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INTEGRATED EFFECTS OF BIOCHAR AND DEFICIT IRRIGATION SUBJECTED AT VARIOUS GROWTH STAGES ON TOMATO YIELD AND WATER USE EFFICIENCY

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ABSTRACT

In recent years, irrigation water resources have been diminishing leading to an exponential growth in agriculture water demand; hence the adoption of water saving techniques is inevitable. This study focused on the assessment of deficit irrigation and biochar amendment on maximizing water use efficiency of tomato with less compromise on yield. The experimental setup was a two-factorial, completely random block system, with three replications. The first factor was irrigation regime (a) full irrigation at all stages as treatments T1 and T2 (b) deficit irrigation at various stages as treatments T3, T4, T5 and T6. The second factor was biochar amendment, where by all treatment had biochar amendment except for treatment T1. The results indicated that biochar enhanced soil water status hence fruit yield and water use efficiency were improved with regard to treatment T2 over T1. Deficit irrigation applied at vegetative stage (T3) had minimal negative effect on yield while water use efficiency was improved. Yield reduction was pronounced when deficit irrigation was applied at flowering and fruit development stage followed by fruit ripening stage. A combination of biochar amendment and deficit irrigation can be a positive approach to save water while maintaining acceptable yields when applied at vegetative stage.

Keywords: Irrigation regimes, Soil water storage conservation, Water stress, Yield reduction.

INTRODUCTION

Competition for water is increasing rapidly, with irrigated agriculture as the main user of fresh water resources globally. The sustainable use of water in irrigation has become a major concern of which the only solution is to consider effective and efficient water saving strategies (Wang *et al*. 2009a). The adoption of water saving strategies and techniques while maintaining satisfactory yields can be a major breakthrough and may add to safeguarding this always confined asset. One of the ways to mitigate water shortage in agriculture is to adopt deficit irrigation (DI), with the primary goal of decreasing irrigation water demand, improve water use efficiency (WUE) and crop yields (Saleh, 2010).

DI is a water-saving approach under which crops are exposed to a certain level of water stress during a certain period of time or over the entire growing season (Djurovic *et al*. 2016). Tomato (*Solanum lycopersicon* L.) is one of the most demanding crops in terms of water use and has the highest acreage of any vegetable crop in the world (Jensen *et al*. 2010). At a moderate water deficit, tomato crop tends to improve water use efficiency with tolerable amount of yield reduction and single fruit weight losses (Cosic *et al*. 2015). Effects of deficit irrigation have been extensively studied on tomato, though with contrasting results (Cantore *et al*. 2016; Kirda *et al*. 2004).

Many studies have demonstrated that the effects of deficit irrigation largely depend on the growth stage, intensity and period at which the stress occurs. Nangare *et al*. (2016) suggested that, benefits of deficit irrigation in terms of improved water productivity while sustaining fruit yield could be achieved with appropriate deficit irrigation during vegetative stage followed by flowering stage. Meanwhile, Chen *et al*. (2013) reported that tomato yield was adversely affected by water stress during fruit development and ripening. According to Patane *et al*. (2011), the adoption of DI strategies on tomato in which a 50% reduction in crop evapotranspiration was applied for partial growing season to save water helped to minimize fruit losses.

In addition to the irrigation management strategies, studies have been conducted to examine alternatives of saving irrigation water by using the complementary properties of soil amendments such as Biochar with the final aim of improving yields (Akhtar *et al*. 2014). Biochar is being used increasingly with an intention to improve soil functions and physical properties such as water holding capacity (Hardie *et al*. 2014). Thus crop productivity can be improved under soil amended with biochar by conserving soil moisture, which leads to a decrease in irrigation frequency and amount.

In the literature, there are few studies that investigated the effects of biochar addition under water stress to enhance yield and quality of tomato (Agbna *et al*. 2017; Akhtar *et al*. 2014); nonetheless limited information is available on maximizing water use efficiency. The objective of the present research was to determine a suitable deficit irrigation strategy to obtain maximum output of water use efficiency with less negative effect on crop yields with biochar amended soil. In other words, to gain insight into the possibility of saving water and increasing water use efficiency of tomato with regulated deficit irrigation and biochar addition while maintaining satisfactory yields.

