



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

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## Authors' contributions

This work was carried out in collaboration among all authors. Author MTO conceptualization, investigation, methodology, formal analysis, validation, data curation, manuscript writing, reviewing and editing. Author DFM conceptualization, investigation, methodology, validation, supervision, reviewing and editing. Author YK formal analysis, and reviewing and editing. Author SAL reviewing and editing, and project administration. Author BBA reviewing and editing. Author SS conceptualization, investigation, methodology, validation, supervision, reviewing and editing, and project leader. All authors read and approved the final manuscript.

## Article Information

DOI: <https://doi.org/10.9734/ajsspn/2024/v10i4429>

## Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/127528>

Original Research Article

Received: 18/09/2024  
Accepted: 26/11/2024  
Published: 03/12/2024

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**Cite as:** Ono, Marcelo Takeda, Milkiyas Ahmed Yasin, Desalew Fentie Meselu, Yudai Kohira, Solomon Addisu Legesse, Berhanu Belay Abune, and Shinjiro Sato. 2024. "Impacts of Acacia Biochar and Irrigation Scheme on Teff Production for Dry Season in Highland of Ethiopia". *Asian Journal of Soil Science and Plant Nutrition* 10 (4):569-83. <https://doi.org/10.9734/ajsspn/2024/v10i4429>.

## 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. High prices and scarcity of fertilizers challenge farmers in teff production. 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, which could contribute to food security and sustainable agriculture. 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<sup>-1</sup> (0ACB, 5ACB, and 20ACB, respectively) and irrigation schemes were 75% and 100% of water requirement (I<sub>1</sub> and I<sub>2</sub>, 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<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-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, 20ABC-I<sub>1</sub> and 20ABC-I<sub>2</sub> presented higher teff dry biomass (22-23% and 21-30%, respectively) and plant height (9.4-9.8% and 13.2-14.7%, respectively) than those with 0ACB and 5ACB, respectively, however only under I<sub>2</sub> 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. However, limited amount of water supplied from irrigation particularly during dry season may mask such effects of biochar on crop growth by limiting interaction of biochar with soil particles compared to wet season. This combination should contribute and stimulate crop production and efficiency of water usage. However, particularly in highland of Ethiopia, to avoid grain loss by rainfall, it is recommended to start growing period early with sowing in December for dry season. Further studies with long-term biochar application and different window of sowing time are necessary for better understanding of such practices.

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

## 1. INTRODUCTION

Demand for food has been pressured due to fast increase in 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 production 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 sowing and harvesting, 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 application 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 in highland of Ethiopia.

## 2. MATERIALS AND METHODS

### 2.1 Study Area Description

A field experiment was conducted during dry growing season from December 2019 to July 2020 at Injibara University campus in Ethiopia (Fig. A1). Injibara is located at 2,560 m above sea level. 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.

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.

### 2.2 Biochar Preparation

Acacia tree (*Acacia decurrens*) locally available in Injibara was used to produce biochar through ground carbonization method by piling-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<sup>-1</sup>; 0ACB, 5ACB, and 20ACB, respectively).

### 2.3 Experimental Design

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<sup>-1</sup> 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).

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<sup>-1</sup>. Chemical fertilizers of diammonium phosphate (100 kg ha<sup>-1</sup>) were applied at planting (26 December 2019; 0 days after planting; DAP), one-third of recommended urea (50 kg ha<sup>-1</sup>) 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<sub>1</sub> and I<sub>2</sub>, respectively). From January to March 2020 during the dry period, 34 and 45 L of water was applied in each plot for I<sub>1</sub> and I<sub>2</sub> 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 <sup>-1</sup> )	Irrigation scheme (%)
0ACB-I <sub>1</sub>	0	75
5ACB-I <sub>1</sub>	5	75
20ACB-I <sub>1</sub>	20	75
0ACB-I <sub>2</sub>	0	100
5ACB-I <sub>2</sub>	5	100
20ACB-I <sub>2</sub>	20	100

ACB: Locally produced acacia biochar; I<sub>1</sub> and I<sub>2</sub>: 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.

#### 2.4 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<sub>c</sub> kg<sup>-1</sup>. Soil total C and total N were 3.71% and 0.483%, respectively. The amount of NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, available phosphorus was 1.52, 15.7, 0.392 mg kg<sup>-1</sup>, 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<sub>c</sub> kg<sup>-1</sup>. Biochar total C and total N were 33.0% and 1.91%, respectively. The amount of

NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, and available phosphorus were 4.03, 1.18, and 310 mg kg<sup>-1</sup>, respectively.

#### 2.5 Soil Sampling and Analyses

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<sup>3</sup>).

#### 2.6 Plant Sampling and Analyses

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.

