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Interaction effects of biochar levels, irrigation regimes, and irrigation water salinity levels on wheat: I: Physiological parameters, evapotranspiration, and yield

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ABSTRACT - Biochar, as a soil amendment, improves soil fertility and enhances crops productivity under water or salinity stresses. This study aimed to investigate the effects of biochar application rates (zero, 40, and 80 Mg ha^{-1}) under three irrigation regimes (50, 75, and 100% of plant water requirement) and salinity levels (0.6, 6, and 12 dS m^{-1}) on physiological parameters, evapotranspiration, and growth of wheat grown under greenhouse condition. The experiment was performed in a complete randomized design with a factorial arrangement in four replications. Application of a high level of salinity (12 dS m^{-1}) declined wheat grain yield by 28%, 57%, and 75% in comparison with that at 0.6 dS m^{-1} under zero, 40, and 80 Mg ha^{-1} biochar application, respectively. The results showed that application of 80 Mg ha^{-1} biochar decreased wheat evapotranspiration by 24.4% in comparison with that at no biochar application. In addition, the application of biochar improved wheat stomatal conductance and canopy temperature under both abiotic stress conditions. Salinity (12 dS m^{-1}) and deficit irrigation (50 %), respectively declined wheat evapotranspiration by 19% and 15% in comparison with that at 0.6 dS m^{-1} and full irrigation. Also, the application of biochar and salinity both declined the root length density due to the accumulation of salt around the root. It is concluded that 40 Mg ha^{-1} of biochar can be applied as a soil amendment to improve wheat yield and reduce evapotranspiration under applied deficit irrigation and salinity stress.

INTRODUCTION

Salinity and water scarcity have been known as the two negative factors affecting crop production, particularly in semi-arid and arid regions (Ray et al., 2013). Thus, there is a growing demand for scientists to develop strategies that will enhance the physical and chemical properties of the low fertile soil, improve soil water retention, and increase crop water use efficiency (Oki and Kanae, 2006).

Water shortage represents a serious risk to global food security (Misra, 2014). Water shortage is one of the environmental stresses that can adversely affect the soil's biological and physicochemical properties, and also, the growth and yield of many crops such as wheat (Pour-Aboughadareh et al., 2020). Moreover, water stress is occurred simultaneously with soil salinity in many regions especially in arid and semi-arid conditions due to high evaporation (Souri et al., 2019). On the other hand, the scarcity of fresh water has forced farmers to irrigate crops using poor-quality water (Usman et al., 2016). However, using saline water for irrigation exacerbates the problem of agricultural fields that face salinity. Currently, about 33% of the global irrigated lands are affected by salinization (Munns, 2005).

Soil salinity is an ongoing issue that has limited world production (Kammann et al., 2011). Salinity causes a decrease in stomatal conductance, leaf water potential, photosynthetic rate, root growth, and dry matter (Ramlow et al., 2019). It has been shown that the number of grains/spikes, grain number/spikelet, and grain yield in wheat is decreased under high salt concentration in soil (Shamsi and Kobraee, 2013). The reason for lower productivity in saline soils is due to salt toxicity and lower organic matter and minerals availability (Ramlow et al., 2019).

Recently, the application of agricultural wastes (such as biochar), has been growing due to its role in sustainability (D'Hose et al., 2020). It has been shown that the addition of biochar to soil enhances the soil's physical and chemical properties (Naiji and Souri, 2018). Hence, the application of organic waste under abiotic stresses is highly interested (Najarian and Souri, 2020).

Biochar is a pyrolyzed organic matter produced under low oxygen conditions or with no supply of oxygen (Gul et al., 2015). Research has indicated that biochar improves the supply of minerals and soil organic matter content, resulting in higher availability of soil nutrient content (Luo et al., 2017; Campos et al., 2018; Akoto-Danso et al., 2019).

Wheat is one of the most important cereals in the human diet. Optimum wheat yield is obtained by supplying the appropriate amount of irrigation water (Tari, 2016). Water resource scarcity and soil degradation due to the effect of salinity are the main challenges for wheat production in arid and semi-arid areas (Tari, 2016). Therefore, this study aimed to investigate the role of biochar on wheat growth and its physiological parameters under salinity and water stress conditions.

