Acacia Biochar and Irrigation Scheme for Dry Season Teff Production in Highland of Ethiopia

ABSTRACT

Teff (*Eragrostis tef*) is one of the essential cereal crops grown mainly in rainy season and barely grown in dry season, but has the lowest yield compared to other cereal crops such as wheat and barley in Ethiopia. Nitisols in tropical Ethiopia have a characteristic of low fertility and high acidity causing low crop productivity, which require application of organic amendment to bring chemical and physical soil properties at levels to achieve a good crop productivity. Therefore, the purpose of this study was to evaluate the effects of different application rates of acacia biochar (ACB) under two different irrigation schemes on soil nitrogen and water dynamics and teff production. Biochar application rates were 0, 5, and 20 t ha^{-1} (0ACB, 5ACB, and 20ACB, respectively) and irrigation schemes were 75% and 100% of water requirement (I_1 and I_2, respectively) by teff according to farmers' practice. Soil pH with 20ACB at 10 cm soil depth was significantly increased in the beginning of growing season. ACB application and irrigation schemes did not significantly affect soil NH_4^+-N and NO_3^--N at both 10 and 30 cm depths throughout growing season. Soil water content limited by dry growing season in this experiment may be critical and underrated for effective amelioration of soil acidity and plant nutrient improvement by biochar application. Under both irrigation schemes, 20ACB presented higher teff dry biomass and plant height than 0ABC and 5ABC, however only under I_2 irrigation scheme it was significant. This study showed that the combination of different irrigation schemes combined with biochar application had somewhat positive impacts on teff biomass production. This combination should contribute and stimulate crop production and efficiency of water usage.

Keywords: Nitisol, plant available water, water potential, water retention

1. INTRODUCTION

Demand for food has been pressured due to fast increase of the population particularly in developing countries [1]. To alleviate food demand, improvement of crop productivity is unavoidably necessary throughout growing seasons in such countries. Increasing a number of harvests per year may be an effective strategy to maximize land-use, resources, and investments. However, to achieve that, it is necessary to implement environmentally sound and low-tech system related to irrigation because most of such areas suffer from scarce and ununiform precipitation patterns particularly during dry season for proper crop production. Moreover, lacks of experiences, equipment, and resources to implement effective irrigation systems have been serious obstacles for best practices to save water and improve crop production [2]. However, the best irrigation practice depends on soil and crop types under different regions.

Production of teff (*Eragrostis tef*) compared to other cereal crops such as wheat and barley has the lowest yield in Ethiopia [3]. Most of teff available is cultivated during the rainy season. Moreover, teff production in Ethiopia has low productivity due to lack of and/or inexistent access to technology implemented in the field such as machinery, mechanization, seed technology, harvest techniques, and organization of the production chain [4]. An alternative to improve teff productivity might be introduction of irrigation technology. Ethiopian government initiated to promote irrigation to increase teff production [5] during dry seasons which usually start on January until May in Ethiopia [6]. Combining irrigation techniques with fertilizer application during dry season presented better performances of teff production than during rainy season [7]. To achieve high productivity of teff under irrigation, further studies are required to meet exact window time for planting, adequate fertilizer application rates, and water amount for irrigation. In 2012, irrigation for crop production represented only 3% with limited crops, mainly sugarcane, cotton, fruits and vegetables in Ethiopia [5]. Maize and wheat are the only cereal crops in which irrigation is applied, however almost nonexistent irrigation production for teff [5].

Nitisols in tropical Ethiopia have a characteristic of low fertility and high acidity which causes low crop productivity. Caused by soil degradation and intensive rainfall, organic matter and other plant nutrients are lost and soil health and fertility are declined particularly in highland of Ethiopia. Such soils in Ethiopia require adequate management such as application of organic amendment to bring chemical and physical soil properties at levels to achieve a good crop productivity.

Biochar (BC), 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 [8]. Biochar contributes to an increase of organic matter with plant nutrients and other improvements such as soil structure and soil water retention [9]. However, biochar application regime combined with irrigation scheme during dry growing season as a means to increase teff production have not been established in Ethiopia. Clarifying the mechanism of these two-factor combined is needed to promote the efficiency of teff production in highland of Ethiopia.

Therefore, the purpose of this study was to evaluate the effects of different application rates of biochar under two different irrigation schemes on soil nitrogen and water dynamics and teff production.

2. MATERIALS AND METHODS

2.1 Study Area, Experimental Design and Land/Plot Preparation

A field experiment was conducted during dry growing season from December 2019 to July 2020 at Injibara University campus in Ethiopia (Fig. S1). The experimental site was once a farm but had been abandoned for at least 5 years. The experimental land was plowed five times by horses and the experimental plots bed of 10 cm height were laid out with a width of 2.0 m and length of 3.0 m. The experiment was laid out in randomized complete block design with four (4) replications with three (3) levels of biochar application rate and two (2) irrigation schemes with a total of 24 experimental plots. Biochar application rates were 0, 5, and 20 t ha^{-1} and irrigation schemes were 75% and 100% of water requirement by teff according to farmers' practice (100% of water requirement corresponded to 52.5 mm of water applied per week).

Dry season in Injibara region has a critical period starting from January extending to March presenting many days without precipitation. From May rain starts periodically, and June rainy season complete a new cycle.