#### 2.7 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 categorical independent variables (factors). The difference among means of treatments were determined using Tukey's Highly Significant Difference (HSD) at the probability of 5% ( $p < 0.05$ ).

**Table 2. Basic Characterization of Soil and Biochar Samples**

	Sand <sup>§</sup>	Silt <sup>§</sup>	Clay <sup>§</sup>	Bulk density	pH	CEC <sup>§</sup>	Total C <sup>#</sup>	Total N <sup>#</sup>	NH <sub>4</sub> <sup>+</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	Av. P <sup>¶</sup>
	———— % ————					cmol <sub>c</sub> kg <sup>-1</sup>	———— % ————		———— mg kg <sup>-1</sup> ————		
Soil <sup>†</sup>	29.1	20.0	50.9	1.05	5.13	2.84	3.71	0.483	1.52	15.7	0.392
Biochar <sup>‡</sup>	—	—	—	—	9.51	3.01	33.0	1.91	4.03	1.18	310

<sup>†</sup> Clayey Nitisol collected at Injibara University, Ethiopia

<sup>‡</sup> Locally produced from acacia tree

<sup>§</sup> Measured by hydrometer method [12]

<sup>§</sup> Cation exchange capacity

<sup>#</sup> Measured by CHN coder

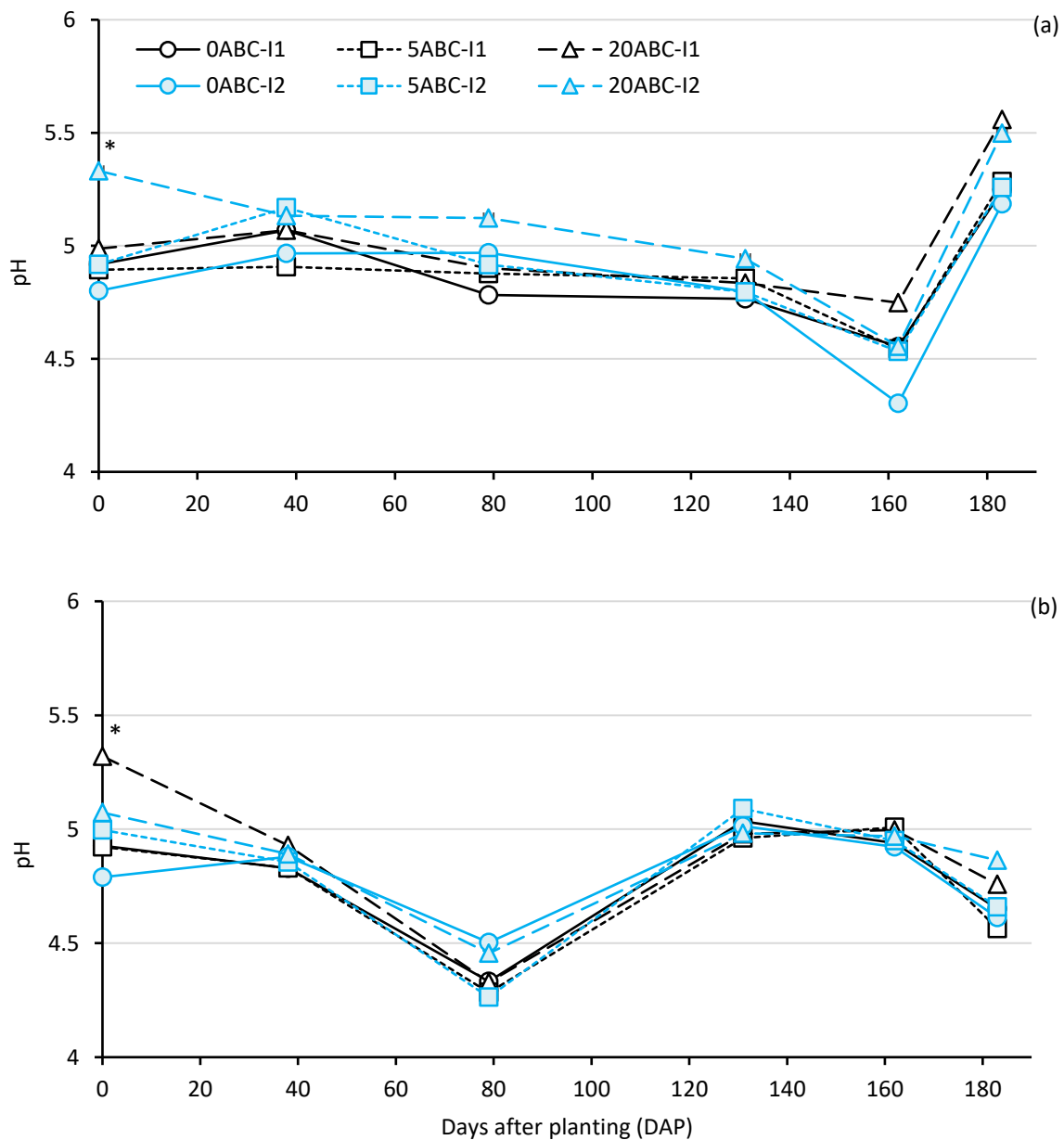
<sup>¶</sup> Available phosphorus extracted by Mehlich-3 solution [13]