MATERIALS AND METHODS

Experimental site

This study was performed in the greenhouse of the Drought Research Center, School of Agriculture, Shiraz University, Shiraz, Iran. Air temperature and relative humidity variation inside the greenhouse and during the crop growing season are shown in Fig. 1.

Experimental design

Three levels of biochar including 0, 40, and 80 Mg ha^{-1} (equivalent to zero, 2.07, and 4.17% by weight named as B_0, B_2, and B_4, respectively), three irrigation water salinity levels (0.6, 6, and 12 dS m^{-1} named as $S_{0.6}$, S_6, and S_{12}, respectively) and three irrigation regimes (50, 75, and 100 % of plant water requirement named as $I_{50\%}$, $I_{75\%}$, and $I_{100\%}$, respectively) were applied.

Treatments were applied in factorial arrangements under a complete randomized design with four replications. Wheat straw was pyrolyzed at 550°C temperature under low oxygen conditions to produce biochar and then passed through a 2 mm sieve and mixed with sieved sandy loam soil. The produced biochar had EC of 9.3 dS m^{-1}, pH of 8.18, and bulk density of 0.25 g cm^{-3}. The soil bulk density, volumetric water content at field capacity, volumetric water content at permanent wilting point, pH, and EC_e were 1.53 g cm^{-3}, 21 %, 8 %, 7.44, and 0.66 dS m^{-1}, respectively. Ten wheat seeds (Shiraz cv.) were sown on 20 Feb. 2016 in pots (20 cm in height and 21.6 cm in diameter and, containing 6 kg of the soil and biochar mixture) and the pots were fully irrigated up to pot water holding capacity with non-saline water (0.6 dS m^{-1}) until complete establishment, then the seedlings were thinned to seven plants per pot. Afterward, the irrigation treatments were initiated, and the pots were irrigated according to irrigation regime treatments. The water salinity levels of 6 and 12 dS m^{-1} were prepared by the solving the sodium chloride (NaCl) and calcium chloride ($CaCl_2$) (equal percent) in tap water (EC=0.6 dS m^{-1}, pH=7, Na=1.2 meq l^{-1}, K=0.05 meq l^{-1}, Ca=1.15 meq l^{-1}). The irrigation water depth for $I_{100\%}$ was determined based on the depth of water required to increase the soil water content to 100% of pot field capacity plus 15 % as leaching fraction. The depth of irrigation water for 75 and 50 % irrigation regimes was calculated based on the depth of water at $I_{100\%}$ in each biochar level.

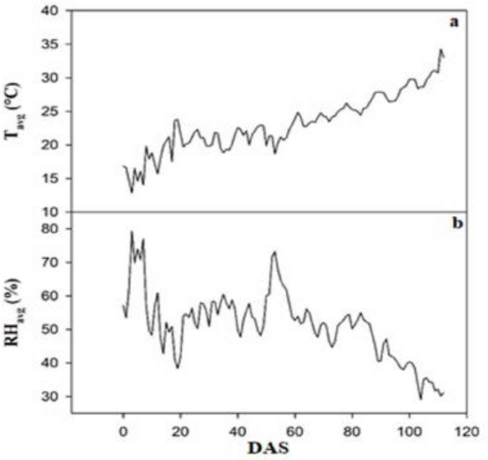

Fig. 1. Variation of (a) air temperature (°C) and (b) relative humidity (%) during crop growing season inside the greenhouse (DAS: Days after sowing)

Measurement of plant parameters

Seasonal Crop Evapotranspiration

Seasonal crop evapotranspiration was determined by using water balance equation as follows:

$$P + I = ET_c + Dp + R \pm \Delta S \qquad (1)$$

where P is the depth of precipitation (which was equal to zero due to the greenhouse experiment), I is the depth of applied irrigation water to each treatment in mm (the depth of water to reach the pot weight to weight at pot field capacity for $I_{100\%}$ considering leaching fraction, and 75 and 50% of irrigation water depth at $I_{100\%}$ for $I_{75\%}$ and $I_{50\%}$, respectively), ET_c is the crop evapotranspiration in mm, Dp is the deep percolation in mm (amount of water drained from the bottom of pots), R is the runoff (equal to zero) and ΔS is the soil water change in pots (difference between two consecutive pot weight) in mm.

