Biochar Locally-produced from Acacia for Soil Nitrogen and Water Dynamics and Teff Production in Highland Ethiopia

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ABSTRACT

Water and nutrient availability are the most important factors which affect crop production. However inconsistent rainfall and high prices of fertilizers have been pushing down crop productivity. The use of biochar (BC) is one of the alternatives to minimize those effects. However, few studies have been conducted under field conditions, especially using BC applied on clayey soil for crop production in a highland of Ethiopian. The objective of this study was to evaluate the effects of BC application on soil water and nutrient dynamics and production of teff. The experimental design was a randomized block design (RBD) with 3 levels of BC application rate (0, 5 and 20 t ha^{-1}; 0ACB, 5ACB, and 20ACB) with five replications. Soil pH was increased with BC application throughout cultivation period. There were no apparent effects of BC application on soil NH_4^+-N and NO_3^--N during cultivation period. Soil water contents at field capacity and permanent wilting point were increased and decreased, respectively, leading to increase in plant available water with BC compared to without BC. BC applied on clayey soils could change soil structure and contribute to adequate drainage water during the rainy period and retention of water during the dry period, which collaborate with proper aeration in soil for health plant growth. Our results showed significantly increased plant height, dry biomass, and grain yields of teff for soil treated with biochar. Soil treatment with 5ACB and 20ACB increased plant height by 17.0% and 40.5%, respectively, dry biomass by 172% and 256%, respectively, and grain yields by 146% and 173%, respectively. Our results showed that BC application improved and regulated water availability for clayey soil during the period of the growing season, which resulted in improved biomass and grain production of teff.

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Keywords: *Nitisol; plant available water; water potential; water retention*

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1. INTRODUCTION

Agricultural production in Ethiopia has been facing challenges due to the increase of population. Demand for food has been stressing efforts to promote and stimulate agricultural productivity, particularly for teff (*Eragrostistef*), one of the major nutritional sources in Ethiopia [1]. Teff is one of the most important grain crops for food security and cultivated in more than 3 million ha annually in Ethiopia [2]. Although domestic and international demands for teff have been increasing due to gluten-free characteristics, the plant does not perform well due to soil acidity, poor nutrients, and water stress (drought and waterlogging) in highland Ethiopia. Therefore, proper soil management is required for healthy teff production using chemical fertilizer and/or organic amendments.

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Soils in highland Ethiopia are typically clayey, acidic, and low in nutrients which require proper soil management. Also, heavy rain in this tropical region can cause significant runoff due to poor water infiltration of clayey soils which can result in decrease of soil nutrient availability [3]. Appropriate regulation of soil water for crop production has recently become harder and harder to control due to extremal meteorological changes. Therefore, water management in soil is one of the most critical issues for proper agricultural production [4].

Biochar, pyrolyzed biomass under limited oxygen conditions, has been drawing much attention recently as one of the most important soil management strategies especially for tropical soils with poor nutrients and severe water stresses [5]. Biochar application has been proven to improve soil nutrient availability [6] and soil water retention and infiltration [7] in tropical clayey soils. However, many aspects of biochar application in clayey soils are still unknown particularly for teff production, and particularly, water dynamics in soils applied with biochar on field scale has not been well studied.

Therefore, the objective of this study was to evaluate the effects of biochar locally-produced from acacia tree on soil nutrient and water dynamics and teff production in highland Ethiopia.

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2. MATERIALS AND METHODS

2.1Experimental land/plot preparation and soil sensors setup

The experiment was conducted from July to December 2019 at Injibara University campus (10.944069^{o} N and 36.918633^{o} E) in Ethiopia. The experimental area was plowed five times by horses and the plots bed of 10 cm height were laid out with a width of 2.0 m and length of 3.0 m. The experimental design was a randomized block design with 3 levels of one treatment (biochar application rate) with five replications with a total of 15 experimental plots.

Local acacia tree (*Acacia decurrens*) biochar was produced in Injibara, Amhara Region, Ethiopia through ground carbonization method by pilling-up tree in a conical shape covered by soil to limit oxygen entry and carbonizing for 2 d before extinguishing at the end. Acacia tree biochar (ACB) was cracked and sieved with a 5 mm sieve before applied on the soil. The experiment consisted of three biochar application rates of ACB (0, 5 and 20 t ha^{-1}; 0ACB, 5ACB, and 20ACB, respectively). For each treatment, the biochar was applied on 01 July 2019 and mixed with the soil within a depth of 10 cm. Teff seeds were sowing at the rate of 13 kg ha^{-1}. Chemical fertilizers of diammonium phosphate (100 kg ha^{-1}) were applied at planting (01 July 2019; 0 d after planting; DAP), one-third of recommended urea (50 kg ha^{-1}) in 1st split on 14 August 2019 (44 DAP) and two-third on 2nd split on 10 October 2019 (95 DAP).