MATERIALS AND METHODS

Experimental site: The research study was conducted during the tomato growing season of 2017 and 2018 at the Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China (31°57′ N, 118°50′ E, and 144 m above MSL). The climatic condition of the study area consists of the humid subtropics which are influenced by the monsoon climate of East Asia. The experiment was carried out under an open end rainshelter with a planting area of 140 m^2. The temperature and relative humidity inside the rainshelter was recorded with time loggers and it ranged from 18 to 39 °C and 40 to 95% respectively. At fifth leaf stage, tomato (var, Jinfen M-5) seedlings were transplanted into plastic pots (0.15m diameter and 1.2 m height) meanwhile clay loam soil was used for this experiment (Table 1). Portions of compound fertilizers (N 15%, P_2O_5 15%, K_2O 15%) were applied as basal dressing at a rate of 500 kg/ha before transplanting.

Biochar amended: Biochar used for this experiment was produced from wheat straw pyrolyzed at 350–550 °C in a vertical kiln made of refractory bricks in Sanli New Energy Company, Henan Province, China. With such a technology, 30% of wheat straw dry matter would be expected to be converted to biochar (Agbna *et al*. 2017, Liu *et al*. 2014). It was grinded into fine powder and mixed thoroughly into soil before filling the pot at 10% by weight of soil. The biochar amendment had an initial pH of 9.9, organic content of 467.20 g/kg, total N of 5.90 g/kg, total P of 14.43 g/kg, total K of 11.50 g/kg and cation exchange capacity of 21.70 c mol/kg.

Experimental Design and irrigation regimes: Six treatments replicated three times were allocated in a completely random design under the rainout shelter. The plants were irrigated to 100% of field capacity for all growth stages for treatments T1 and T2. The experimental treatments were based upon the growth stages: the vegetative stage (stage I) was from transplanting to first fruit set; the flowering and fruit development stage (stage II) was from first fruit set to first fruit maturity; and the fruit ripening stage (stage III) was from first fruit maturity to final harvest. Further details can be found in Chen *et al.* (2013). The four deficit irrigation treatments received 30% decreased amount of irrigation of T2 but at differing stages: treatment T3 during stage I, T4 during stage II, T5 during stage III and T6 during stages II and III. Except for stages that were subjected to water stress, irrigation amounts were the same as for treatment T2 (Table2). Irrigation was applied when the soil moisture content of T2 reached 70% of field capacity. There was no biochar amendment for treatment T1 while other treatments had biochar amendment of 10% by weight of soil. After transplanting soil moisture was monitored regularly at four days intervals using the gravimetric method at 10cm increments to a depth of 30 cm.

Crop Water Use: In order to approximate crop water use, the soil-water balance approach was used by observing soil moisture change. There was no ground water contribution as pots were used and no precipitation and runoff. Drainage outlet of pots were closed for the entire growing season so there was no drainage influence thus Eq. (1) was used;

$$ET = I + \Delta\theta \quad (1)$$

Where ET was actual crop water use (mm); I was irrigation amount (mm) and $\Delta\theta$ was the change in moisture content (mm).

Yield, response factor and water use efficiency: During the fruit ripening stage, tomato fruits were harvested (three harvests in each season) to determine the individual fruit weight and fresh yield, when they reached the mature grade color. In this study linear programming technique was used to achieve the best optimal solution for water use efficiency (WUE) for different treatments. The model was prepared as follows:

$$WUE = \frac{Y_i}{ET} \quad (2)$$

Where Y_i was the total fruit yield of treatment i .Water deficit was introduced as percentage of decreased applied water of T2 according to different growth stages, *d.* Two matrices were defined for optimization purpose. One was the amount of water required for irrigation and the other was the least possible amount of water applied to the crop. Both matrices were optimized in order to achieve minimum crop water consumption while maximizing water use efficiency. The linear limitation was introduced as follows:

$$\Delta\theta \leq ET \quad (3)$$

$$\sum_{i=1}^{n} w_i \leq (1-d) \times W \quad (4)$$

$$\begin{bmatrix} w_{1,1} & \cdots & w_{n,1} \\ \vdots & \ddots & \vdots \\ w_{1,m} & \cdots & w_{n,m} \end{bmatrix} \leq \begin{bmatrix} wr_{1,1} & \cdots & wr_{n,1} \\ \vdots & \ddots & \vdots \\ wr_{1,m} & \cdots & wr_{n,m} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} w_{1,1} & \cdots & w_{n,1} \\ \vdots & \ddots & \vdots \\ w_{1,m} & \cdots & w_{n,m} \end{bmatrix} \geq \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix} \quad (6)$$