Stomatal Conductance

Stomatal conductance (g_s, mmol m^{-2}s^{-1}) was measured at 21, 40, 55, and 73 days after sowing (DAS) using the Leaf Portable Porometer (Leaf Porometer, Decagon Devices, Pullman, Washington, USA). Measurements were performed on two fully expanded leaves from the top of the canopy between 10:00 am to 2:00 pm in all treatments and four replicates.

Green Canopy Temperature

Green canopy temperature (CT, °C) was measured at 21, 40, 55 and 73 DAS between 10:00 am to 2:00 pm on healthy green leaves from different angles by an infrared thermometer (Kyorisu Model 5500).

Grain Yield, Above-ground Dry Matter

Wheat was cut from the soil surface at harvest (24 June 2016) and dried at 75 °C (in the oven) for 48 h.

Root Length Density and Dry Weight Density

The soil samples were taken from 0-10 and 10-20 cm soil depth at harvest to determine the root length density (LD, cm cm^{-3}) and root dry weight density (DD, kg m^{-3}). Then, the samples were soaked in water and washed several times to ensure that all roots were removed from the soil. Thereafter, the roots were put on the sieve (250 mm diameter). The length of fresh roots (cm) was read by the method of Newman (1966) and then divided by the soil sample volume to obtain LD. Fresh roots were then dried at 60 °C for 24 h and weighed to calculate the root dry weight. Root dry weight density (DD) was determined by dividing the root dry weight by soil volume.

Statistical analysis

Statistical analyses were performed using PROC GLM of SAS (SAS Institute Inc., 2007). Normality and homogeneity tests showed that all the data are normal and homogeneous. Interaction effects between different experimental treatments on the measured parameters were evaluated by analysis of variance (ANOVA). A comparison between means at the 5% level of probability was conducted using Duncan's Multiple Range Test (DMRT).

RESULTS AND DISCUSSION

Grain yield

Wheat grain yield (g pot^{-1}) was declined by increasing salinity at each biochar and irrigation water level (Table 1). The application of deficit irrigation reduced the wheat grain yield at each biochar rate and salinity level. The maximum and minimum value of grain yield was 11.0 and 0.55 g pot^{-1} under $B_4S_{0.6}I_{100\%}$ and $B_4S_{12}I_{50\%}$ treatments, respectively. The results of the main effects showed that the wheat grain yield in the B_2 treatment was 4.6 g pot^{-1} (1.21 times of B_0, 21% increase) and no significant difference was seen between the grain yield at B_2 and B_4 (Table 1).

Biochar can hold higher water and nutrients and therefore, provides better conditions for wheat to grow (Rezaie et al., 2019). In this regard, Vaccari et al. (2011) stated that with the application of 60 Mg ha^{-1} of biochar, a 30% increase in wheat yield was observed.

Application of $I_{75\%}$ and $I_{50\%}$ in the current study reduced the wheat grain yield by 25% and 28% as compared with that in $I_{100\%}$, respectively. It has been reported that the significant reduction of grain yield due to water stress is due to the negative effects of this stress on the mungbean leaf area, crop growth rate, and crop components (Pannu and Singh, 1993). In the current study, salinity had an adverse effect on the wheat grain yield, as increasing the levels of salinity significantly decreased the grain yield. Akhtar et al. (2015b) investigated the effect of biochar (zero and 5% by weight) and salinity (tap water (S_0), 25 mM, and 50 mM NaCl solutions) on wheat growth and reported that the wheat growth and yield were influenced positively with the application of biochar, particularly under high salinity level (50 mM NaCl). On the contrary, the results of the current study showed that the wheat grain yield was reduced by the application of biochar at 12 dS m^{-1} salinity in all irrigation water levels (Table 1). It has been supposed that a high level of salinity (12 dS m^{-1}) and the salinity of biochar (9.3 dS m^{-1}) used in the current study together resulted in a lower grain yield.