### 3. RESULTS

#### 3.1 Effects of Biochar on Soil pH

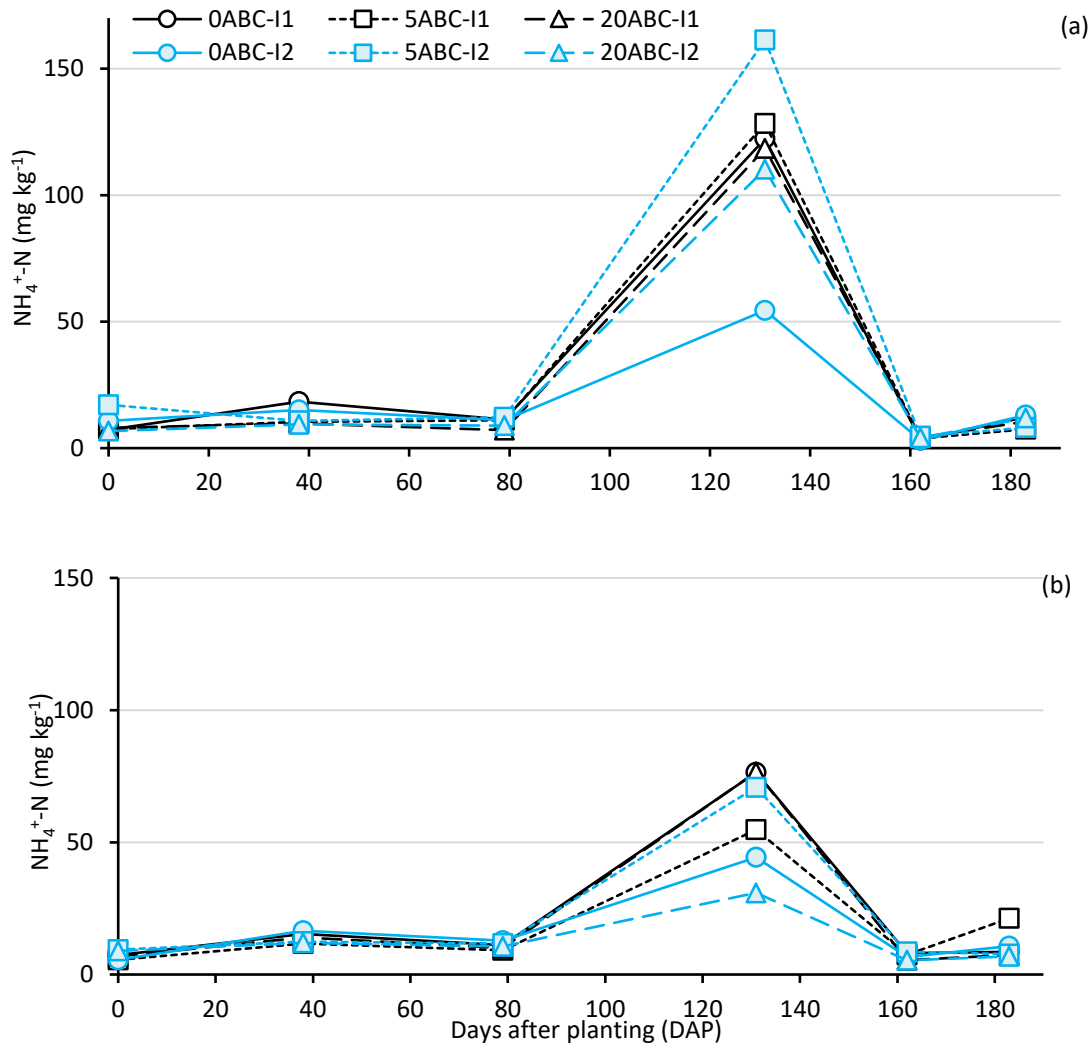
Soil treated with 20ACB-I<sub>1</sub> and 20ACB-I<sub>2</sub> has increased soil pH at top 10 cm depth for each sampling date, but not significantly except for 0 DAP (Fig. 1a). The factorial ANOVA result has shown that the main effect was significant ( $p < 0.05$ ) on soil pH (5.33) for 20ACB-I<sub>2</sub> 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<sub>1</sub> 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