Where w_i was the net amount of water applied to crop i (mm), W was the total amount of water applied under full irrigation (mm), wr_i was the net amount of crop water requirement (mm).

The number of stress days (*SD*) was calculated from Eq. (7):

$$SD = \sum_{i=1}^{n} SD(i) = \sum_{i=1}^{n} \left[1 - \frac{ET_{ai}}{ET_{mi}}\right] \cdot N_i \quad (7)$$

Where ET_{ai} and ET_{mi} was actual and maximum crop evapotranspiration of deficit and full irrigation treatment, respectively; N_i was the number of days at the growth stage *'i'*; *n* is the number of growth stages.

The relative yield reduction (*Fy*) is given as

$$Fy_i = 1 - \frac{Y_{ai}}{Y_{mi}} \quad (8)$$

Where Y_{ai} and Y_{mi} was yield of the deficit and full irrigation treatment, respectively.

The yield response factor (*Ky*) was calculated from equation (9):

$$1 - \frac{Y_{ai}}{Y_{mi}} = Ky_i \cdot \left[1 - \frac{ET_{ai}}{ET_{mi}}\right] \quad (9)$$

Where Ky_i was the yield response factor of treatment *i*', and the other parameters as previously defined.

Statistical analysis: All statistical analyses involved in this study were performed using the statistical product and service solutions 16.0 version software (SPSS Inc., USA). The data were evaluated using one-way analysis of variance (ANOVA) and the least significant differences (LSD) test at $p \leq 0.05$ was used to assay statistical differences between the means of each treatment. Data were presented are means ± standard errors (S.E).

RESULTS

Soil moisture depletion: The trends for soil moisture content during both seasons for the different irrigation treatments were similar (Fig. 1 and Fig. 2). Soil moisture content of treatment T2 was higher than that of treatment T1 in both growing seasons despite being subjected to the same irrigation regime. This difference could be attributed to biochar through its complementary characteristics of modifying soil pore size distribution associated with aggregation improvements. The reduction in irrigation amount during any growth stage decreased soil moisture, which exposed crops to water stress (Fig. 2 A-H).

Yield and Response factor: The total yields of tomato varied from 84.01 to 141.94 t/ha and 95.13 to 139.09 t/ha for the 2017 and 2018 seasons respectively. The lowest yields were obtained for treatment T6 meanwhile the highest yields were attained on treatment T2, in both seasons. Biochar influenced yields positively as there was a significant difference between treatment T2 and T1 ($P < 0.05$) in spite of the fact that their irrigation regime was the same. It can be noted that yields are reduced when water stress is applied on stage II although the statistical difference with stage III was not significant ($P>0.05$) in 2017 season (Table 3).

Generally, the number of stress days increased with decreasing the total ET amount. Compared to the well-watered treatment (T2), the SD was significantly increased by 0.94 and 1.50 days for stage I and stage II in 2017 season, and 0.49 and 1.03 days in 2018 season, respectively. There are similar tendencies of the relative yield reduction (F), the ratio of the relative yield reduction to the number of stress days (F/SD), and yield response factor (Ky) at different growth stages in both seasons (Table 4). Yield response factor values that are greater than 1.0 indicates that the crop is not adaptable to water stress exposed to it. The largest values of drought sensitivity indexes were realized when water stress was applied consecutively at stage II and III. Other than that largest values were obtained at stage II, followed by those of stage III, and stage I had the least.