Dry matter

The same as grain yield, the wheat dry matter was decreased by increasing salinity at each biochar and irrigation water level (Table 1). Application of deficit irrigation declined the wheat dry matter at each biochar rate and salinity level. Considering the main effects, biochar levels had a significant effect on the dry matter weight of wheat, so the increase in biochar rate increased the dry matter, and the maximum value of dry matter (10.0 g pot^{-1}) was obtained under B_2. Furthermore, the dry matter was also reduced by increasing salinity and deficit irrigation. In this regard, Afzal et al. (2006) studied the effect of salinity stress on wheat and concluded that instant germination, vegetative growth, and flowering are inversely affected by high salt concentrations in the soil and ultimately declined wheat yield. Also, Park et al. (2011) reported that the addition of biochar to the soil increased the dry weight of wheat by 35.3% compared to that obtained under no biochar application. Regarding the simultaneous effect of biochar and salinity stress, Thomas et al. (2013) concluded that 50 Mg ha^{-1} biochar application alleviated salt-induced mortality in *Abutilon theophrasti* and prolonged survival of *Prunella vulgaris*. Contrary to grain yield, the application of biochar in the current study enhanced the dry matter under different salinity and irrigation water levels, and the dry matter yield was higher under B_2 in comparison with that under B_4 for different levels of salinity and irrigation water levels (Table 1), which might be due to the fact that the nutrient of biochar mainly resulted in higher grain yield than straw yield.

Seasonal wheat evapotranspiration

The data of the seasonal wheat evapotranspiration (mm) is given in Table 1. The maximum value of wheat seasonal evapotranspiration was 436 mm in $B_0S_{0.6}I_{100\%}$ treatment and the minimum value was 221 mm in $B_4S_{12}I_{50\%}$ treatment, which was about a 50% reduction.

Considering the interaction effects, the application of biochar declined the wheat evapotranspiration under different irrigation water and salinity levels.

The results of this study showed that the addition of biochar had a significant effect on the reduction of wheat evapotranspiration. The B_4 had the lowest value (272 mm) of evapotranspiration (Table 1), as B_2 and B_4 evapotranspiration was 14.7 and 24.4% lower than that in the B_0, respectively. The decrease in evapotranspiration was due to the positive effects of biochar on soil surface evaporation, as it has been shown that biochar had a high specific surface area, high porosity, and high capacity to retain water and prevent evaporation and loss of water in the soil (Ogawa et al., 2006).

The value of wheat evapotranspiration declined by 6.8% and 15.4% in $I_{75\%}$ and $I_{50\%}$ in comparison with that in $I_{100\%}$. The seasonal evapotranspiration value was reduced by increasing salinity levels. It has been shown that the irrigation water salinity reduces the osmotic potential by increasing the concentration of solutes in the soil, and also reduces the total soil water potential and therefore, declines water absorption by the plant (Alburquerque et al., 2013).

Stomatal conductance (g_s)

The main effects of treatments on the stomatal conductance (g_s) of wheat during the growing period are shown in Fig 2. The results showed that the application of biochar significantly increased the g_s to its maximum values up to 55 DAS and then declined sharply to 41 mmol m^{-2} s^{-1} for B_2 and 49 mmol m^{-2} s^{-1} for B_4 at 73 DAS**.** This increase and decrease trend of g_s was also observed under B_0, but with a lower rate. Moreover, the maximum g_s for different salinity levels and irrigation water levels were observed at 55 DAS. The decrease in g_s after 55 DAS in all biochar rates and in all treatments might be due to a sharp increase in air temperature inside the greenhouse (Fig. 1).

It has been also reported that the values of g_s for biochar–treated potato plants were significantly higher than that in non-biochar-treated potato plants throughout the growing season (Akhtar et al., 2015a). In this regard, Park et al. (2011) reported that the application of 5% by weight of biochar in the soil increased the stomatal conductivity of tomatoes significantly under deficit irrigation conditions. Biochar, with its high specific surface area and high porosity, can retain water and is less exposed to water stress (Ali et al., 2017). Similar to the results of Razzaghi et al. (2011, 2012) on *Chenopodium quinoa*, the g_s value of wheat under $I_{75\%}$ and $I_{50\%}$ treatments in the current study decreased compared to the control treatment ($I_{100\%}$) on each day of measurements. Application of salinity also decreased the g_s value on each day of measurements in comparison with that at $S_{0.6}$. It has been claimed that salinity-induced water stress occurs in the form of closed stomata in the plant and therefore, negatively affects the growth and development of the plant (Afzal et al., 2006).

