33
Bulk density (g/cm^3)	1.50	1.50	1.49

The biochar used for the two experiments was derived from rice husks. The bulk density was 0.23 g/cm with a size less than 2 mm.

3.2. Effect of biochar on soil physical properties

3.2.1. Soil porosity and bulk density (BD)

The porosity and bulk density for the different soils used in this study under different biochar applications are represented in Figure 1. The results showed there were significant differences ($p < 0.05$) among the different soil series with regard to both BD and porosity. The BD ranged from 1.47 to 1.38 g/cm3, following a decreasing trend at Wa> Navrongo> Tamale. The opposite trend was observed for porosity with values ranging from 43 to 49%. The Wa location (Varempere series) recorded the highest clay ratio (CR) whilst the lowest was recorded at the Tamale location (Lima series). This indicates a negative relationship between clay content and BD while a positive relationship with porosity.

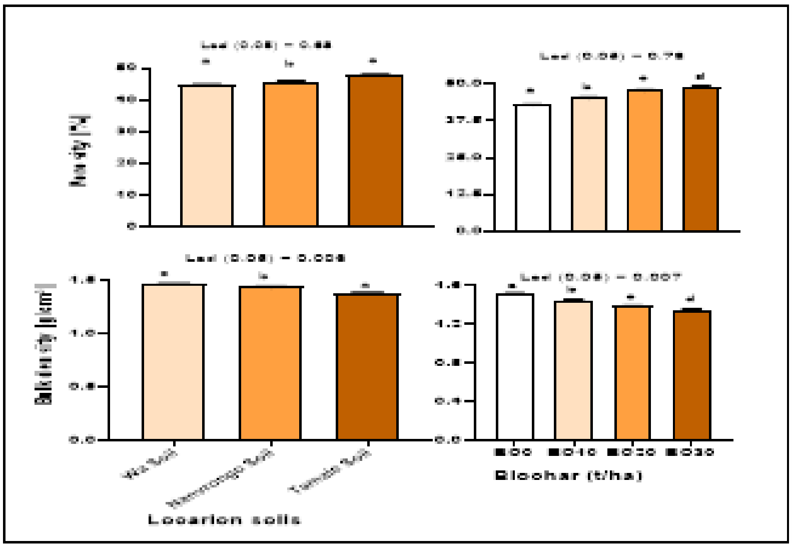

Figure 1 Porosity and bulk density under different biochar treatment and soil with different clay ration

Biochar had a significant ($p < 0.05$) effect on both soil bulk density and porosity (Figure 2). The bulk density decreased in the order of B0 > B10 > B20> B30. The highest BD recorded under B0 treatment was 1.52 g/cm3, which significantly differed from other biochar plot treatments. The values of BD were 1.45, 1.39, 1.35 g/cm3, for B10, B30 and B30, respectively. Contrary to BD, addition of biochar to the soil was found to increase soil porosity at 43, 45, 48, 49% for B0, B10, B20 and B30 respectively. Both porosity and BD were significantly affected by biochar application , this may be the underlying reason why biochar application increases soil macro and meso-pore of soil [5], as pores are created at the interface between biochar and soil particles or small aggregates [6] resulting in low bulk density. A similar result was reported [7], who indicated that biochar application helped to reduce the bulk density of sandy loam soils. The study further showed soil x amendment (biochar) to have a significant interaction effect on BD and porosity (Figure 2). Biochar effectiveness was texture-dependent [8] and more effective in sandy soils than clayey soils.