Crop Water Consumption and Water use efficiency: Quadratic polynomial regression models were adjusted to WUE and ET values (Fig. 3), of which maximum values were obtained for 2017 (35.27kg/m^3, 455.67 mm) and 2018 (33.41kg/m^3, 458.70 mm) respectively. The crop water consumption of 2018 season ranged from 516.30 to 423.88mm which were higher than in the 2017 season due to a higher demand in evapotranspiration. Irrigation regime and biochar addition clearly affected WUE during the growing season. Comparisons between mean values of water stressed treatments showed that deficit irrigation at stages I (T3) recorded the highest WUE.

Under the two treatments (T1 and T2) which had the same irigation regime, addition of biochar significantly ($P < 0.05$) increased WUE which was 24.80% and 24.01% greater for 2017 and 2018 seasons respectively. DI imposed at two consecutive stages (T6) tend to have a negative effect on WUE as it tends to be predominantly decreased. The largest WUE values were obtained under the T2 and T3 treatments (35.27 and 32.66 kg/m^3) in 2017season, meanwhile the lowest values were for treatmen T6 (19.73 and 22.44 kg/m^3) for both seasons respectively.

Economic aspect: The effects of biochar and deficit irrigation at different growth stages on reduction of fruits yield and irrigation water savings for 2017 and 2018 seasons are summarized in figure 4. The least values were obtained on treatment T3 as the average of the two seasons resulted in a reduction of total fruits yield by 10.89 and 10.28%, but saved 1.96 and 3.76% of irrigation water compared to treatment T2. The statistical difference between water savings of treatment T3 and T4 in both seasons was not significant (P>0.05), although yield reduction is more pronounced on T4. It can be deduced that stage II is the most sensitive growth stage to water stress. Water supply limitation subjected at consecutive growth stages (T6) attained the highest yield reduction when compared to treatment T2 at 47.73% and 37.93% yield reduction for 2017 and 2018 seasons respectively, however with substantial amount of irrigation water was savings. Furthermore, the results indicate that reduced irrigation has adverse negative impact on tomato fruit yield over irrigation water saving.

Table 1. Tomato transplanting date and soil characteristics in 2017 and 2018 cropping seasons.

Cropping season	Transplanting date	Dry bulk density (g cm^{-3})	Field capacity (cm^3/cm^3)	Organic matter content (%)	pH
2017	April 03	1.35	0.46	0.72	6.3
2018	March 28	1.36	0.46	0.75	6.1

Table 2. Description of irrigation treatments.

Treatment	Description
T1	Irrigation lower limit is 70% of field capacity for all growth stages, without biochar amendment.
T2	Irrigation lower limit is 70% of field capacity for all growth stages, with biochar amendment.
T3	30% decreased water of T2 was applied at vegetative stage at the time of irrigation, with biochar amendment.
T4	30% decreased water of T2 was applied at flowering and fruit development stage at the time of irrigation, with biochar amendment.
T5	30% decreased water of T2 was applied at fruit ripening stage at the time of irrigation, with biochar amendment.
T6	30% decreased water of T2 was applied at flowering and fruit development and fruit ripening stages at the time of irrigation, with biochar amendment.

*Irrigation upper limit for T1 and T2 is 100% field capacity.

Table 3. Average fruit weight (FW), total fruit yield and water use efficiency (WUE) under different irrigation regimes.

Cropping Season	Treatment	FW (g)	Yield (t/ha)	WUE(kg/m^3)
2017	T1	119.74b	141.94b	28.26c
	T2	141.66a	160.72a	35.27a
	T3	126.65b	143.22b	32.66b
	T4	91.54cd	104.60d	23.98d
	T5	99.76c	124.53c	28.82c
	T6	87.66d	84.01e	19.73e
2018	T1	129.18b	139.09b	26.94c
	T2	146.65a	153.26a	33.41a
	T3	133.96b	137.51b	30.58b
	T4	106.01c	113.99c	25.60c
	T5	112.3c	119.98c	27.96c
	T6	83.33d	95.13d	22.44d

Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SE (n = 3).

Table 4. Total evapotranspiration (ET), number of stress days (SD), relative yield reduction (F), ratio of the relative yield reduction to the number of stress days (F/SD), and yield response factor (Ky) under different treatments.