Table 1. Wheat grain yield (g pot^{-1}), dry matter (g pot^{-1}), and evapotranspiration (mm) at different levels of irrigation, salinity, and biochar used in this study

Characteristics		Biochar levels								
		B_0			B_2			B_4		
		Salinity levels								
		$S_{0.6}$	S_6	S_{12}	$S_{0.6}$	S_6	S_{12}	$S_{0.6}$	S_6	S_{12}
Grain yield (g pot^{-1})	$I_{100\%}$	5.50^{k*}	5.30^{d}	4.09^{e}	8.54^{b}	6.69^{c}	3.58^{ef}	11.04^{a}	5.92^{cd}	2.63^{fgh}
	$I_{75\%}$	4.48^{e}	3.93^{e}	3.89^{e}	5.61^{d}	5.54^{d}	2.53^{ghi}	6.12^{cd}	4.10^{e}	2.16^{hij}
	$I_{50\%}$	3.44^{efg}	2.28^{hij}	1.60^{ij}	3.73^{e}	3.61^{ef}	1.57^{ij}	3.97^{e}	2.50^{ghi}	0.55^{k}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		3.8(B**)	4.6(A)	4.2(AB)	5.82(A)	4.43(B)	2.52(C)	5.92(A)	4.26(B)	2.58(C)
Dry matter (g pot^{-1})	$I_{100\%}$	13.16^{cd}	10.53^{de}	5.20^{gh}	18.05^{a}	15.26^{b}	6.76^{f}	16.01^{ab}	11.85^{d}	6.17^{fgh}
	$I_{75\%}$	11.93^{d}	4.63^{hi}	2.41^{ij}	15.55^{b}	11.84^{d}	4.96^{h}	13.54^{c}	9.01^{ef}	4.03^{hij}
	$I_{50\%}$	5.67^{g}	4.10^{hij}	2.08^{j}	9.66^{e}	4.90^{h}	3.50^{i}	6.30^{fg}	4.33^{hij}	2.70^{ij}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		6.6(C)	10.0(A)	8.2(B)	12.2(A)	7.3(B)	4.2(C)	10.3(A)	7.5(B)	4.8(C)
Evapotranspiration (mm)	$I_{100\%}$	436^{a}	381^{b}	347^{cd}	372^{bc}	316^{def}	293^{ef}	344^{cd}	295^{ef}	259^{fg}
	$I_{75\%}$	389^{b}	362^{bcd}	319^{def}	351^{c}	302^{e}	276^{f}	264^{fg}	261^{fg}	253^{fgh}
	$I_{50\%}$	359^{c}	336^{d}	308^{e}	306^{ef}	281^{ef}	271^{f}	269^{fg}	231^{gh}	221^{h}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		360(A)	307(B)	272(C)	349(A)	307(B)	283(C)	338(A)	315(B)	286(C)

[*] Small and capital letters indicate significant differences ($p < 0.05$) between the interaction effects and main effects of treatments, respectively.

[**] B_0, B_2, and B_4 represent biochar rates of 0, 40, and 80 Mg ha^{-1}, $S_{0.6}$, S_6, and S_{12} indicate irrigation water salinity of 0.6, 6, and 12 dS m^{-1} and $I_{100\%}$, $I_{75\%}$, and $I_{50\%}$ refer to irrigation regimes of 100, 75, and 50 % of plant water requirement, respectively.

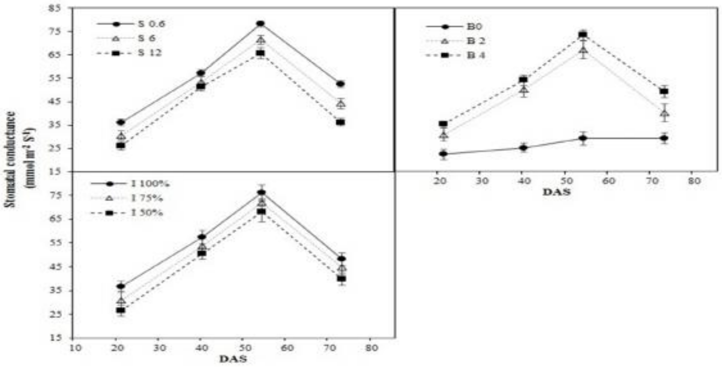

Fig. 2. Stomatal conductance (g_s, mmol m^{-2} s^{-1}) at different irrigation, salinity, and biochar levels. Bars indicate the standard error of the mean.