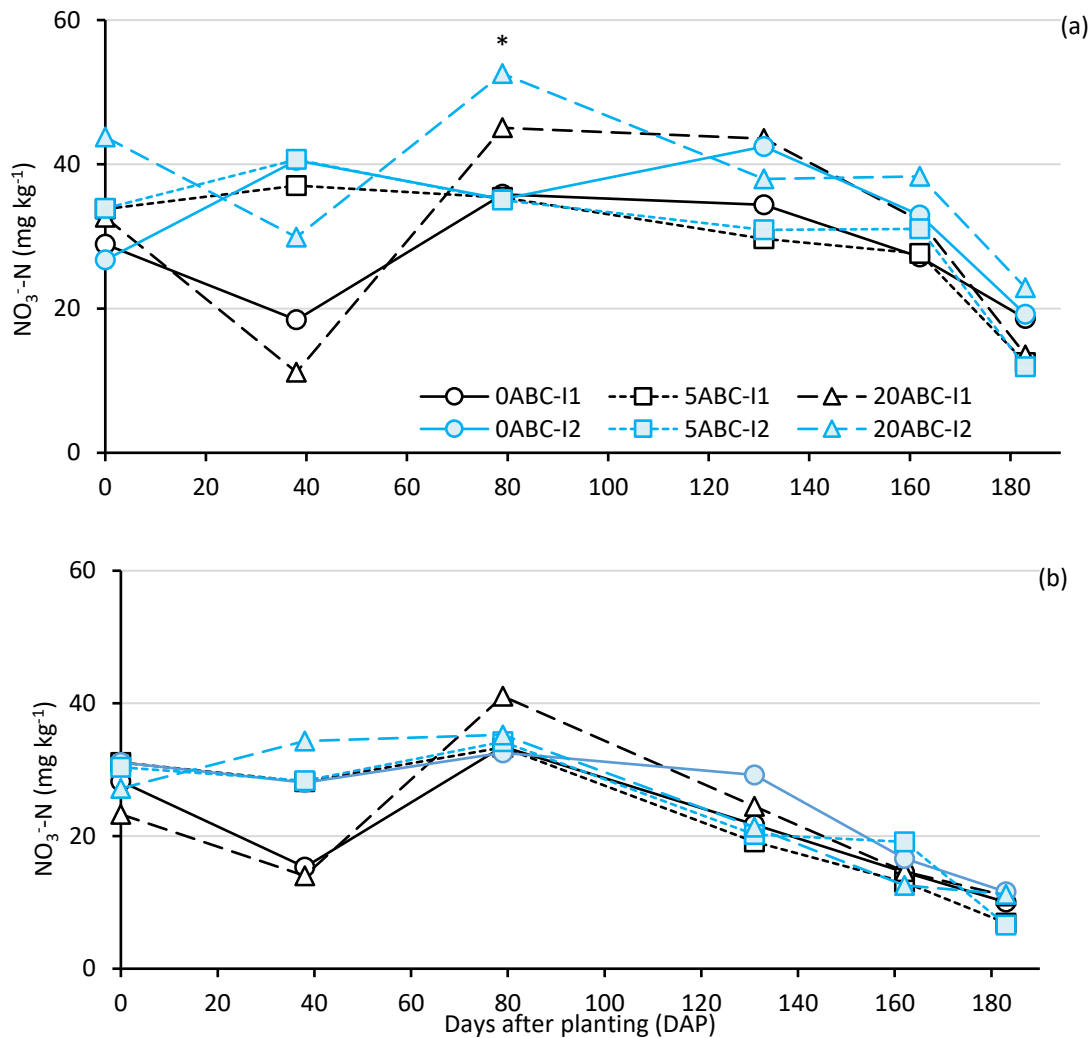
**Fig. 2. Effects of biochar application and irrigation scheme on soil  $\text{NH}_4^+\text{-N}$  at two different depths (a) 10 and (b) 30 cm for teff production**

### 3.2 Effects of Biochar on Soil Ammonium-Nitrogen

There were no significant differences among treatments at both 10 and 30 cm depth for  $\text{NH}_4^+\text{-N}$  concentration (Fig. 2a and 2b). At top 10 cm depth,  $\text{NH}_4^+\text{-N}$  concentration of all treatments slowly decreased from 38 to 79 DAP. After applying the 2nd split of fertilizer on 109 DAP,  $\text{NH}_4^+\text{-N}$  concentration at 10 cm depth increased from around 10 to more than 50 up to 161  $\text{mg kg}^{-1}$  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  $\text{mg kg}^{-1}$  on 131 DAP for all treatments. Then, for both layers,  $\text{NH}_4^+\text{-N}$  concentration decreased to less than 10  $\text{mg kg}^{-1}$  on harvest time.