Soil sensors (TEROS 11, METER Group) were installed in two different depths in planting bed (10 and 30 cm depths) to measure water content and temperature. Soil sensor (TEROS 21, METER Group) was installed at 10 cm depth to measure water potential and temperature. Weather station (Atmos 41, METER Group) was installed in the experimental site to collect weather and atmospheric data from this experiment.

2.2 Soil sampling and analyses

Soil samples were taken on 0 DAP after mixing ACB and chemical fertilizer from each plot, then taken from each plot on 15, 30, 52 (only for pH), 100, 125, 145 and 175 DAP at two different depths (10 and 30 cm). The samples were stored in a deep-freezer at −25^{o}C until being analyzed.

Volumetric water content (VWC) of the soil sample was measured from 4 g of wet soil. The samples were weighed into an aluminum dish and then dried in an oven at 105°C for 24 hr. Soil and biochar pH was measured from 10 and 2 g of air-dried (45℃) samples with 25 and 20 mL of pure water, respectively, added in a 50 ml centrifuge tube, shaken with a horizontal shaker at 160 strokes min^{-1} for 1 hr, allowed to stand for 30 min, and then measured using a pH meter (LAQUA F-71). To analyze ammonium- and nitrate-nitrogen (NH_4^+-N and NO_3^--N) concentration of the soil and biochar samples, the samples were extracted from 2.0 g of dry-weight equivalent wet soil and biochar samples with 20 mL of 2 mol L^{-1} potassium chloride solution in a centrifuge tube [8]. Tube was shaken for 1 hr on a horizontal shaker at 160 strokes min^{-1}. After filtrating through a 0.45 µm filter membrane, the concentration of NH_4^+-N and NO_3^--N in the extractant was determined at 670 and 540 nm, respectively, by using an auto-analyzer 2000 (FIAlyzer-1000, FIAlab Instruments).

Soil was sampled at 10 cm depth on 30 DAP from the plots, using a 50 ml cylindrical metal to determine soil water retention curve (SWRC). The most widely used model for the determination of the SWRC is Van Genuchten (VG) model [9]. The apparatus pressure plate, pF equipment (DIK3404, Daiki Co.) was used to obtain SWRC. After that, RETC ver. 6.02 was used to develop SWRC and get the VG parameters. Field capacity (FC) and plant available water (PAW) were obtained following the “S” curve theory [10]. Physical properties such as air capacity, macroporosity, FC and PAW are reflected in the slope of the tangent line to the inflection point of SWRC [11] [12]. Soil bulk density was measured from the same soil samples after drying them in an oven at 105^{o}C until constant mass was achieved. Bulk density was calculated as mass of the sample dried at 105°C minus mass of the sample holder (g) divided by the volume of the sample holder (cm^3).

2.3 Plant height, dry biomass, and grain yield

Five plant sub-samples were randomly selected at the harvest stage of the crop from each plot from six central rows to avoid border effects, and plant height was measured from the ground until the tip of the plant. After the full maturity of the crop, the whole above-ground of all plants from six central rows were harvested and weighed to measure dry biomass by sun-drying before threshing. Grain yield was weighed after separating teff straw from the grain from all plants from six central rows.

2.4 Statistical analysis

Analysis of variance was conducted using the STATISTICA program (Tulsa, OK, USA). The difference among means of treatments was determined using Tukey’s Highly Significant Difference (HSD) at the probability of 5% ($p< 0.05$).

3. RESULTS AND DISCUSSION

3.1 Characteristics of soil and biochar

The field experiment was conducted on a soil classified as a clayey texture with 50.9%, 20.0%, and 29.1% clay, silt, and sand contents, respectively (Table 1). The soil was acidic with a pH of 5.13. Soil cation exchange capacity (CEC) was 2.84 $cmol_c$ kg^{-1}. Soil total C and total N were 3.71% and 0.483%, respectively. The amount of NH_4^+-N, NO_3^--N, available phosphorus was 1.52, 15.7, 0.392 mg kg^{-1}, respectively.

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The biochar had an alkaline pH of 9.51 (Table 1). Biochar CEC was 3.01 $cmol_c$ kg^{-1}. Biochar total C and total N were 33.0% and 1.91%, respectively. The amount of NH_4^+-N, NO_3^--N, and available phosphorus were 4.03, 1.18, 310 mg kg^{-1}, respectively.