2.2 Biochar Preparation, Irrigation Scheme and Soil Sensor Setup

Acacia tree (*Acacia decurrens*) locally available in Injibara was used to produce biochar through ground carbonization method by pilling-up branches 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 to 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 26 December 2019 and mixed with 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 (26 December 2019; 0 days after planting; DAP), one-third of recommended urea (50 kg ha^{-1}) in 1st split on 26 January 2020 (30 DAP) and remaining two-third on 2nd split on 24 April 2020 (109 DAP).

Two irrigation schemes were applied for this experiment representing 75% and 100% of the water requirement by the crop (I_1 and I_2, respectively). From January to March 2020 during the dry period, 34 and 45 L of water was applied in each plot for I_1 and I_2 plot, respectively, every day and gradually reduced when precipitation started during the experiment after April.

The combination of the biochar application and irrigation scheme resulted in six different treatments for this experiment (Table 1).

Table 1. Treatments of field experiment for 2020 dry season experiment

Treatments	Biochar application (t ha^{-1})	Irrigation scheme (%)
0ACB-I_1	0	75
5ACB-I_1	5	75
20ACB-I_1	20	75
0ACB-I_2	0	100
5ACB-I_2	5	100
20ACB-I_2	20	100

ACB: Locally produced acacia biochar; I_1 and I_2: irrigation scheme 75% and 100% water requirement by plant, respectively

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. Weather station (Atmos 41, METER Group) was installed in the experimental site to collect weather and atmospheric data from this experiment

2.3 Soil Sampling and Analysis

Soil samples were taken on 0 DAP after mixing ACB and chemical fertilizer in each plot, then taken from each plot on 38, 79, 131, 162 and 183 DAP at two different depths (10 and 30 cm). The samples were stored in a deep-freezer at −25°C until being analyzed. Soil bulk density was measured from the same soil samples after drying them in an oven at 105°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).

2.4 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 sundrying before threshing. Grain yield was weighed after separating teff straw from the grain from all plants from six central rows.

2.5 Statistical Analysis

Analysis of variance was conducted using the STATISTICA program (Tulsa, OK, USA). Factorial ANOVA used to analyze the higher-order interactive effects of multiple categorial independent variables (factors). The difference among means of treatments were determined using Tukey's Highly Significant Difference (HSD) at the probability of 5% ($p < 0.05$).

3. RESULTS

3.1 Physicochemical Properties of Soil and Biochar

The soil used in the experiment was classified as a clayey texture with 29.1%, 20.0%, and 50.9% sand, silt, and clay 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. Basic physicochemical properties of the experimental site were similar to those found in other site of the same experimental area [10, 11].

The biochar used in the experiment had an alkaline pH of 9.51 (Table 2). 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, and 310 mg kg^{-1}, respectively.

Table 2. 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) [12]*
$ *Cation exchange capacity*
# *Measured by CHN coder*
¶ *Available phosphorus extracted by Mehlich-3 solution (Mehlich, 1984) [13]*

3.2 Effects of Biochar on Soil Parameters

Soil treated with 20ACB-I_1 and 20ACB-I_2 has increased soil pH at top 10 cm depth for each sampling date, but not significantly except for 0 DAP (Fig. 1a). The factorial ANOVA result has shown that the main effect was significant ($p < 0.05$) on soil pH (5.33) for 20ACB-I_2 on 0 DAP. All treatments showed a decreasing pH trend until 162 DAP and increasing pH trend on 183 DAP at harvest. At 30 cm depth, all treatments did not cause significant effects on soil pH throughout the cultivation period (Fig. 1b) except for 20ACB-I_1 on 0 DAP, which presented significantly ($p < 0.05$) higher pH of 5.32 mainly due to biochar treatment. Similarly to 10 cm depth, pH of all treatments at 30 cm depth decreased from 0 to 79 DAP and later increased on 131 DAP. Thereafter, soil pH decreased at the harvest time on 183 DAP.