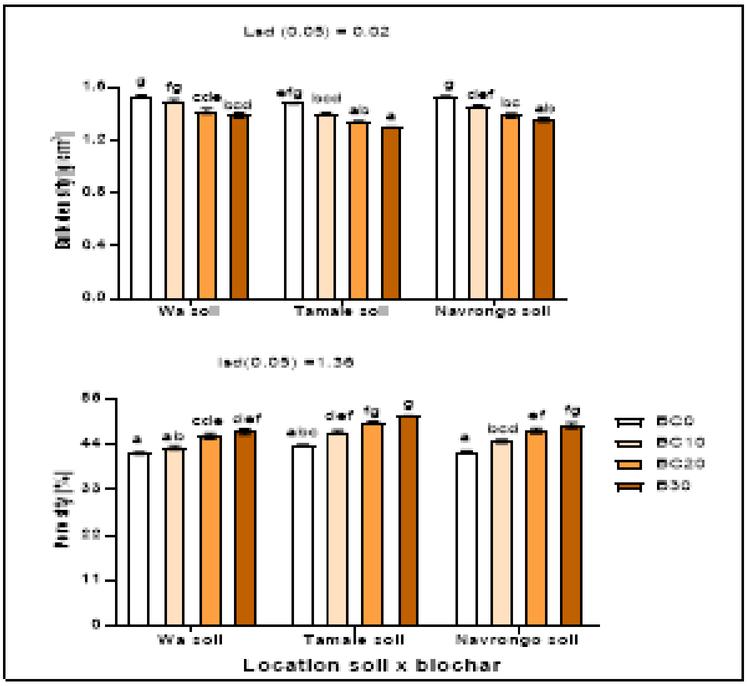

Figure 2 Interactive effect of biochar x location on BD and porosity under different soil series

3.2.2. Soil available water capacity

Available Water Capacity (AWC) is one of the important soil physical properties that affects soil productivity and crop yield especially under low rainfall conditions. The AWC is determined as the amount of water retained in the soil between the ''Field Capacity'' (FC) and the ''Permanent Wilting Point' (PWP) [9]. Figures 3 and 4 indicate that FC, PWP and AWC followed a similar trend, and varied with locations (Tamale > Navrongo> Wa). Both PWP and FC showed a significant different (< 0.05) among the different soil series, with values ranging from 0.06 to 0.09 cm3/cm3 and 0.10 to 0.14 cm3/cm3, respectively, but the FC for Tamale and Navrongo were not different statistically (Figure 3). However, the AWC of the different location (soil series) were statistically similar, probably due to the higher PWP.

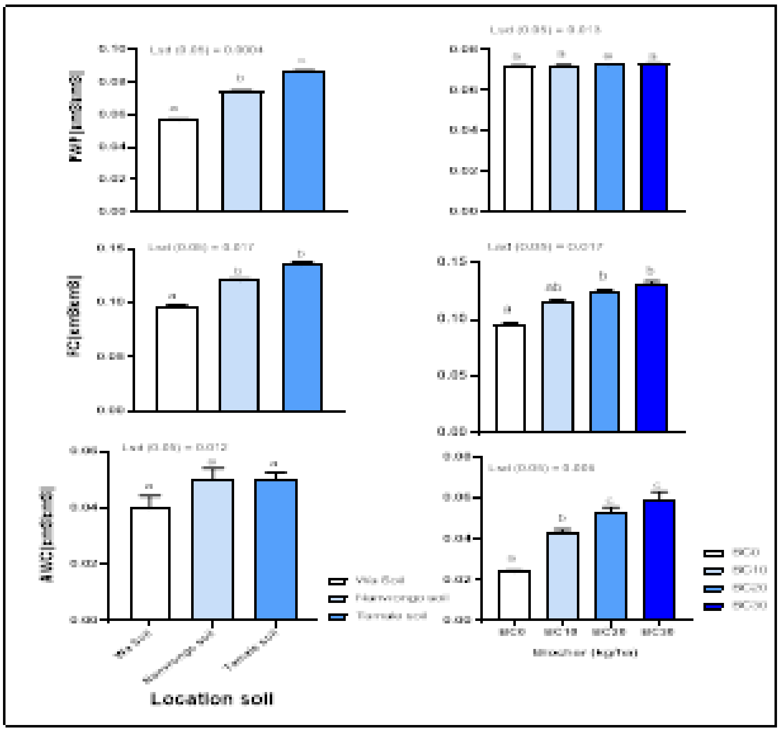

Figure 3 AWC, FC and PWP under different biochar treatment and soils with different clay ration