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Table 1. Basic characterization of soil and biochar samples

	Sand§	Silt§	Clay§	Bulk density	pH	CEC$^\$$	Total C$^\#$	Total N$^\#$	NH_4^+-N	NO_3^--N	Av. P¶

	%					cmol$_c$ kg^{-1}	%		mg kg^{-1}		
Soil[†]	29.1	20.0	50.9	1.05	5.13	2.84	3.71	0.483	1.52	15.7	0.392
Biochar[‡]	–	–	–	–	9.51	3.01	33.0	1.91	4.03	1.18	310

[†] *Clayey Nitisol collected at Injibara University, Ethiopia*
[‡] *Locally produced from acacia tree*
[§] *Measured by hydrometer method (Bouyoucos, 1962) [13]*
[$] *Cation exchange capacity*
[#] *Measured by CHN coder*
[¶] *Available phosphorus extracted by Mehlich-3 solution (Mehlich, 1984) [14]*

3.2Effects of biochar on soil parameters

Soil treated with 5ACB and 20ACB have increased soil pH on top 10 cm depth, but not significantly except for 52 DAP (Fig. 1a). Soil treated with 20ACB had significantly ($p < 0.05$) higher pH of 5.22 compared to other treatments only on 52 DAP. Biochar addition increased soil pH from 5.42 (0ACB) up to 5.58 (20ACB) on 0 DAP, and soil pH was higher with 20ACB throughout cultivation period. Trends of all treatments were decreasing pH until 100 DAP and increasing pH until 175 DAP at harvest. On 30 cm depth, all biochar treatments did not cause significant changes on soil pH throughout the cultivation period (Fig. 1b). Similarly to 10 cm depth, pH of all treatments on 30 cm depth tended to decrease from 0 to 52 DAP and thereafter to increase until 145 DAP. Soil pH was highest with 0ACB from 0 to 30 DAP, then with 20ACB from 52 to 175 DAP.

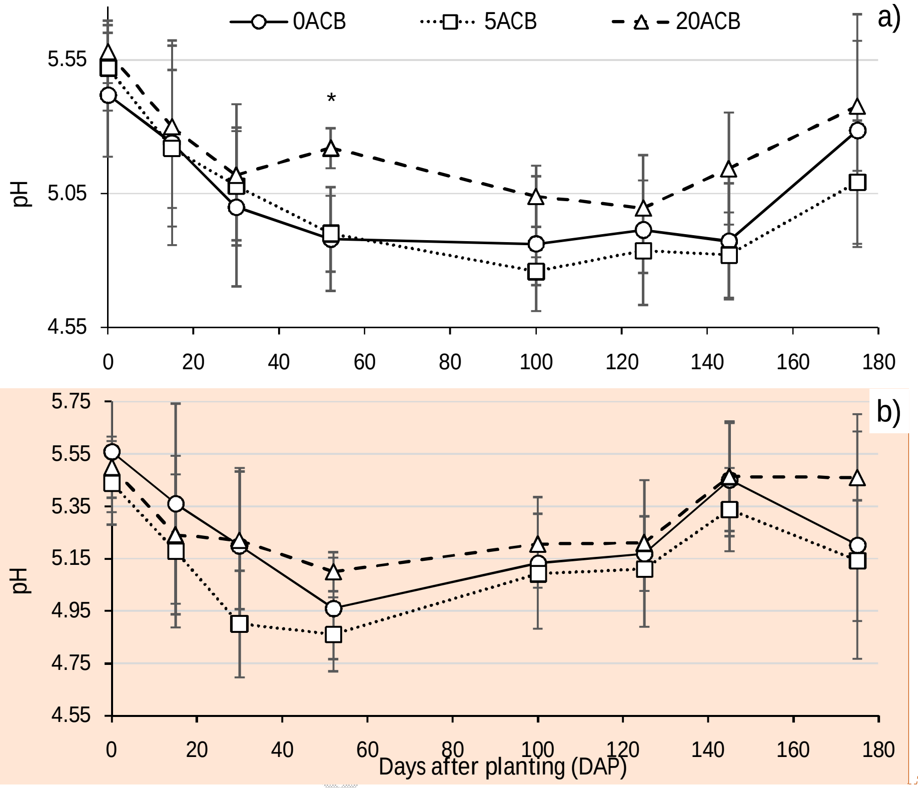

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Fig. 1. Effects of biochar application on soil pH at two different depths (a) 10 and (b) 30 cm for teff production

, **, and * denote significant difference by $p < 0.05$, 0.01, and 0.001, respectively, among different treatments for each sampling date.*

There were no significant differences among treatments on both 10 and 30 cm depth for NH_4^+-N concentration (Fig. 2a and 2b). On top 10 cm depth, NH_4^+-N concentration of all treatments slowly decreased from 30 to 100 DAP. After applying the 2nd split of fertilizer on 95 DAP, NH_4^+-N concentration on 10 cm depth increased from 4 to more than 40 mg kg^{-1} on 125 DAP for all treatments. For 30 cm depth, trend was similar to 10 cm depth increasing from 4 to more than 25 mg kg^{-1}. on 125DAP for all treatments. Then, for both layers, NH_4^+-N concentration decreased to 4 mg kg^{-1} on harvest time.