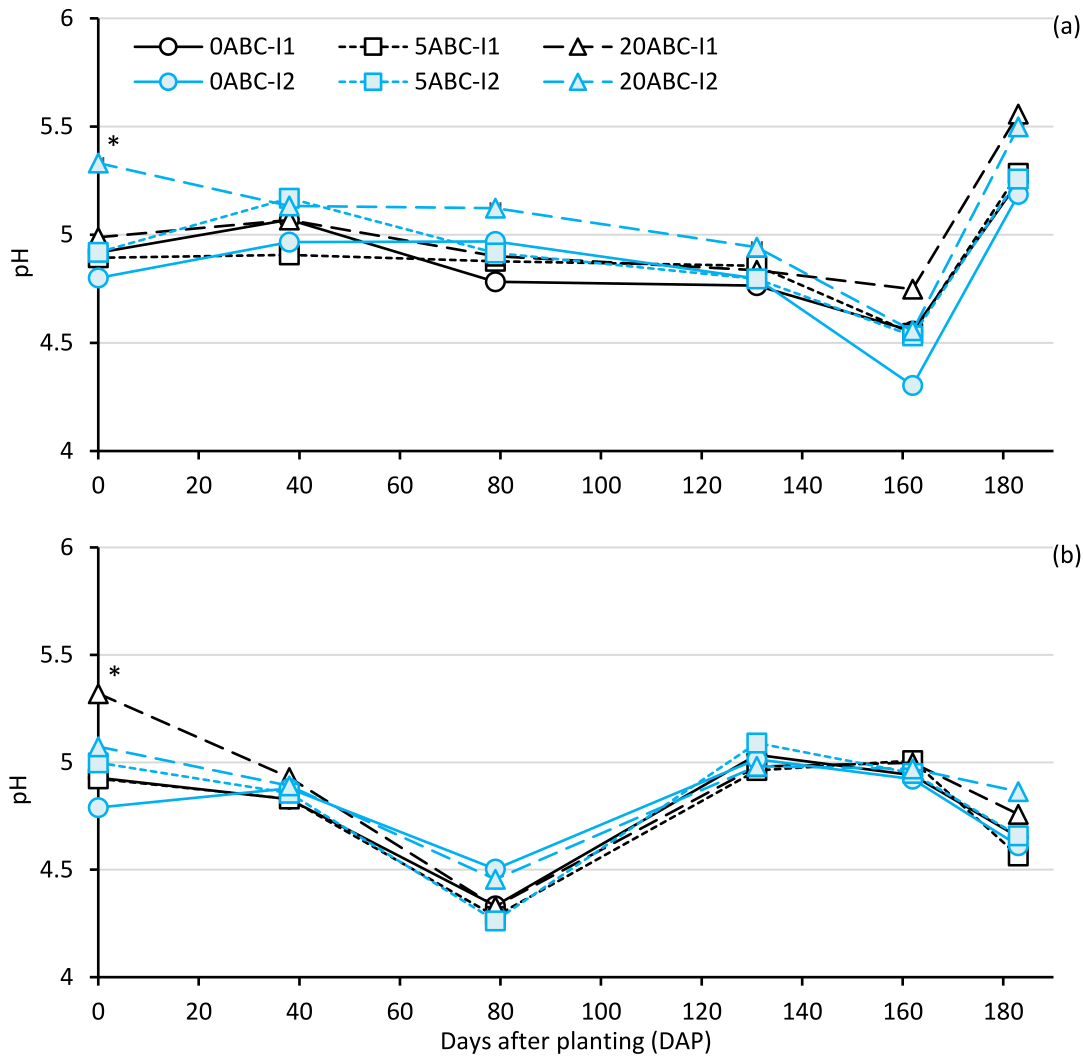

Fig. 1. Effects of biochar application and irrigation scheme on soil pH at two different depths (a) 10 and (b) 30 cm for teff production

** denote significant difference by $p < 0.05$ among different treatments for each sampling date.*

There were no significant differences among treatments at both 10 and 30 cm depth for NH_4^+-N concentration (Fig. 2a and 2b). At top 10 cm depth, NH_4^+-N concentration of all treatments slowly decreased from 38 to 79 DAP. After applying the 2nd split of fertilizer on 109 DAP, NH_4^+-N concentration at 10 cm depth increased from around 10 to more than 50 up to 161 mg kg^{-1} on 131 DAP for all treatments. For 30 cm depth, trend was similar to 10 cm depth increasing from around 10 to more than 30 up to 76 mg kg^{-1} on 131 DAP for all treatments. Then, for both layers, NH_4^+-N concentration decreased to less than 10 mg kg^{-1} on harvest time.