### 3.3 Effects of Biochar on Soil Nitrate-Nitrogen

For  $\text{NO}_3^-\text{-N}$  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<sub>2</sub> presented significantly ( $p < 0.05$ ) higher  $\text{NO}_3^-\text{-N}$  of 52.6  $\text{mg kg}^{-1}$  due to biochar treatment. At top 10 cm depth,  $\text{NO}_3^-\text{-N}$  concentration decreased from 0 to 38 DAP for 0ACB-I<sub>1</sub>, 20ACB-I<sub>1</sub>, and 20ACB-I<sub>2</sub>. Other treatments maintained with very small changes until 79 DAP. All treatments at the harvest time decreased  $\text{NO}_3^-\text{-N}$  concentration at 10 cm depth. For 30 cm depth, from 38 DAP, all treatments increased  $\text{NO}_3^-\text{-N}$  concentration until 79 DAP, then until harvest time all treatments decreased to around 10  $\text{mg kg}^{-1}$ .



**Fig. 3. Effects of biochar application and irrigation scheme on soil  $\text{NO}_3\text{-N}$  at two different depths (a) 10 and (b) 30 cm for teff production**

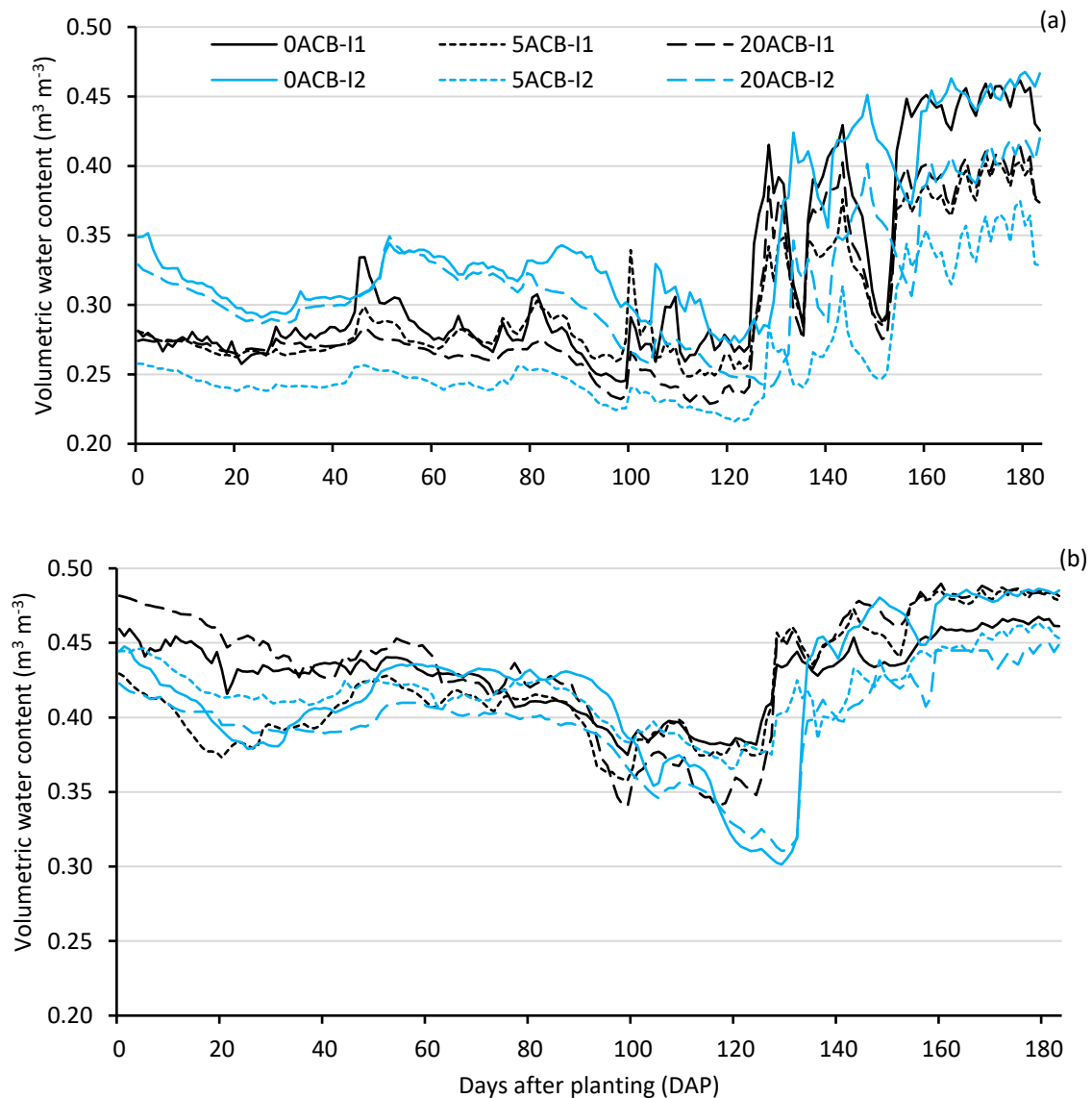
\* denote significant difference by  $p < 0.05$  among different treatments for each sampling date