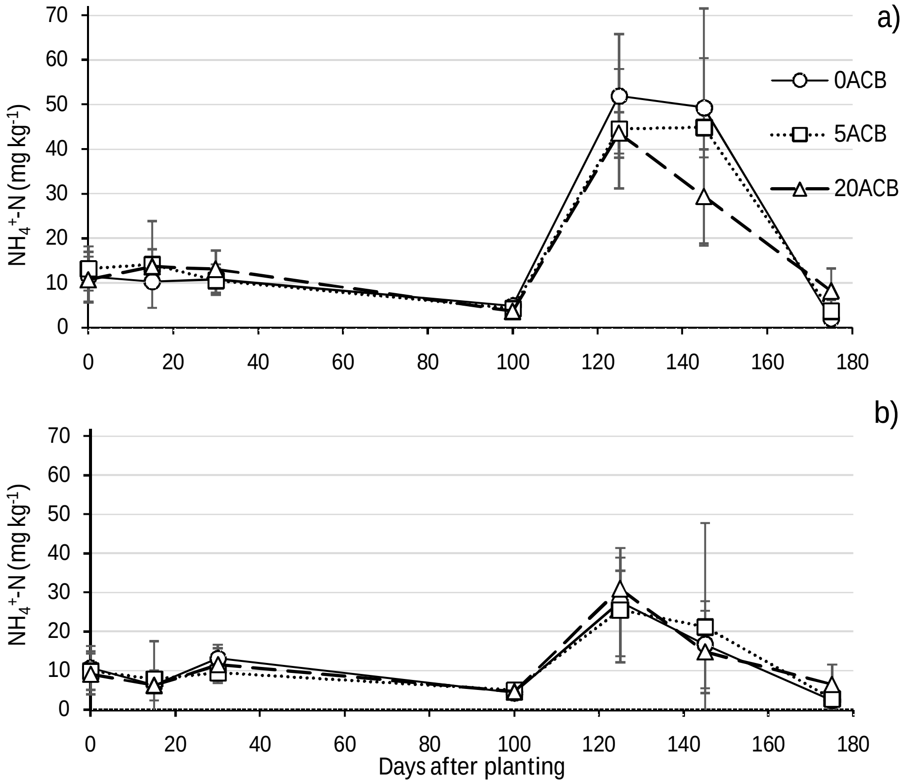

Fig. 2. Effects of biochar application on soil NH_4^+-N at two different depths (a) 10 and (b) 30 cm for teff production

, **, and * denote significant difference by $p < 0.05$, 0.01, and 0.001, respectively, among different treatments for each sampling date.*

For NO_3^--N concentration, there were no significant differences among treatments on both 10 and 30 cm depths throughout cultivation period (Fig. 3a and 3b). On top 10 cm depth, NO_3^--N concentration slowly decreased from 0 to 15 DAP. After applying the 1st split of fertilizer, NO_3^--N concentration on 10 cm depth increased from around 10 to around 60 mg kg^{-1} on 100 DAP for all treatments. For 30 cm depth, trend was similar to 10 cm depth increasing from around 10 to around 30 mg kg^{-1} on 100 DAP for all treatments. Then, for both depths, NO_3^--N concentration decreased to less than 10 mg kg^{-1} on harvest timedifferent treatments for each sampling date.