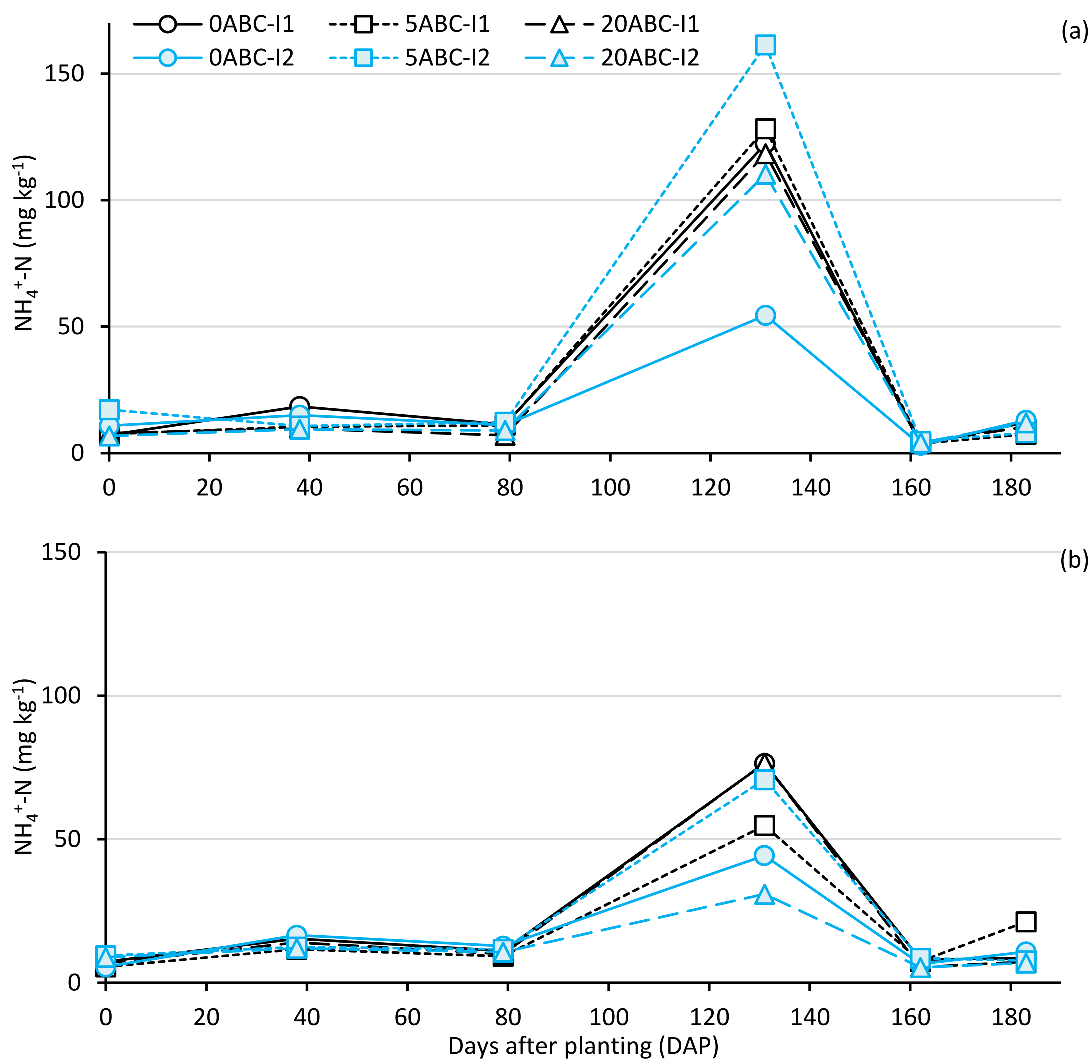

Fig. 2. Effects of biochar application and irrigation scheme on soil NH_4^+-N at two different depths (a) 10 and (b) 30 cm for teff production

For NO_3^--N concentration, there were no significant differences among treatments at both 10 and 30 cm depths throughout cultivation period (Fig. 3a and 3b) except on 79 DAP. A treatment of 20ACB-I_2 presented significantly ($p < 0.05$) higher NO_3^--N of 52.6 mg kg^{-1} due to biochar treatment. At top 10 cm depth, NO_3^--N concentration decreased from 0 to 38 DAP for 0ACB-I_1, 20ACB-I_1, and 20ACB-I_2. Other treatments maintained with very small changes until 79 DAP. All treatments at the harvest time decreased NO_3^--N concentration at 10 cm depth. For 30 cm depth, from 38 DAP, all treatments increased NO_3^--N concentration until 79 DAP, then until harvest time all treatments decreased to around 10 mg kg^{-1}.