### 3.4 Effects of Biochar on Soil Volumetric Water Content

Volumetric water contents 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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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  $\text{m}^3 \text{m}^{-3}$  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**

### 3.5 Effects of Biochar on Teff Dry Biomass, Grain Yield, and Plant Height

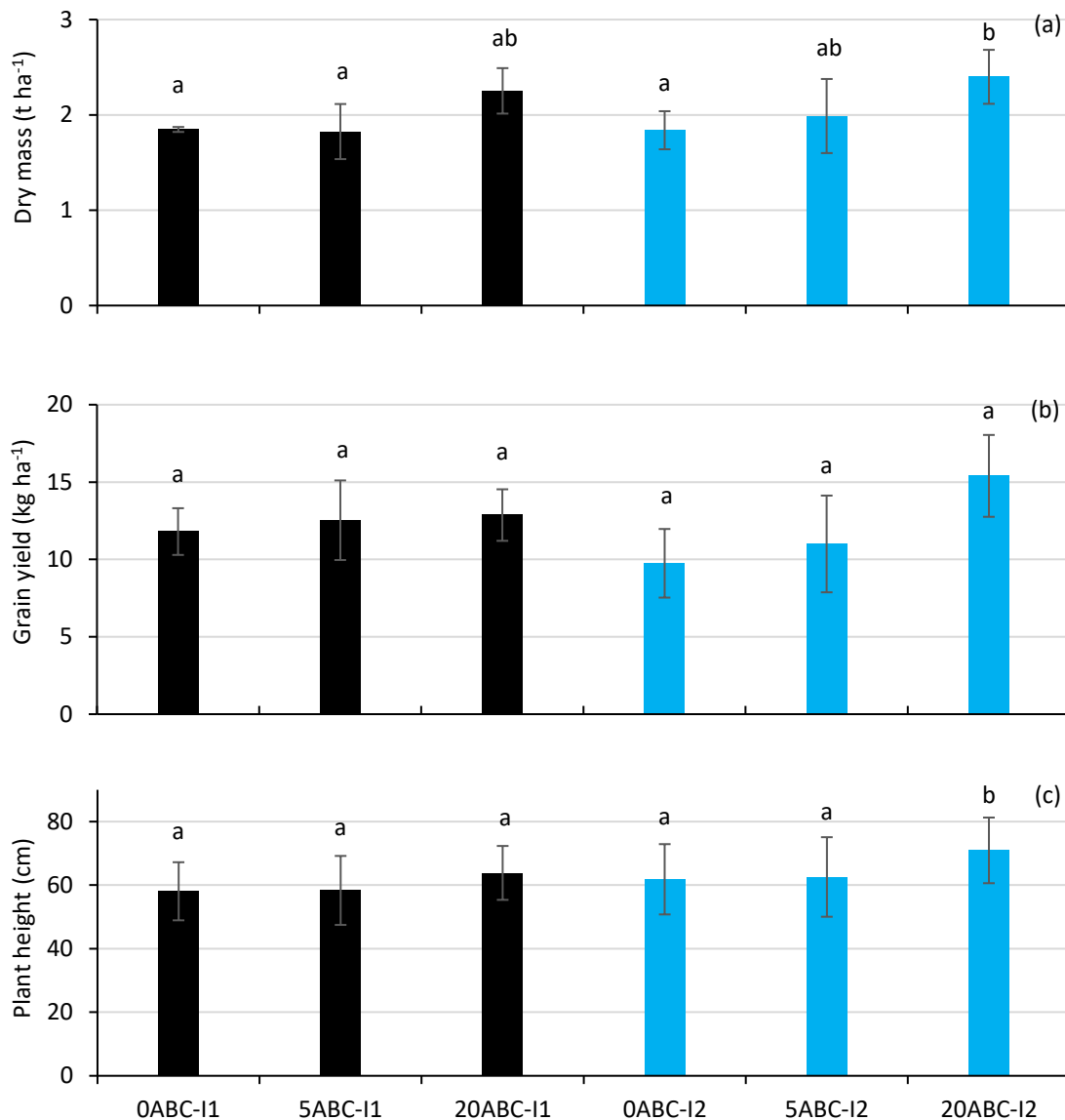
Under both irrigation schemes, 20ACB treatment presented higher teff dry biomass than 0ACB and 5ACB, however only under I<sub>2</sub> irrigation scheme it was significant ( $p < 0.05$ ; Fig. 5a). Dry biomass with 20ACB-I1 and 20ACB-I2 was 22-23% and 21-30% higher than those with 0ACB and 5ACB, respectively, under each irrigation scheme.