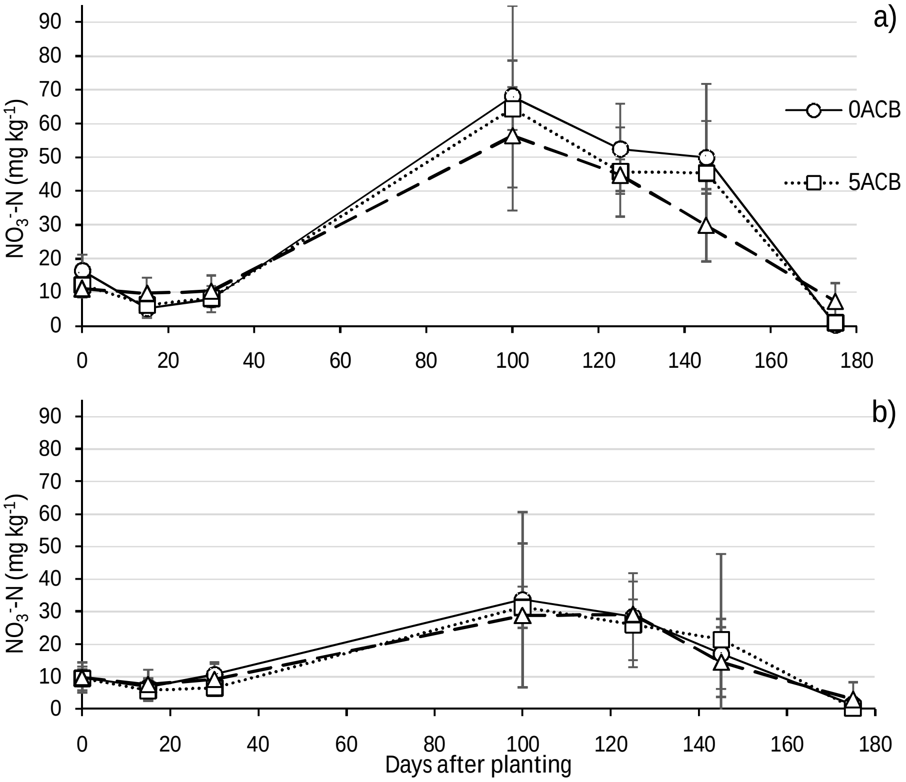

Fig. 3. Effects of biochar application on soil NO_3^--N at two different depths (a) 10 and (b) 30 cm for teff production
, **, and * denote significant difference by $p < 0.05$, 0.01, and 0.001, respectively, among*

Soil water retention curves showed a typical decreasing trend of VWC with increasing pressure (pF) for all treatments (Fig. 4). Biochar addition decreased VWC compared to control throughout pressure range. VWC at saturation was 0.671, 0.667, and 0.675 $m^3 m^{-3}$ for 0ACB, 5ACB, and 20ACB, respectively (Table 2). VWC at FC and PWP was 0.410, 0.415, and 0.426 $m^3 m^{-3}$, respectively, and 0.280, 0.272, and 0.274 $m^3 m^{-3}$ for 0ACB, 5ACB, and 20ACB, respectively. Calculated PAW was 0.130, 0.143, and 0.152 $m^3 m^{-3}$ for 0ACB, 5ACB, and 20ACB, respectively, therefore soils treated with 5ACB and 20ACB increased PAW by 10.0% and 16.9%, respectively. Bulk density of soil treated with 0ACB, 5ACB and 20ACB presented 0.84, 0.80 and 0.77 g cm^{-3}, respectively.

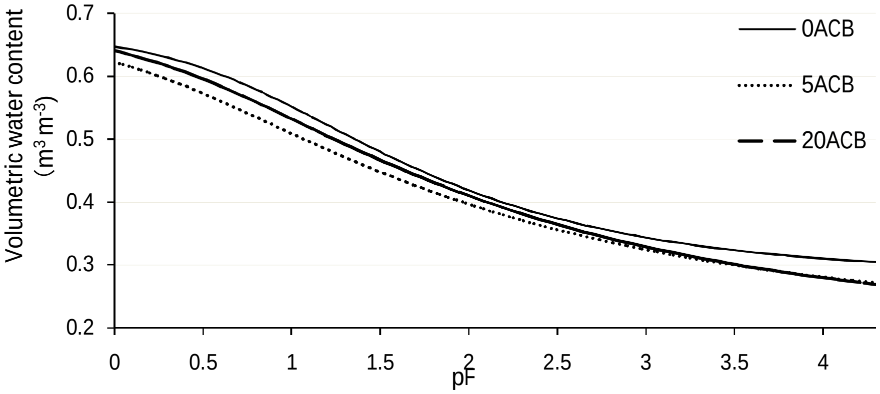

Fig. 4. Effects of biochar application on soil water retention curve for samples collected from the field on 30 DAP

Table 2. Soil water contents at saturation, field capacity, permanent wilting, and bulk density curve for samples collected from the field on 30 DAP

Treatment[†]	SAT[‡]	FC[‡]	PWP[‡]	GWC[‡]	PAW[‡]	PAW change[‡]	Bulk Density
	————————		cm cm^{-3}	————————		%	g cm^{-3}
0ACB	0.671 ^{a}	0.410	0.280 ^{a}	0.261	0.130 ^{a}	–	0.84
5ACB	0.667 ^{a}	0.415	0.272 ^{a}	0.252	0.143 ^{a}	+10.0%	0.80
20ACB	0.675 ^{a}	0.426	0.274 ^{a}	0.249	0.152 ^{a}	+16.9%	0.77

[‡] SAT: water content at saturation, FC: water content at field capacity, PWP: water content at permanent wilting point, GWC: gravitational water content calculated as (SAT–FC), PAW: plant available water calculated as (FC–PWP), PAW change: percentage increase in PAW relative to control.

The same letters among different treatments for each plant parameter denote non-significant differences for each cropping season.