The above result followed the same trend as soil clay ratio (Table 1) hence soil water content increased as the clay ratio decreased. Addition of biochar to soils leads to increased soil porosity and decreased soil BD, which together significantly ($P < 0.05$) increased both FC and AWC but showed no effect on PWP (Figure 3). The values ranged from 0.072 to 0.073 cm3/cm3 for PWP, 0.096 to 0.13 cm3/cm3 for FC and 0.02 to 0.06 cm3/cm3 for AWC. The treatment control (B0) had the least AWC value and this was significantly different from the biochar application treatments. The AWC of the biochar treatments were on average, 80%, 120%, 145% for B10, B20 and B30, respectively higher than the control. This finding is in agreement with studies by several other researchers [1]; [10]; [2]. The positive effect of biochar on AWC can be explained by its capacity to increase soil water retention/storage [11] because of its micro- and macro-pores as well as the pores created at the interface between biochar and soil particles or small aggregates [6]. It was also found that soils and biochar interactions had an effect on FC and AWC (Figure 4). The mean values of the interactions of location (soil series) with biochar on AWC were 0.022cm3/cm3, 0.024 cm3/cm3 and 0.026 cm3/cm3 for Wa, Navrongo and Tamale respectively.

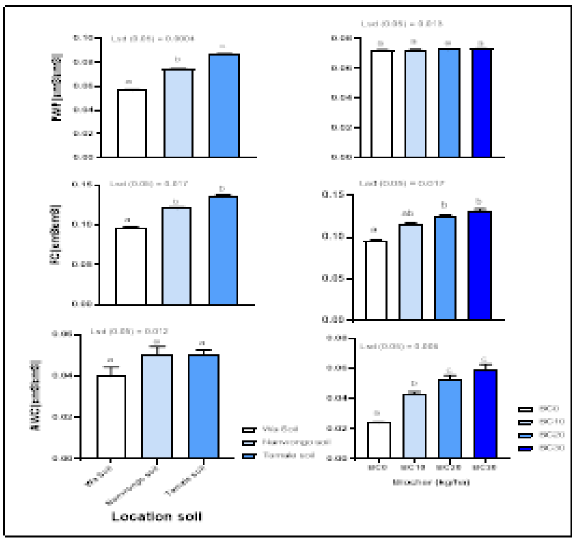

Figure 4 Interactive effect of biochar x location on AWC of different soil series

Generally, AWC and FC increased with increasing biochar application rate across soil series (Figure 4). Tamale and Navrongo (lima and Tenchera series) had lower clay ratios and showed significant differences between B30 and the other application rates. In the case of Wa location (varempere series) the effects at the different biochar application rates were statistically similar.

3.2.3. Runoff + drainage

The average measured runoff + drainage (R+D) values for the different soil series during different irrigation events are presented in Table 2. Biochar application was found to significantly reduced (R+D). Though, R+D for B0 and B10, in most of the cases were statistically similar, the effect of B20 was significantly different (< 0.05) from B0. The effectiveness of biochar addition to reduce R+D has been reported by other studies [11], [12]. Therefore, it is proposed that biochar amendment can improve soil productivity even under low rainfall conditions (Xiang et al., 2017).

As for soil bulk density, R+D reduction by biochar application was found to be soil texture dependent. For the first irrigation even, the total water applied was 49.8 mm of which R+D ranged from 32.99 to 33.89 (mm), 30.27 to 30.44 (mm) and 26.44 to 27.03 mm for B0, B10 and B20 respectively after 17.8 min of water application. Under the different location, R+D decreased in the order of Wa > Navrongo > Tamale but were not significantly different.