Cropping Season	Treatment	ET(mm)	SD(days)	F	F/SD	Ky
2017	T1	502.32a				
	T2	455.67b				
	T3	438.54c	0.94c	0.11d	0.12c	2.90d
	T4	436.16c	1.50b	0.35b	0.23a	8.16a
	T5	432.11c	1.55b	0.23c	0.15b	4.36c
	T6	425.38d	4.26a	0.48a	0.11c	7.28b
2018	T1	516.30a				
	T2	458.70bc				
	T3	449.73c	0.49d	0.10d	0.21a	5.26b
	T4	455.20c	1.03c	0.26b	0.25a	8.71a
	T5	429.20d	1.94b	0.22c	0.11b	3.36c
	T6	423.68d	4.93a	0.38a	0.08c	5.00b

Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the LSD test. Each value is the mean ± SE (n = 3).

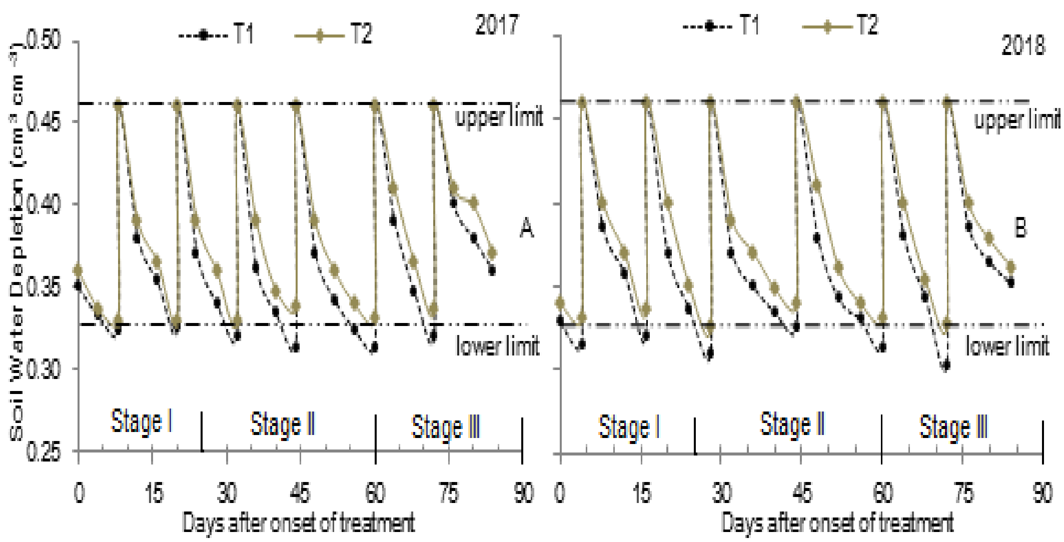

Figure 1. Trends of soil water depletion (0-30cm depth) of treatments with the same irrigation regime (100% FC) during the cropping cycle in 2017 season (A) and 2018 season (B). Upper constant horizontal dash line indicates upper irrigation limit, 100% field capacity. Lower constant horizontal dash line indicates lower irrigation limit, 70% field capacity. T1 had no biochar amendmet and T2 had biochar amendment of 10% by weight of soil.