Under both irrigation schemes, 20ACB treatment presented higher teff grain yield than 0ACB and

5ACB, 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 0ACB and 5ACB, however only under I<sub>2</sub> 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<sub>2</sub>) in the beginning of growing season (Fig. 1a). Soil pH at 10 cm depth on 0 DAP with 20ACB-I<sub>2</sub> 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<sub>1</sub> scheme, while it was elevated

to around 33-35% (v/v) under I<sub>2</sub> 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<sup>-1</sup>) 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  $\text{NO}_3^-$ -N concentrations (Fig. 3b) by nitrification which could acidify soil pH.

Biochar application or irrigation scheme did not significantly affect soil  $\text{NH}_4^+$ -N concentration throughout growing season at both depths except for 131 DAP (Fig. 2). Elevated  $\text{NH}_4^+$ -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  $\text{NH}_4^+$ -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  $\text{NH}_4^+$ -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  $\text{NO}_3^-$ -N concentration at both 10 and 30 cm depths throughout growing season (Fig. 3). Overall elevated  $\text{NO}_3^-$ -N concentration from the original soil  $\text{NO}_3^-$ -N (Table 1) throughout growing season was probably caused by chemical fertilizer application followed by nitrification in soil. Similar trends of  $\text{NO}_3^-$ -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 crop growth [17]. Soil temperature for 20ACB treatment during nighttime could keep temperature 1°C 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. A2a). 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 14°C (Fig. A2b) with extreme low temperatures of 2.5°C at some nights, which could make teff plants to

grow slower and take longer to achieve maturity [21,22].

### 4.3 Limitations and Future Directions

Based on results of this study, it was found clear that effects of biochar application on soil physicochemical properties and plant growth were positive to some extent but generally limited particularly under irrigation practice during dry growing season. Since biochar interactions with soil particles require sufficient soil water content for effective changes in soil properties, it is recommended to optimize irrigation schemes and window of sowing time for proper teff production in highland of Ethiopia under extensive and extremely dry periods.

For future implication of teff production, further studies are necessary to comprehend long-term effects of biochar application that extends for both dry and rainy growing seasons on soil properties and plant growth, and possibility of using dry- and low temperature-resistant teff varieties for growing particularly in dry season.

## 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. However, in highland of Ethiopia with extremely dry period, to avoid grain loss by rainfall and lodging by time of harvesting, it is recommended to start growing period early with sowing in December.

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. Further studies with long-term biochar application and different window of sowing time is necessary for better understanding.

## 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 this manuscript.

## ACKNOWLEDGEMENTS

This research was supported by Plankton Ecoengineering for Environment and Economic Transformations Project (PLAN3T) funded by MEXT of Japan and Science and Technology Research Partnership for Sustainable Development (SATREPS; Grant Number JPMJSA2005) funded by Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA) of Japan.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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## APPENDIX