VWC of the soil with 0ACB on top 10 cm depth presented the highest compared to those treated with 5ACB and 20ACB throughout cultivation period (Fig. 5a). The VWC with 0ACB was relatively constant between 0.430 and 0.465 m^3 m^{-3} during all experiment period, while those with 5ACB and 20ACB were relatively constant between 0.438 to 0.440 m^3 m^{-3} until 90 DAP. After 90 DAP until the end of experiment period, VWC with 5ACB and 20ACB fluctuated widely between 0.452 and 0.262 m^3 m^{-3} and 0.450 and 0.335 m^3 m^{-3}, respectively. On 30 cm depth, VWC with 0ACB was relatively constant between 0.460 and 0.520 m^3 m^{-3}, while those with 5ACB and 20ACB were lower than that with 0ACB throughout experiment period (Fig. 5b). VWC with 5ACB and 20ACB was relatively constant until 108 DAP in the range of 0.460 to 0.490 m^3 m^{-3} and 0.445 to 0.460 m^3 m^{-3}, respectively. Thereafter, VWC with 5ACB and 20ACB fluctuated widely to reach the minimum of 0.380 and 0.330 m^3 m^{-3}, respectively.

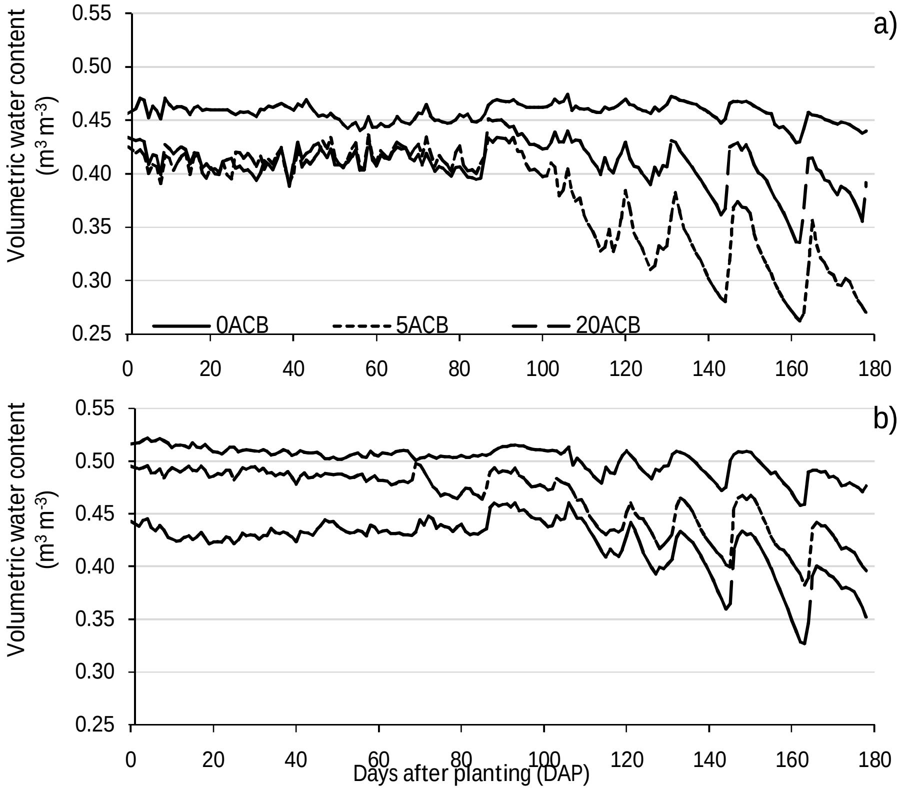

Fig. 5. Effects of biochar application on soil water content at two different depths (a) 10 and (b) 30 cm for teff production

Water potential (WP) was constant and similar values for all treatments from 0 DAP to 110 DAP (Fig. 6). WP started to oscillate during the dry period of the season starting from around 110 DAP. On the 1st wave of drought (123 to 129 DAP), WP of the treatments 0ACB, 5ACB and 20ACB had the minimum value of −51.6, −24.5 and −24.5 kPa, respectively. On the 2nd wave of drought (137 to 145 DAP), WP of the treatments 0ACB, 5ACB and 20ACB had the minimum value of −111, −43.0 and −39.4 kPa, respectively. On the 3rd wave of drought (153 to 165 DAP), WP of the treatments 0ACB, 5ACB and 20ACB had the minimum value of −324, −95.8 and −66.4 kPa, respectively.