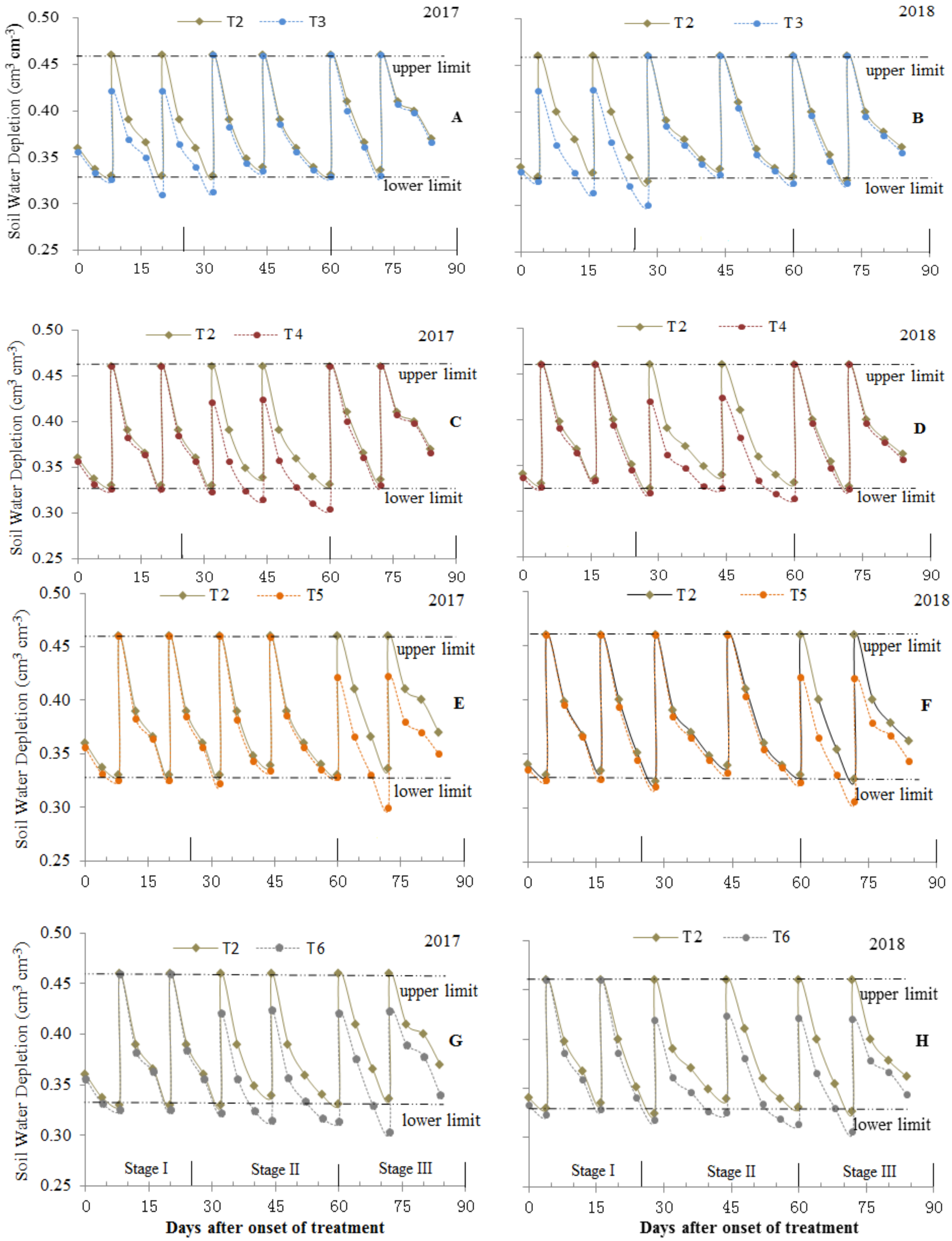

Figure 2. Trends of soil water depletion (0-30cm depth) of deficit irrigation treatments and fully irrigated treatment T2, during the cropping cycle in 2017 season (A, C, E, G) and 2018 season (B, D, F, G). Upper constant horizontal dash line indicates upper irrigation limit, 100% field capacity. Lower constant horizontal dash line indicates lower irrigation limit, 70% field capacity. All treatments had biochar amendment of 10% by weight of soil.