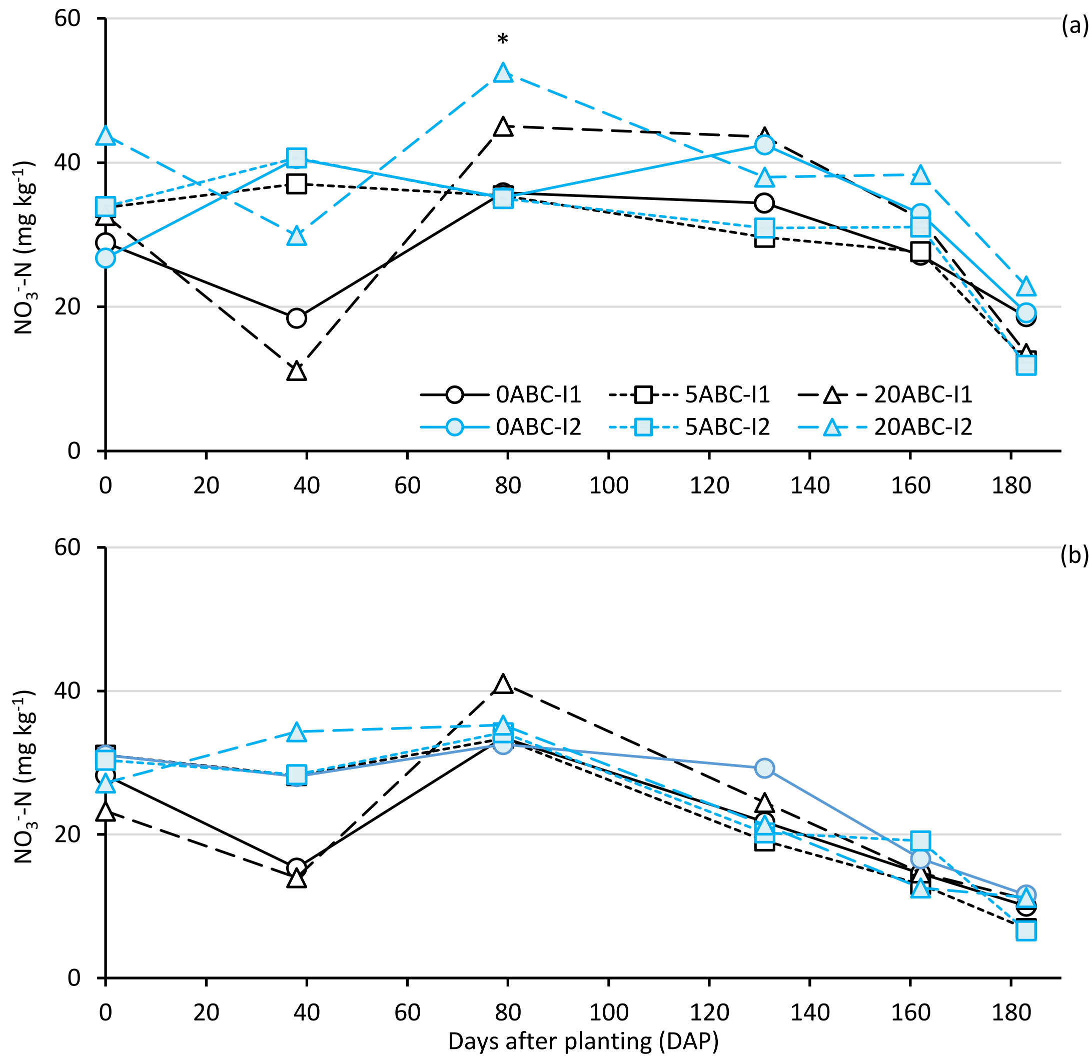

Fig. 3. Effects of biochar application and irrigation scheme on soil NO_3^--N at two different depths (a) 10 and (b) 30 cm for teff production
** denote significant difference by $p < 0.05$ among different treatments for each sampling date.*

VWCs of the soil on top 10 cm depth under I_1 irrigation scheme (75%) presented relatively constant between 0.245 and 0.334, 0.250 and 0.339, and 0.229 and 0.284 $m^3 m^{-3}$ with 0ACB, 5ACB, and 20ACB, respectively, until around 125 DAP (Fig. 4a). After 125 DAP until the end of experiment period, VWCs fluctuated widely between 0.284 and 0.462, 0.285 and 0.403, and 0.275 and 0.417 $m^3 m^{-3}$ with 0ACB, 5ACB, and 20ACB, respectively. On 30 cm depth, VWCs steadily decreased regardless of treatment from 0.429-0.483 to 0.341-0.376 $m^3 m^{-3}$ until around 125 DAP (Fig. 4b). After 125 DAP until the end of experiment period, VWCs increased from 0.348-0.383 to 0.461-0.484 $m^3 m^{-3}$ regardless of treatment.

VWCs of the soil on top 10 cm depth under I_2 irrigation scheme (100%) presented relatively constant between 0.273 and 0.352, 0.217 and 0.256, and 0.240 and 0.349 $m^3 m^{-3}$ with 0ACB, 5ACB, and 20ACB, respectively, until around 125 DAP (Fig. 4a). After 125 DAP until the end of experiment period, VWCs fluctuated widely between 0.285 and 0.463, 0.218 and 0.374, and 0.240 and 0.419 $m^3 m^{-3}$ with 0ACB, 5ACB, and 20ACB, respectively. On 30 cm depth, VWCs steadily decreased regardless of treatment from 0.417-0.444 to 0.301-0.379 $m^3\ m^{-3}$ until around 125 DAP (Fig. 4b). After 125 DAP until the end of experiment period, VWCs increased from 0.301-0.375 to 0.444-0.483 $m^3\ m^{-3}$ regardless of treatment.