Green canopy temperature

The mean values of the green canopy temperature during the growing period are shown in Fig 3. The results showed that the plants treated with biochar were less prone to stress, improved the conditions of plant growth, and increased water availability in the soil and thus reducing the green canopy temperature in the plant.

The mean green canopy temperatures in B_2 and B_4 were 23º and 27º C, respectively, which decreased by 42 % and 32 % compared to that of the control treatment (no biochar, B_0), respectively. Also, using deficit irrigation treatments of $I_{75\%}$ and $I_{50\%}$ during the growing season increased the green canopy temperature in the tested plants. Salinity levels showed a significant increase in the green canopy temperature. It has been shown that under salinity stress conditions, the mungbean plants absorb less water, thus increasing the green canopy temperature, which indicates that the plants are under stress (Pannu and Singh, 1993), thereby reducing their stomatal conductivity (Akhtar et al., 2015b). The highest and lowest values of green canopy temperatures were observed in two treatments of $B_0S_{12}I_{50\%}$ and $B_4S_{0.6}$ $I_{100\%}$ (data not shown).

Root dry weight density (DD) and root length density (LD)

Interaction and the main effect of treatments on the root dry weight of wheat (DD, kg cm^{-3}) and root length density (LD, cm cm^{-3}) are shown in Table 2. According to the results, the amount of DD in salinity levels was reduced compared to the control treatment ($S_{0.6}$). At a salinity level of 12 dS m^{-1}, a 34.0 % reduction in DD was observed compared to the control salinity level (0.6 dS m^{-1}).

In a greenhouse experiment, Hardie et al. (2014) examined the effect of salinity levels (zero, 4, 8, and 12 dS m^{-1}) on the growth and yield of rice. Their results showed that increasing the salinity decreased the yield and dry weight of stems and roots, as at salinity levels of 4, 8, and 12 dS m^{-1}, 43.6 %, 57 %, and 79.4% decrease in dry weight of rice root was observed, respectively. They mentioned that salinity reduced the dry weight of plant material and rice grain by reducing the leaf photosynthesis, reducing the inflammation of cells, as a result of reducing soil water potential and disrupting plant nutrient supply.

The application of biochar levels in the current study reduced DD of wheat. In the depths of the soil, application of 40 and 80 Mg ha^{-1} of biochar (B_2 and B_4) compared to the control treatment (B_0) reduced the DD by 43.1 % and 67.2 %, respectively. Increased salinity by using biochar may be the reason for the decrease in DD of wheat. Also, the interaction effect of the treatments showed that the highest and lowest values of DD at the soil depth with the values of 0.33 and 0.04 (g), respectively, were observed in the $B_0S_{0.6}I_{100\%}$ and $B_4S_6I_{50\%}$ treatments, respectively.

Table 2 also shows the main effects and the interaction effects of the treatments on the LD of wheat (cm cm^{-3}) in the tested soil. According to the results obtained in the control treatment of biochar (B_0), an increase in salinity showed a significant decrease in the LD compared to the control treatment of salinity ($S_{0.6}$). The salinity level of 12 dS m^{-1} (S_{12}) and irrigation treatment of $I_{100\%}$ resulted in a decrease of 35 % of the LD in comparison with that at $S_{0.6}$ and $I_{100\%}$, under no biochar application. It is supposed that in the treatments of salinity stress, the accumulation of salts around the root causes the formation of water stress (due to the increase of osmotic pressure), ionic toxicity, and root growth encountered to problem (Rezaie et al., 2019).