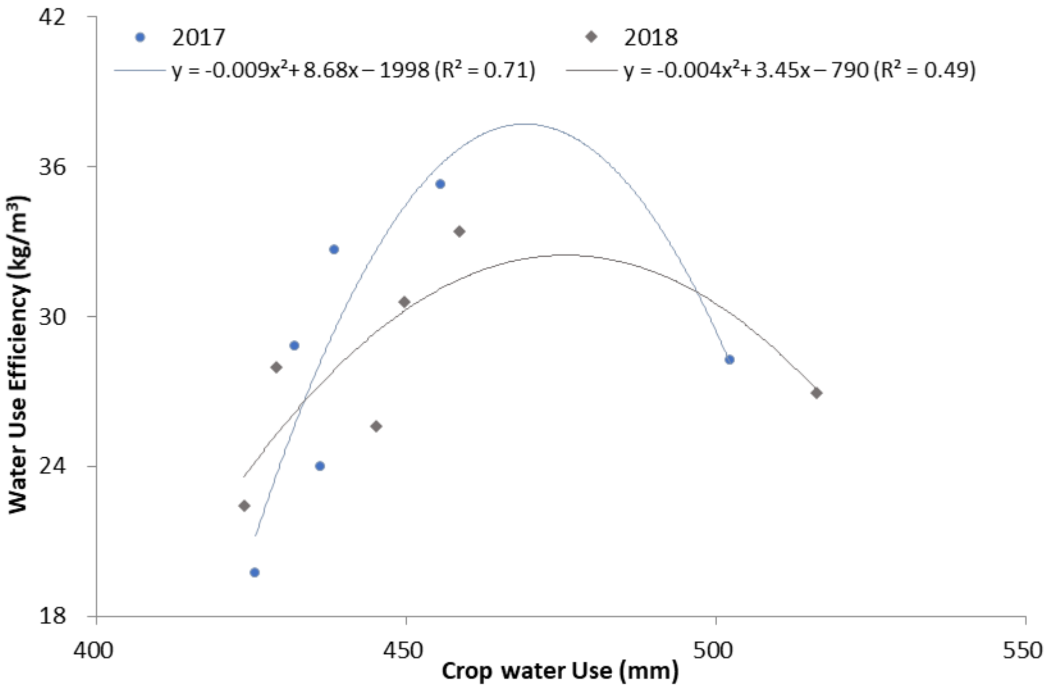

Figure 3. Polynomial curves showing the change of water use efficiency (WUE) with crop water consumption (ET) of tomato crops in 2017 and 2018 seasons.

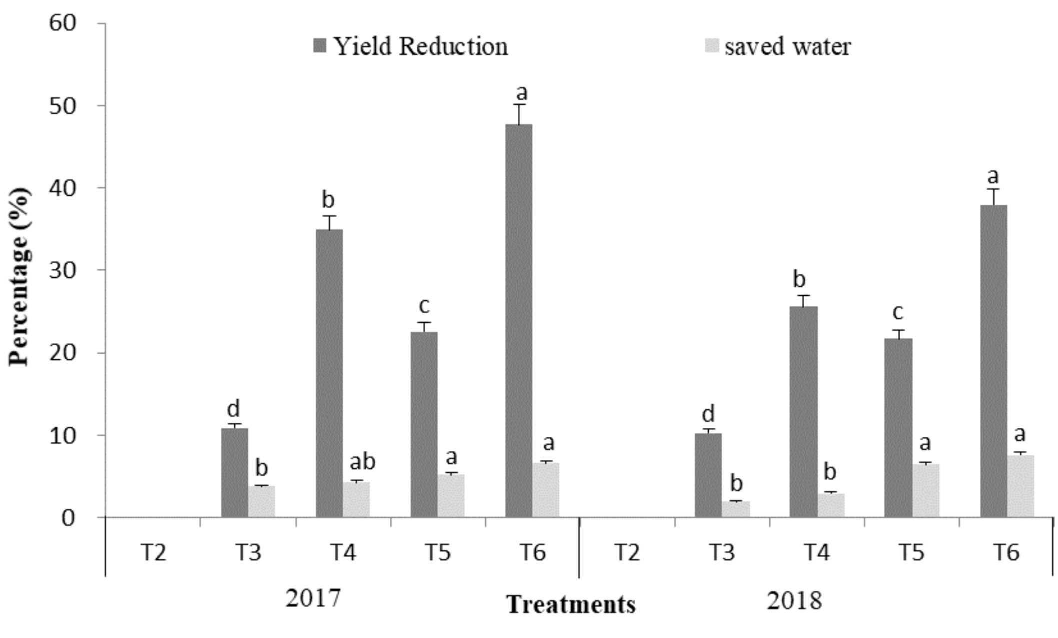

Figure 4. Yield reduction and irrigation water saving percentages of tomato in cropping cycles of 2017 and 2018 seasons. Water savings were computed as $1\text{-}ET_{ai}/ET_{mi}$.