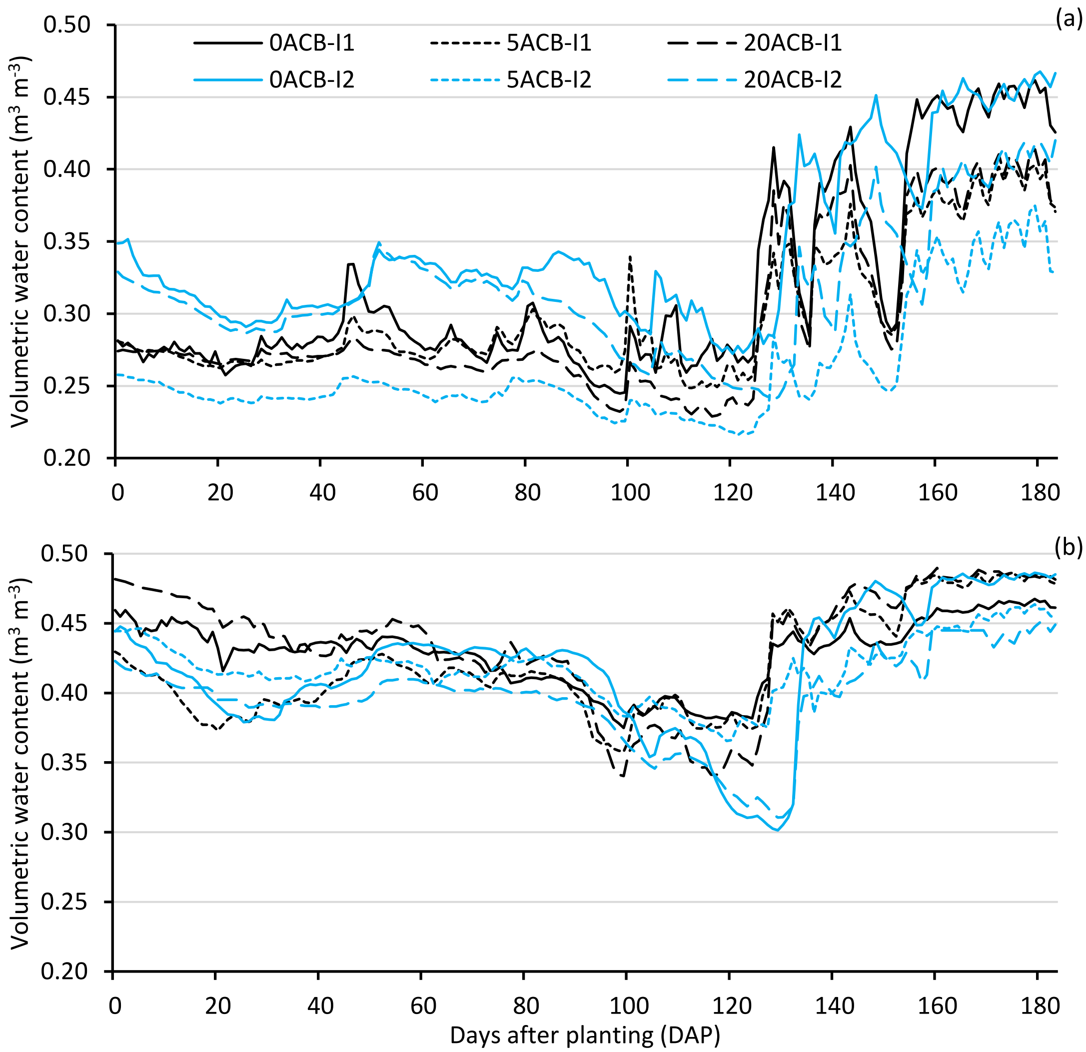

Fig. 4. Effects of biochar application and irrigation scheme on soil volumetric water content at two different depths (a) 10 and (b) 30 cm for teff production.

3.3 Effects of Biochar on Plant Parameters

Under both irrigation schemes, 20ACB treatment presented higher teff dry biomass than 0ABC and 5ABC, however only under I_2 irrigation scheme it was significant (p < 0.05; Fig. 5a). Dry biomass with 20ABC-I1 and 20ABC-I2 was 22-23% and 21-30% higher than those with 0ACB and 5ACB, respectively, under each irrigation scheme.

Under both irrigation schemes, 20ACB treatment presented higher teff grain yield than 0ABC and 5ABC, however it was not significant (Fig. 5b). Grain yield with 20ABC-I1 and 20ABC-I2 was 2.7-9.1% and 40-58% higher than those with 0ACB and 5ACB, respectively, under each irrigation scheme.

Under both irrigation schemes, 20ACB treatment presented higher plant height than 0ABC and 5ABC, however only under I_2 irrigation scheme, it was significant ($p < 0.05$; Fig. 5c). Plant height with 20ABC-I1 and 20ABC-I2 was 9.4-9.8% and 13.2-14.7% higher than those with 0ACB and 5ACB, respectively, under each irrigation scheme.