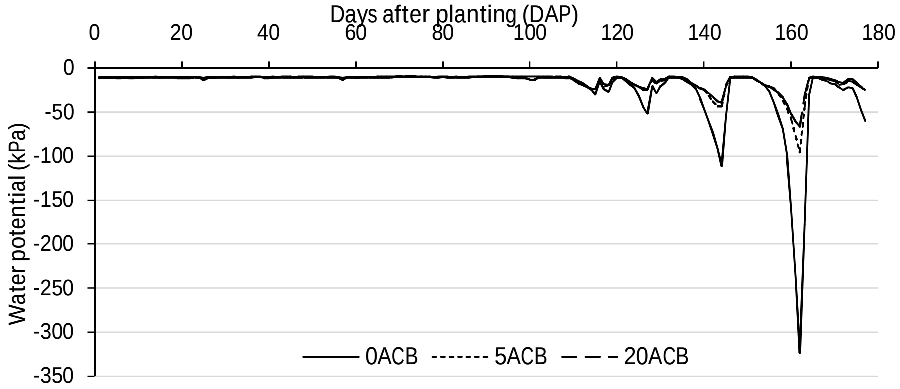

Fig. 6. Effects of biochar application on soil water potential at 10 cm depth

3.3Effects of biochar on plant parameters

Both biochar treatments with 5ACB and 20ACB significantly (*p*< 0.05) increased teff plant height, dry biomass, and grain yield compared to no biochar 0ACB (Table 3). Plant height was 17% and 40% increase with 5ACB and 20ACB compared to 0ACB, respectively. Dry biomass was 172% and 256% increase with 5ACB and 20ACB compared to 0ACB, respectively. Grain yield was 146% and 173% increase with 5ACB and 20ACB compared to 0ACB, respectively.

Table 3. Effects of biochar and fertilizer application on plant parameters (plant height, dry biomass, and grain yield) during cropping rainy seasons for teff production

Treatment	Plant height	Dry biomass	Grain yield
	cm	t ha^{-1}	kg ha^{-1}
0ACB	57.8 ± 16.9 ^{a}	1.80 ± 1.43 ^{a}	126 ± 66.8 ^{a}
5ACB	67.6 ± 13.1 ^{b}	4.90 ± 0.95 ^{b}	310 ± 94.5 ^{b}
20ACB	81.2 ± 11.9 ^{c}	6.40 ± 0.85 ^{b}	344 ± 92.3 ^{b}

The same letters among different treatments for each plant parameter denote non-significant differences for each cropping season.

4. DISCUSSION

4.1Effects of biochar on soil parameters

Soil sample used for this experiment was very clayey (50.9%), acidic (pH 5.13), and low with nutrients (Table 1), which is a typical tropical soil in highland Ethiopia [15]. Acacia biochar used in this experiment was very alkaline (pH 9.51; Table 1). Soil pH with all treatments at both 10 and 30 cm depths on 0 DAP was higher than the original soil pH (5.13) probably because the experiment land was plowed and disturbed allowing oxygen entry within 30 cm depth before the experiment causing pH to rise temporarily (Fig. 1). Furthermore, biochar application raised soil pH even more due to the alkaline property of biochar particularly at top 10 cm where biochar was mixed. Similar results were found in a past study [16] where an acidic soil from highland Ethiopia increasing pH from 4.85 to 5.18 with 1% (20 t ha^{-1}) biochar derived from water hyacinth. A decreasing trend of pH until 100 DAP was probably due to acidification caused by nitrification of N fertilizer applied. However, pH decrease was mitigated with particularly 20ACB because biochar buffered soil pH change [16].

There were no apparent effects of biochar application on soil NH_4^+-N during cultivation period at both soil depths (Fig. 2). However, higher NH_4^+-N than the original soil NH_4^+-N until 30 DAP and a peak after 120 DAP were probably from chemical fertilizers applied prior to each period (DAP and the second split of urea on 0 and 95 DAP, respectively). Similar results were found in a past study [15], where higher NH_4^+-N was found shortly after more chemical fertilizer was applied. Although not significant, NH_4^+-N was lower with 5ACB and 20ACB compared to that with 0ACB particularly at top 10 cm possibly due to absorption of N by plant which grew better with biochar application (discussed in section 4-2).

There were also no apparent effects of biochar application on soil NO_3^--N during cultivation period at both soil depths (Fig. 3). However, NO_3^--N peaks on 100 and 140 DAP were probably caused by nitrification from the first and second splits of urea applied on 44 and 95 DAP, respectively. Similarly to NH_4^+-N, although not significant, NO_3^--N was lower with 5ACB and 20ACB compared to that with 0ACB particularly at top 10 cm probably due to absorption of N by plant which grew better with biochar application (discussed in section 4-2).

Biochar application caused to change general shape of soil water retention curves compared to that of 0ACB (Fig. 4). As a result, soil water contents at FC and PWP were increased and decreased, respectively, leading to increase in PAW with biochar application compared to those of 0ACB (10.0%–16.9%; Table 2). Similar results were found in the past studies [17], when willow biochar was applied (5%) to a clayey soil PAW increased by 17% to 32%. Higher water contents at FC with biochar were possibly explained by lower bulk density (Table 2), or inversely higher porosity, retaining more water in soil pore spaces after biochar application than without biochar. Particle size of biochar used in this experiment was less than 5 mm which was larger than soil sand particle size of 2 mm, possibly causing higher porosity than soil without biochar. Water at PWP (pF 4.2) represents water molecules strongly adhered to surfaces of soil particles and/or other components enough not to be extracted by plant roots. Lower water contents at PWP with biochar application were possibly because water molecules could have been more easily extracted thus lost from pore spaces of biochar and/or soil aggregates caused by biochar than from surfaces of soil particles. Biochar can promote formation of soil aggregates to retain water in soil [18], where mean weight diameter (indicator for soil aggregate size and stability) increased with increasing biochar application rates (0–29 t ha^{-1}). Therefore, PAW has improved due to biochar application in this study since PAW was calculated by the difference between water contents at FC and PWP (Table 2).