In treatments of B_2 and B_4 of biochar and salinity levels of 6 and 12 dS m^{-1} (S_6, and S_{12}) significant decrease was observed in the LD compared with the control treatment (B_0). So that, 40 Mg ha^{-1} biochar (B_2) compared to the control treatment (B_0) reduced the LD by 3.2 %, and of course, this decrease was observed in the treatment of B_2 at two salinity levels of 6 and 12 dS m^{-1}. Treatment of B_4 compared to control treatment (B_0) resulted in a decrease of 4.25 % of the LD. In a pot experiment, Alburquerque et al. (2013) investigated the effect of two types of biochar from wheat straw (at 370 ° C) and olive tree pruning (at 450 ° C) on root growth characteristics of wheat. Their results showed that the addition of all levels of biochar from wheat straw reduced the root growth. However, the addition of biochar from olive tree pruning did not have a significant effect on the root growth.

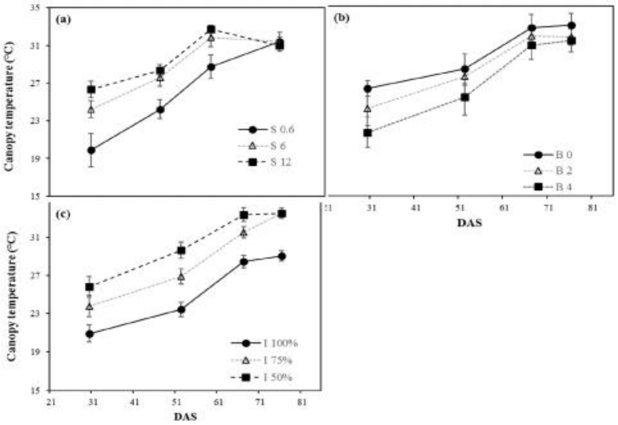

Fig. 3. Green canopy temperature (°C) at different irrigation, salinity, and biochar levels. Bars indicate the standard error of the mean.

Table 2. The root dry weight density (mg cm^{-3}) and root length density (cm cm^{-3}) at different levels of irrigation, salinity, and biochar used in this study

Characteristics		Biochar levels								
		B_0[**]			B_2			B_4		
		Salinity levels								
		$S_{0.6}$	S_6	S_{12}	$S_{0.6}$	S_6	S_{12}	$S_{0.6}$	S_6	S_{12}
Root dry weight density (mg cm^{-3})	$I_{100\%}$	0.33^{a*}	0.155^{d}	0.175^{c}	0.165^{cd}	0.126^{ef}	0.125^{ef}	0.08^{g}	0.07^{gh}	0.077^{gh}
	$I_{75\%}$	0.31^{ab}	0.135^{def}	0.146^{de}	0.135^{def}	0.1^{f}	0.1^{f}	0.05^{hij}	0.055^{hi}	0.06^{h}
	$I_{50\%}$	0.295^{b}	0.128^{e}	0.14^{de}	0.12^{efg}	0.08^{g}	0.08^{g}	0.048^{i}	0.04^{ij}	0.056^{hi}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		$I_{100\%}$	0.33^{a*}	0.155^{d}	0.175^{c}	0.165^{cd}	0.126^{ef}	0.125^{ef}	0.08^{g}	0.07^{gh}
Root length density (cm cm^{-3})	$I_{100\%}$	5.89^{bc}	3.8^{ef}	3.8^{ef}	4.24^{de}	2.92^{fgh}	2.98^{fgh}	1.28^{i}	2.52^{gh}	2.41^{ghi}
	$I_{75\%}$	6.03^{b}	3.96^{ef}	4.19^{de}	4.53^{cd}	2.33^{ghi}	3.11^{fg}	1.75^{hij}	2.56^{gh}	2.17^{hi}
	$I_{50\%}$	6.92^{a}	4.07^{de}	4.46^{cde}	4.68^{cd}	3.25^{fg}	3.58^{efg}	2.13^{hi}	2.99^{fgh}	2.61^{gh}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		$I_{100\%}$	5.89^{bc}	3.8^{ef}	3.8^{ef}	4.24^{de}	2.92^{fgh}	2.98^{fgh}	1.28^{i}	2.52^{gh}

[*] Small and capital letters indicate significant differences ($p < 0.05$) between the interaction effects and main effects of treatments, respectively.