Table 2 Effect of biochar on runoff + drainage under different soil series

Biochar (ton/ha)	**Irrigation (mm)**	**Runoff +Drainage**			**Rainfall loss**		
		(mm)			**(%)**		
Event1	49.76	Navrongo	Tamale	Wa	Navrongo	Tamale	Wa
Event 1							
BC0		33.22b	32.99b	33.89b	66.76b	66.3b	68.12b
BC10		30.44ab	30.27ab	30.37ab	61.17ab	60.83ab	61.04ab
BC20		26.59a	26.44a	27.03a	53.48a	53.13a	54.32a
Event 2							
Event2	19.9						
BC0		5a	6.67a	0a	5a	6.667a	0a
BC10		0a	0a	0a	0a	0a	0a
BC20		0a	0a	0a	0a	0a	0a
Event3							
Event3	37.32						
BC0		13.77cd	13.77cd	14.10c	36.89c	36.89c	37.78c
BC10		12.82ab	12.77ab	12.93ab	34.36b	34.22ab	34.67b
BC20		12.40ab	12.03a	12.60ab	33.25ab	32.22a	33.78ab
Event4							
Event4	29.9						
BC0		7.962f	5.64cd	8.542f	36.89c	36.89c	37.78c
BC10		6.718de	4.313ab	6.801e	34.36b	34.22ab	34.67b
BC20		5.391bc	3.981a	4.727abc	33.25ab	32.22a	33.78ab
Event5							
Event5	9.95						
BC0		0	0	0	0	0	0

BC10		0	0	0	0	0	0
BC20		0	0	0	0	0	0

In the case of the second irrigation event which had an intensity of 132.67 mm/hr runoff and drainage were generated for only the B0 treatment. For the low irrigation intensity event of 5 (11.06 mm/hr) no R+D was measured given that the rainfall rate was lower than the soil infiltration capacity. For event 3 (169.63 mm/hr) after 13.27 mn of water application, there were significant differences in R+D between control and biochar treatments. For event 4 (142.38 mm/hr) there were significant differences between B0, B10 and B20 except for the Tamale location. It was found that events with higher rainfall intensity generated more R+D compared to those with lower rainfall intensity (Table 2).

3.2.4. Relationships between biochar, application rate and soil physical properties

A linear regression analysis was carried out to establish the relationship between some measured soil physical parameters of runoff + drainage and biochar and soil clay ratio. The relationship between biochar application rate and soil porosity, BD, AWC and R+D are presented in Figure 5. As expected, both porosity and AWC were positively correlated with biochar application. Therefore, AWC increased with increasing biochar application rate. The R^2 showed that biochar accounted for over 90 % of the variations in both measured AWC and soil porosity. As hypothesized a negative correlation between biochar and BD and R+D was found, with R2 being more than 0.90.

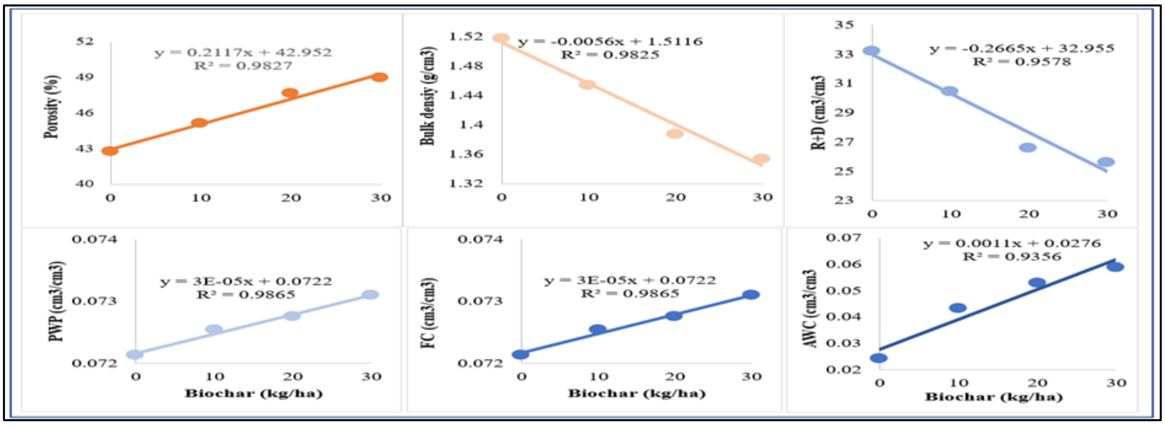

Figure 5 Relationship between biochar and soil physical properties (R+D, Bulk density, porosity, AWC, FC, and PWP). R+D, AWC, FC and PWP are runoff+drainage, available water capacity, Field capacity and Permanent wilting point respectively

This finding indicated a positive relationship between the latter two soil parameters and AWC as well as soil porosity. On the other hand soil clay ratio (sand + silt/ clay) also accounted for more than 90% of above parameters (Figure 6) since biochar effectiveness is texture dependent.