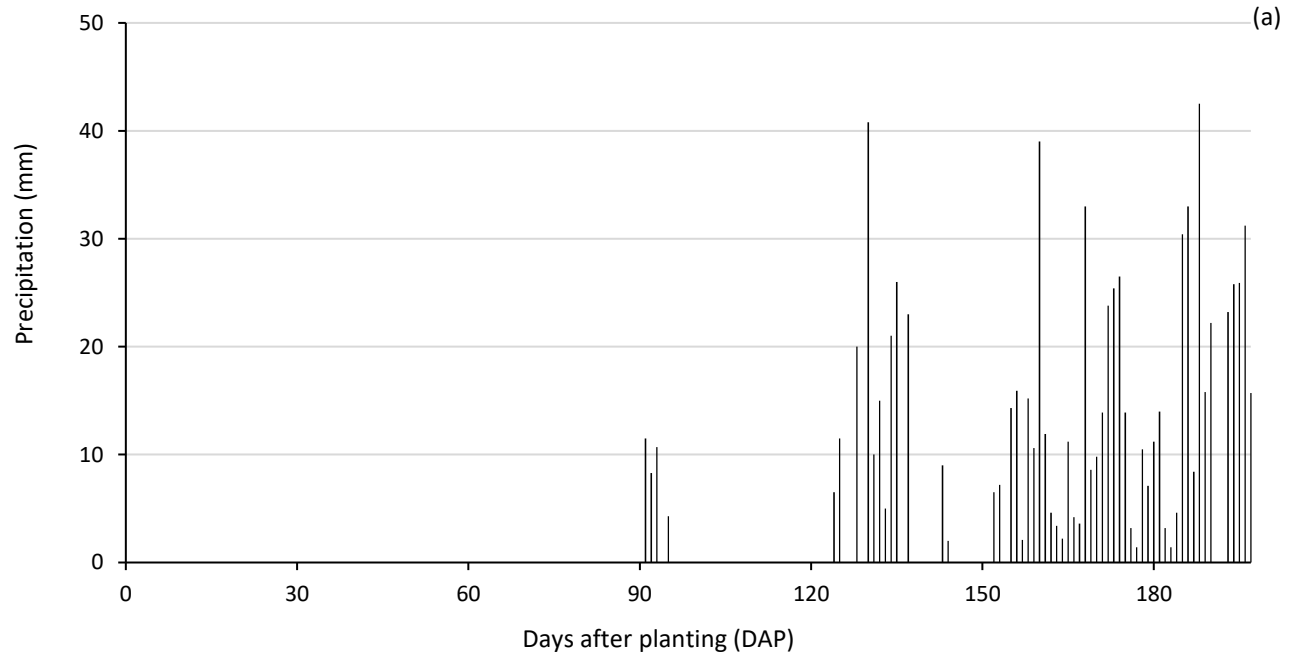
(a)

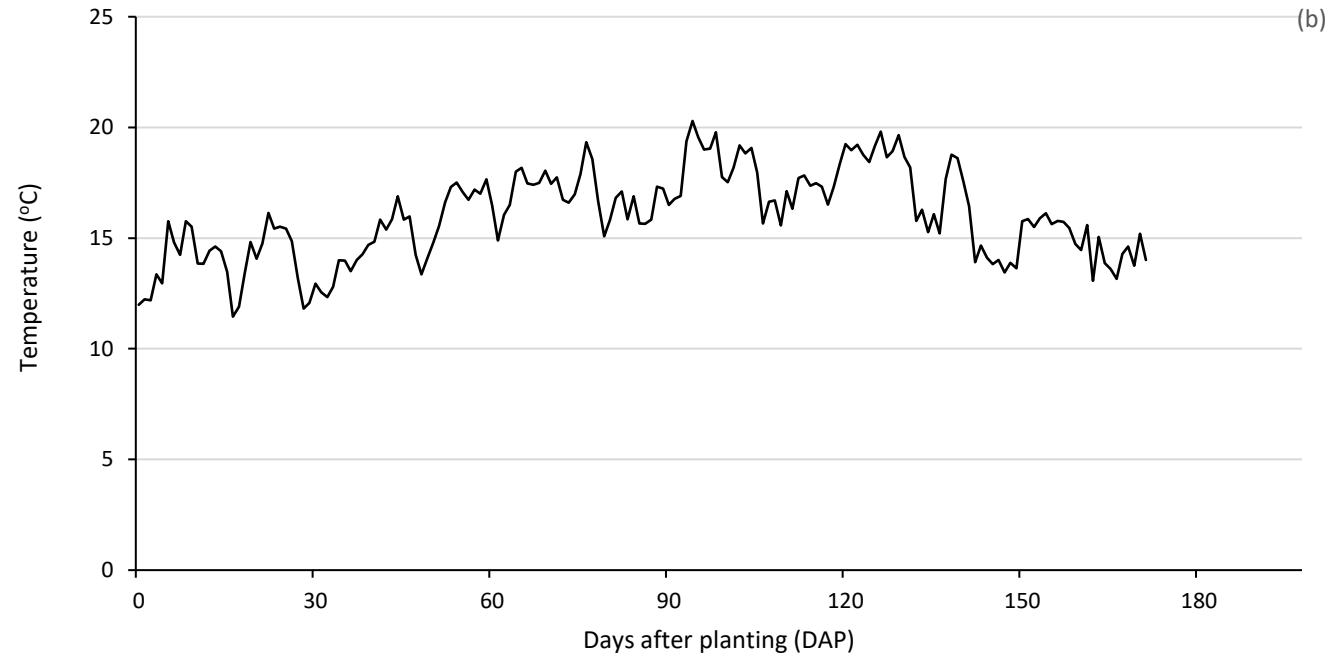


(b)



**Fig. A1. (a) Layout of experimental plots, treatments, and teff germination, and (b)teff stand performance at harvest**





**Fig. A2. (a) Daily precipitation and (b) average temperature during the experimental period**

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