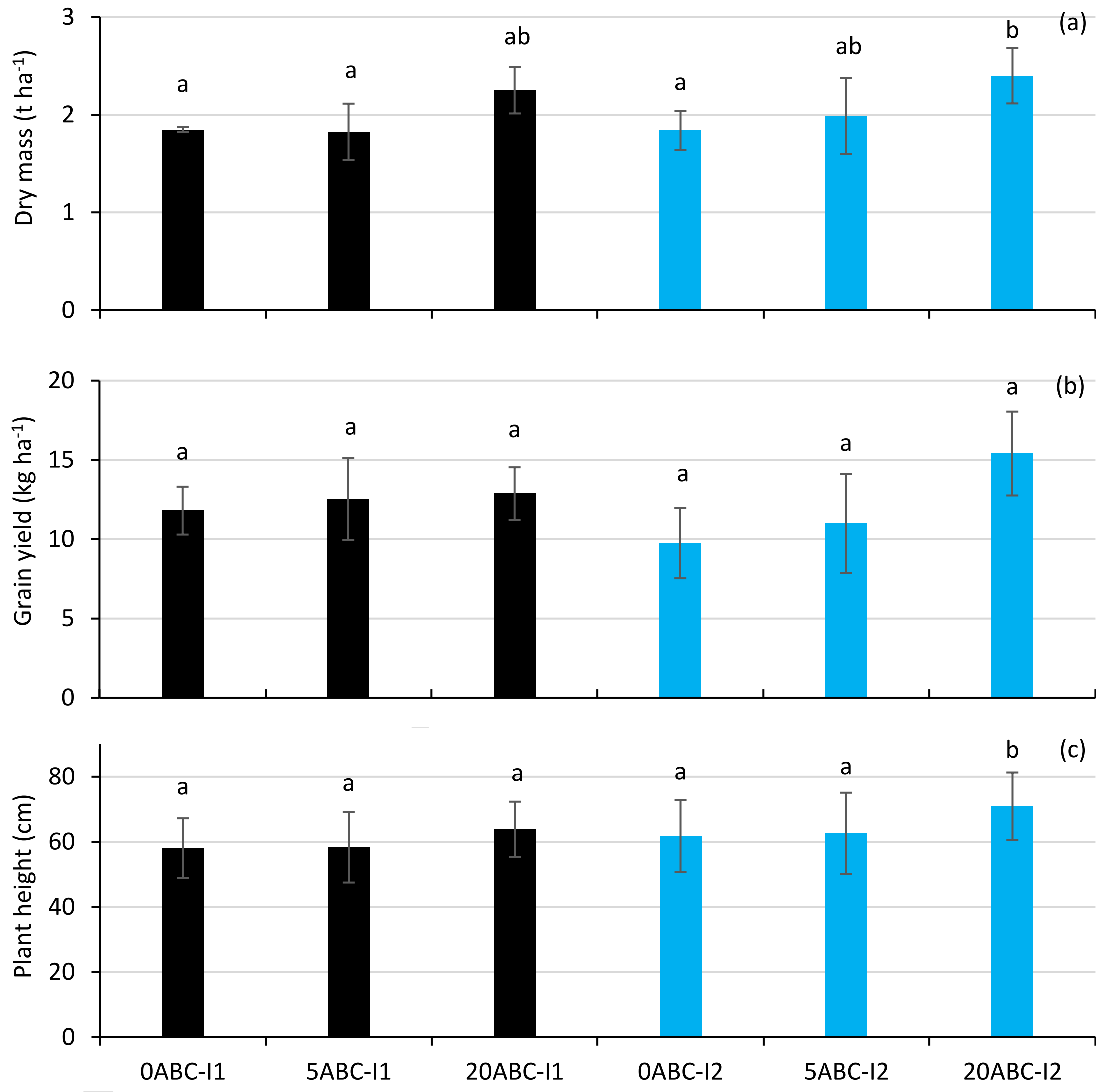

Fig. 5. Effects of biochar application and irrigation scheme on (a) teff dry biomass, (b) grain yield, and (c) plant height.

4. DISCUSSION

4.1 Effects of Biochar on Soil Parameters

The originally acidic soil (pH 5.13) was raised only with higher application rate of biochar under 100% irrigation scheme (20ACB-I_2) in the beginning of growing season (Fig. 1a). Soil pH at 10 cm depth on 0 DAP with 20ACB-I_2 increased significantly ($p < 0.05$) than those with other treatments. This might be due to lack of water content in the soil to interact with soil water and particles to alleviate acidity in soil [14]. In fact, soil water content was extremely low at around 27% (v/v) under I_1 scheme, while it was elevated to around 33-35% (v/v) under I_2 scheme on 0 DAP (Fig. 4a). When teff was produced in wet growing season in the same field, soil pH was raised by 0.10-0.16 unit by biochar application (5 and 20 t ha^{-1}) compared to no biochar-applied soil on 0 DAP under soil water contents of 43-46% (v/v) [10]. Soil water content may be critical for effective amelioration of soil acidity by biochar application to acidic soil. Over time from 0 to 162 DAP soil pH decreased slightly and toward 183 DAP at harvest time pH had a sudden increase with all treatments (Fig. 1a). On around 130 DAP rainy season has started with infrequent precipitation which increased soil water content to 40-45% (v/v) toward the end of growing season. For 30 cm depth, soil pH maintained relatively constant at the original soil pH level except for 79 DAP with pH decrease (Fig. 1b). This might be related to elevated NO_3^--N concentrations (Fig. 3b) by nitrification which could acidify soil pH.

Biochar application or irrigation scheme did not significantly affect soil NH_4^+-N concentration throughout growing season at both depths except for 131 DAP (Fig. 2). Elevated NH_4^+-N concentration on 131 DAP at 10 cm was most likely caused by second split application of urea fertilizer applied on 109 DAP which underwent ammonification as well as mineralization of some organic matter in soil. Similar NH_4^+-N peaks after chemical fertilizer (first and second splits) application of urea was observed in highland of Ethiopia under wet growing season [10, 11]). Elevated NH_4^+-N concentration at 30 cm may have been caused partially by leaching with the beginning of precipitation started on around 130 DAP.

There were no significant differences among treatments (biochar and irrigation scheme) on NO_3^--N concentration at both 10 and 30 cm depths throughout growing season (Fig. 3). Overall elevated NO_3^--N concentration from the original soil NO_3^--N (Table 1) throughout growing season was probably caused by chemical fertilizer application followed by nitrification in soil. Similar trends of NO_3^--N peaks after chemical fertilizer application was observed under wet growing season [10, 11].

At top 10 cm, 100% irrigation scheme (I_2) could maintain higher soil water content than 75% irrigation scheme (I_1) throughout almost all growing season until the rainy season started on around 120 DAP (Fig. 4a; except for 5ACB-I_2). Important effects of biochar application to soil may include in soil structure, soil aggregation, and soil water retention which can contribute to improved soil water dynamic for short-term period [15]. However, effect of biochar application on soil water content was not apparent throughout growing season possibly because clayey soil such as Nitisol in this study already possessed high water holding capacity as limited amount of water applied would be effectively held in soil particle with or without biochar present in soil. Biochar effect on retention of soil water may be more pronounced in sandy soils than clayey soils [16].

4.2 Effects of Biochar on Plant Parameters

Important effects of biochar application to soil may include in both soil chemical and physical improvements which can contribute to improved crop growth and production. However, limited amount of water supplied from irrigation particularly during dry season may mask such effects of biochar on soil properties and crop growth by limiting interaction of biochar with soil particles compared to wet season. The results of this experiment showed a significant ($p < 0.05$) increase of teff dry biomass for treatment of 20ACB-I_2 by 30% and 21% more compared to 0ACB-I_2 and 5ACB-I_1, respectively (Fig. 5a). Likewise, grain yield (not significant) and plant height (significant; $p < 0.05$) were 40-58% and 13-15% higher, respectively, with 20ACB-I_2 compared to 0ACB-I_2 and 5ACB-I_1 (Fig. 5b, 5c). However, as biochar effects on soil chemical properties were not apparent in this study, such effects may have been underrated for dry season under irrigation. Even under limited water content, biochar application could enhance soil structure such as improved soil aggregation and porosity in clayey soil which could enhance root development for cop growth [17]. Soil temperature for 20ACB treatment during nighttime could keep temperature 1ºC higher than 0ACB which might contribute to better performance of dry mass and plant height [18].