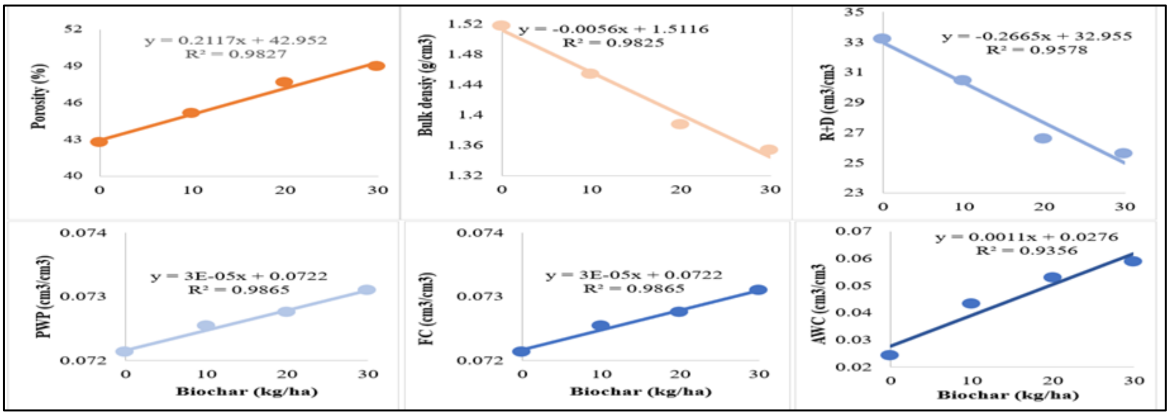

Figure 6 Relationship between soil clay ratio and soil physical properties (R+D, BD, porosity, AWC, FC, and PWP). R+D, BD, AWC, FC and PWP are R+D, AWC, FC and PWP are runoff+drainage, available water capacity, Field capacity and Permanent wilting point respectively

The relationship between the combined effect of biochar and clay ratio on measured parameters derived as multiple regressions are present in table 3. The regression coefficients for all the parameters were found to be significant ($p < 0.001$). This implies that knowing the clay ratio (CR) of a given soil and the rate of biochar application, R+D, BD, AWC of that soil can be predicted.

Table 3 Multiple relationships between biochar and different parameters

Parameter	Equation (Eq 6)	R^2	P <	
Runoff+drainage (R+D)	-41.1+(0.633 *Rain) + (0.0527*CR) -(1.92*BC) -(1.7*BD)	0.98	0.001	Eq 6a
Bulk density	1.411 + (0.00771 * CR) - (0.00568 * BC)	0.98	0.001	Eq 6b
PWP	0.206 - (0.00252 * CR) - (0.000268 * BC) - (0.0688 * BD)	0.95	0.001	Eq 6c
FC	0.144 - (0.00365 * CR) + (0.00116 *BC) + (0.0705 * BD)	0.94	0.001	Eq 6d
AWC	0.124 - (0.000524 * CR) + (0.000852 * BC) - (0.0594 * BD)	0.89	0.001	Eq 6e

CR = clay ratio, PWP = permanent wilting point, FC = field capacity, AWC =available water capacity

4. Conclusion

Biochar application to the soil at the first 10 cm was found to significantly reduce both the bulk density and runoff and drainage (R+D). Contrary to BD addition of biochar to the soil, there was increased soil porosity and Available water capacity. In most of the cases there were no significant differences between B10 and B20. The study also showed that the effectiveness of biochar upon soil physical properties are soil texture dependence which increased as the clay ratio decreased (i.e. high CR = low clay). It is concluded that though this study was limited to laboratory work biochar technology appears to be a promising technology that can be used to improve soil physical properties

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declared that there is no conflict of interest.

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