DISCUSSION

The result of this study showed that addition of biochar to soil increased its capability to conserve volumetric water content. This trend was more evident as distinguished by soil water content between 0-30cm layers of treatments with and without biochar (treatment T1 and T2 of the same irrigation regime). The differences in moisture content can be attributed to biochar addition because it increases soil organic matter content which in turn improves soil moisture conservation. The study of Liu *et al.* (2014), demonstrated that adding 40 t/ha of biochar in 0–15 cm root zone depth improved soil organic matter from 10.38 (at 0.0 biochar) to 28.10 g/kg, which represented an increase of 170% in comparison to the control. Organic matter is an important component of the soil as it contributes to the stability of soil aggregates and increase pore space through the bonding or adhesion properties of organic materials (Akhtar *et al*. 2014).

Furthermore, biochar amendment improved plant water status as illustrated by the enhanced water use efficiency. The enhancement of plant water status could have contributed positively to crop productivity as proportionality of WUE to fruit yield improved in biochar amended treatments. It is evident from the results of this study that, applying biochar to treatment T2 increased fruit yields significantly, as compared to the control (treatment T1) as well as, fruit yield from treatment T3 as it was not statistically different from treatment T1 at P>0.05. In this case, it is conclusive that a combining biochar and deficit irrigation at a certain level results in similar yields to those obtained under full irrigation with no biochar amendment. Our discoveries are like those acquired by (Agbna *et al*. 2017) who revealed that roughly 25–50% less water was needed when biochar was applied to the soil to obtain comparable yields to those accomplished through traditional irrigation methods. The yield increase in biochar treated soil is explained by its increased water retention capabilities as opposed to ordinary soil.

A number of studies have demonstrated that water stress at certain levels have a negative effect on tomato yield (Patanè *et al*. 2011; Zegbe-DomíNguez *et al*. 2003). The yield reduction in deficit irrigation is mainly due to the decline in fruit weight with decrease in applied water. If the crop evapotranspiration is more than water supply, the rate at which roots absorb water will be lessened, which triggers an internal water deficiency affecting photosynthesis resulting in reduced cell size and intercellular volume, as well as fruit water accumulation and consequently fruit weight decrease (Wang *et al*. 2011). In this study yield reduction for DI treatments was significant (P<0.05) except for treatment T3 when comparing them to their counterpart fully irrigated treatments. Our results indicate that yield reduction is significant when water stress is applied after stage I, more especially at flowering stage (stage II) and it is more susceptible when applied at subsequent stages. Nonetheless the results of Nangare *et al*. (2016) showed that deficit irrigation of 0.6 ETc applied for longer periods i.e. either of two stages resulted in 14–18% yield reduction which presents a similar trend to our findings.

In areas where there is lack of water with long dry summer seasons, augmenting water efficiency might be more beneficial to the farmer than expanding crop yields (Wahb-allah and Al-omran, 2012). The results of this study showed that, when the same irrigation regime was employed, treatment T2 is better than treatment T1 in term of improving crop WUE. In this case, it is evident that the effectiveness of the irrigation regime was increased by biochar amendment and in agreement with this; enhanced water use efficiency with biochar amendment has also been demonstrated by the studies of Kammann *et al*. (2011) and Agbna *et al*. (2017). Djurovic *et al*. (2016) reported that deficit irrigation resulted in higher water use efficiency compared to full irrigation and this corresponds with experimental researches carried out in China (Wang *et al*. 2015), Italy (Patane and Cosentino, 2010) and Turkey (Topcu *et al*. 2007). In contrary to this, our research study recorded higher water use efficiency values in full irrigation treatments, nonetheless it should be appreciated that water use efficiency changes with the phenological stage during the growing season.

It is important to come up with more effective water management strategies to improve water use efficiency without sacrificing yield. Our results clearly illustrated that adding biochar to the soil improves its moisture retention capability. The combination of biochar amendment with deficit irrigation at vegetative stage (when crop water requirements are low) has the ability to supply supplementary substrates to the soil to mitigate water stress on tomato to maintain satisfactory levels of yield and WUE. Despite having saved water, reduced irrigation demonstrated no constructive outcome on yield when applied at stage II and III. This is most likely because of the high sensitivity of tomato to water stress and the scalarity of flowering.

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