The teff grain yield during dry season compared to that during rainy season was 10 to 20 times less [10]. This noteworthy reduction in grain yield in dry season might have been caused by rainfall events in the beginning of rainy season that coincided with the harvest time (Fig. S2a). In highland of Ethiopia represented by Injibara where the experiment was conducted, rainy season usually starts in June, and intensive precipitation could have washed of teff grain from panicle which could cause tremendous loss of grain yields [19]. In fact, shattering and lodging of teff plant at harvest time were observed due to the maturity overlapping rainfall in rainy season [20, 21, 22, 23]. Therefore, in the case of Injibara, to avoid grain loss by rainfall, it is recommended to start growing period early with sowing in December. Another important factor which contributes to the performance of teff growth is ambient temperature. Highland Injibara region has registered daily average temperatures from January to March (dry season) below 14ºC (Fig. S2b) with extreme low temperatures of 2.5ºC at some nights, which could make teff plants to grow slower and take longer to achieve maturity [21, 22].

5. CONCLUSION

This study showed that the combination of different irrigation schemes combined with biochar application had somewhat positive impacts on teff biomass production. This combination should contribute and stimulate crop production and efficiency of water usage.

More studies are required to better understand the effects of biochar and irrigation scheme on soil characteristics and crop production, but acacia biochar can be recommended for the cultivation of teff during the dry season.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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APPENDIX

(a)

(b)

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

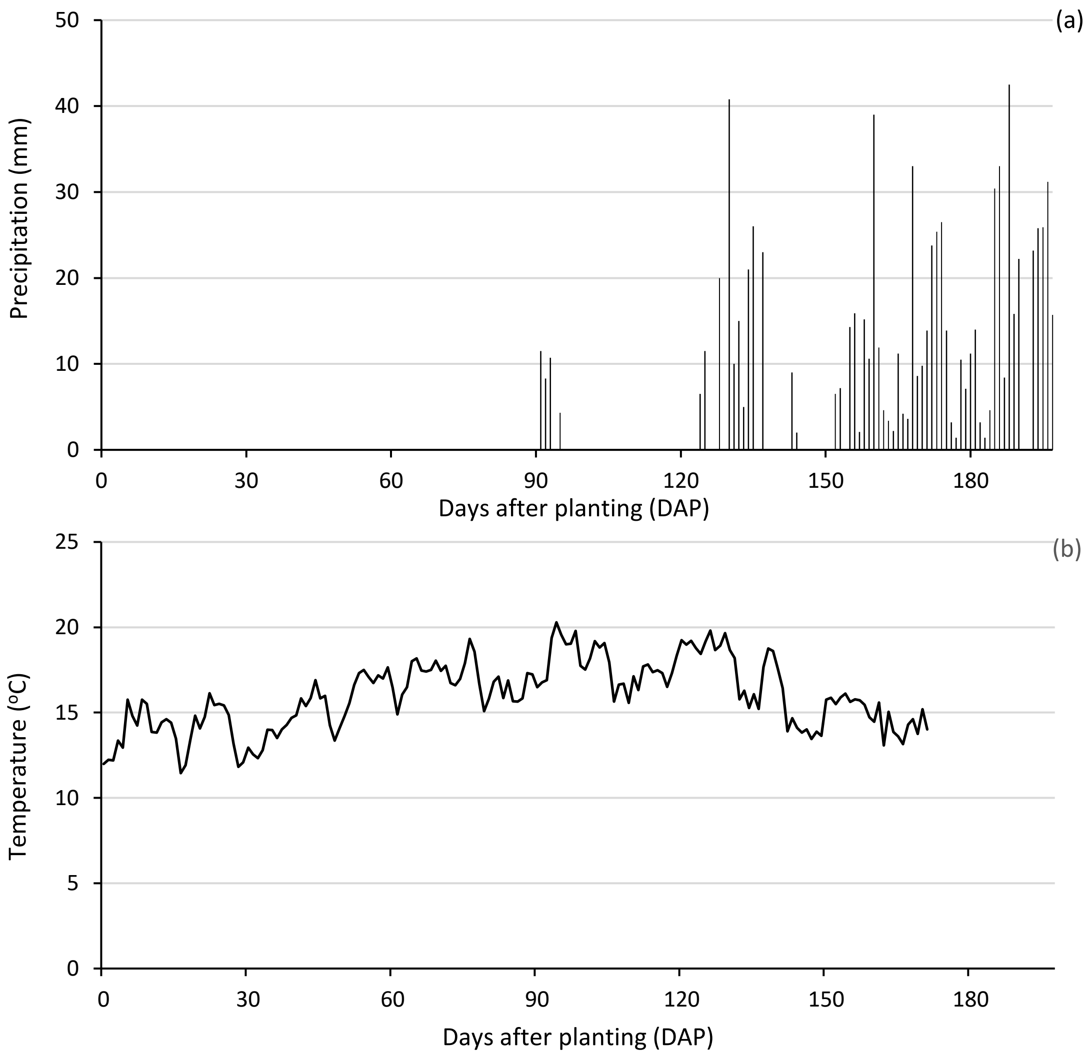

Fig. S2. (a) Daily precipitation and (b) average temperature during the experimental period