At both 10 and 30 cm depths, 0ACB presented higher VWC compared to 5ACB and 20ACB throughout the growing season (Fig. 5). Soil water can be lost by evapotranspiration to atmosphere and/or infiltration to groundwater from soil. Soils treated with biochar presented lower water contents than without biochar because water molecules could be more easily lost by evaporation, plant absorption, and infiltration from pore spaces of biochar and/or soil aggregates than soil particle surfaces particularly at 10 cm depth (Fig. 5a). After the rainy period (around 100 DAP), VWC showed recurrent oscillation due to infrequent and scarce precipitation in the beginning of dry period (Fig. S2). At both 10 and 30 cm depths, VWC with

0ACB was higher than those with biochar application throughout the growing season (Fig. 5) probably because of poor infiltration rate of the clayey soil in the study site. Yet, VWC at 10 cm depth in the soil with 20ACB was higher than that with 5ACB particularly during the dry period (Fig. 5a) probably because more amounts of biochar applied could have held more water. In fact, water potential in the soil with biochar application at 10 cm depth was less negative than that without biochar especially on days with no precipitation (Fig. S2) during the dry season (Fig. 6), implying more water was available for plant in soils with biochar application. At 30 cm depth (Fig. 5b) VWC for 5ACB presented higher volume compared to 20ACB most likely due to more water was held with more amounts of biochar applied at 10 cm depth coupled with poor infiltration.

4.2 Effects of biochar on plant parameters

Biochar applied on clayey soils could change soil structure and contribute to adequate drainage water during the rainy period and retention of water during the dry period, which collaborate with proper aeration in soil for health plant growth [19]. Our results showed significantly increased plant height, dry biomass, and grain yields for soil treated with biochar (Table 3). Soil treatment with 5ACB and 20ACB increased plant height by 17.0% and 40.5%, respectively, dry biomass by 172% and 256%, respectively, and grain yields by 146% and 173%, respectively (Table 3). One of the main possible explanations for this may be biochar capacity to maintain relatively adequate water contents in soil for both rainy and dry periods (Figs. 5 and 6). A previous study showed 154% and 186% increases in dry biomass and grain yield of teff, respectively, grown in soil with 12 t ha^{-1} biochar application in highland Ethiopia [5].

5. CONCLUSION

Our results showed that biochar application improved and regulated water availability for clayey soil during the period of the growing season, which resulted in improved biomass and grain production of teff. The particle size of biochar used in this study was less than 5 mm which was larger than soil sand particle size of 2 mm, possibly causing higher porosity than soil without biochar, which contributed to higher water availability. Major parameters of chemical properties of soil such as pH, NH_4^+-N, and NO_3^--N were not significantly affected by biochar application. Therefore, the amendment of the soil with acacia biochar can be recommended to increase crop production for clayey soil in sustainable conditions.

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APPENDIX

(a)

(b)

Fig. S1. (a) Layout of experimental plots and treatments, teff germination (b) teff stand performance at harvest.

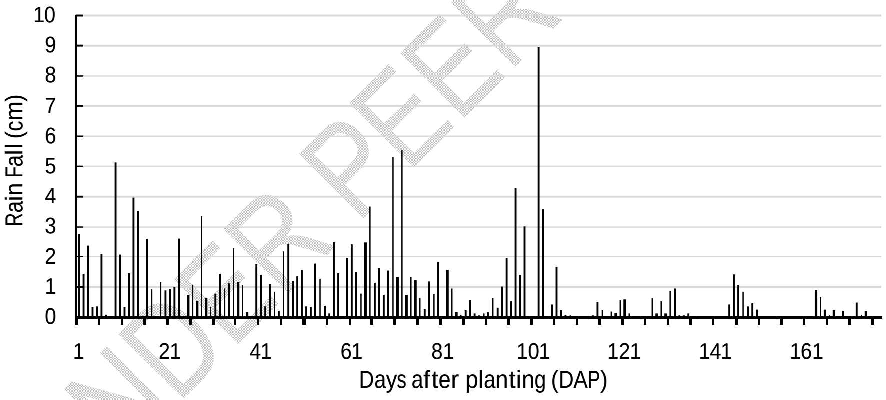

Fig. S2. Daily rainfall during the experimental period