[**] B_0, B_2 and B_4 represent biochar rates of 0, 40 and 80 Mg ha^{-1}, $S_{0.6}$, S_6 and S_{12} indicate irrigation water salinity of 0.6, 6 and 12 dS m^{-1} and $I_{100\%}$, $I_{75\%}$ and $I_{50\%}$ refer to irrigation regimes of 100, 75 and 50 % of plant water requirement, respectively.

CONCLUSIONS

According to the results of this study, the addition of 40 Mg ha^{-1} biochar significantly increased the grain yield and dry matter of wheat, as the maximum values of 4.6 g pot^{-1} and 10 g pot^{-1} were obtained, respectively, although B_2 treatment had lower evapotranspiration in comparison with that at B_0. Also, the application of a high level of salinity declined wheat grain yield by 28%, 57%, and 75% in comparison with that at 0.6 dS m^{-1} under zero, 40, and 80 Mg ha^{-1} biochar application, respectively. In addition, salinity (12 dS m^{-1}) and deficit irrigation (50 %), respectively declined the wheat evapotranspiration by 19% and 15% in comparison with that at 0.6 dS m^{-1} and full irrigation. Wheat stomatal conductance was enhanced by the addition of biochar in the soil. Root dry weight density and root length density was decreased by the application of biochar and salinity, while they increased by the application of deficit irrigation. It is suggested to evaluate the results of this experiment under field conditions.

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اثرات متقابل سطوح بیوچار، رژیم‌های آبیاری و سطوح شوری آب آبیاری بر گندم: I: پارامترهای فیزیولوژیکی، تبخیر-تعرق و محصول

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واژه‌های کلیدی:
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هدایت روزنه‌ای

چکیده - بیوچار، به عنوان اصلاح کننده خاک، سبب حاصلخیزی خاک و افزایش بهره‌وری محصولات تحت تنش‌های آبی یا شوری می‌شود. این مطالعه با هدف بررسی اثرات میزان مصرف بیوچار (صفر، ۴۰ و ۸۰ مگاگرم بر هکتار) در سه رژیم آبیاری (۵۰، ۷۵ و ۱۰۰ درصد نیاز آبی گیاه) و سطوح شوری (۰/۶، ۶ و ۱۲ دسی زیمنس بر متر) بر پارامترهای فیزیولوژیکی، تبخیر-تعرق و رشد گندم کشت شده در شرایط گلخانه انجام شد. آزمایش در قالب طرح کاملا تصادفی با آرایش فاکتوریل در چهار تکرار انجام شد. اعمال شوری در سطح بالا (۱۲ دسی‌زیمنس بر متر) باعث کاهش به ترتیب ۲۸٪، ۵۷٪ و ۷۵٪ عملکرد دانه گندم در مقایسه با ۰/۶ دسی‌زیمنس بر متر مربع در سطوح مصرف صفر، ۴۰ و ۸۰ مگاگرم در هکتار بیوچار شد. نتایج نشان داد که مصرف ۸۰ مگاگرم در هکتار بیوچار باعث کاهش تبخیر-تعرق گندم به میزان ۲۴/۴ درصد در مقایسه با عدم مصرف بیوچار شد. علاوه بر این، کاربرد بیوچار باعث بهبود هدایت روزنه‌ای و دمای پوشش سبز گندم در هر دو شرایط تنش غیرزیستی شد. شوری (۱۲ دسی‌زیمنس بر متر) و کم آبیاری (۵۰ درصد) به ترتیب ۱۹ و ۱۵ درصد تبخیر- تعرق گندم را در مقایسه با ۰/۶ دسی‌زیمنس بر متر و آبیاری کامل کاهش دادند. همچنین، کاربرد بیوچار و شوری بدلیل تجمع نمک در اطراف ریشه، سبب کاهش تراکم طولی ریشه شدند. نتیجه‌گیری می‌شود که مصرف ۴۰ مگاگرم بر هکتار بیوچار می‌تواند به عنوان اصلاح‌کننده خاک برای بهبود عملکرد گندم و کاهش تبخیر-تعرق در شرایط تنش کم‌آبیاری و شوری به کاربرده شده، استفاده شود.