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Interaction of wheat straw biochar with irrigation water and irrigation water salinity to improve water use efficiency and yield of faba bean

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ABSTRACT - Faba bean, although, is widely cultivated, its yield is affected by drought and salinity stresses. Biochar can potentially reduce the negative effects of drought and salinity stress. In this study, the interaction effects of biochar, irrigation water regimes, and irrigation water salinities on faba bean yield, crop water use efficiency (CWUE), and ion concentrations were evaluated under greenhouse conditions. The treatments included 0, 1.25, and 2.5% w/w biochar (as B_0, $B_{1.25}$, and $B_{2.5}$ treatments, respectively), irrigation water regime (50, 75, and 100% of crop water requirement, as $I_{50\%}$, $I_{75\%}$, and $I_{100\%}$, treatments, respectively) and irrigation water salinity (0.6, 4, and 8 dS m^{-1}, as $S_{0.6}$, S_4, and S_8 treatments, respectively), that were arranged in a factorial arrangement using a complete randomized design with four replications. Biochar applied at 2.5% w/w significantly decreased actual crop evapotranspiration by 11% in comparison with that obtained in B_0. The maximum dry seed yield (14.4 g pot^{-1}) was obtained under $B_{2.5}S_{0.6}I_{100\%}$ treatment. The value of CWUE in the $B_{2.5}S_8I_{50\%}$ treatment was 0.47 kg m^{-3}, which was 1.27 times the CWUE in the $B_0S_{0.6}I_{100\%}$ treatment. Seed sodium concentration under $B_{2.5}S_8I_{50\%}$ treatment (0.34 g kg^{-1}) was significantly lower than that obtained in $B_0S_8I_{50\%}$ treatment (0.55 g kg^{-1}). Biochar application increased the plant tolerance to salinity, as the maximum threshold of soil-saturated electrical conductivity of 5.2 dS m^{-1} was observed under $B_{2.5}I_{50\%}$ treatment, which was higher than 2.5 dS m^{-1} obtained in $B_0I_{50\%}$ treatment. Finally, cultivation of the faba bean using 2.5% w/w biochar and full (100%) irrigation with non-saline water is recommended for maximum production of the faba bean.

INTRODUCTION

Water stress and salinity are two main abiotic stresses that adversely affect crop growth and yield, and influence crop productivity worldwide (Athar and Ashraf 2009). Both water stress and salinity stresses reduce soil water potential, water and nutrient uptake, as well as leaf water potential followed by stomatal closure and, finally, crop yield (Athar and Ashraf 2009). The water stress and salinity effect on crops occurs with different intensities depending on their physiological, biochemical, and tolerance mechanisms (Mariani and Ferrante 2017).

Plants use a variety of mechanisms to overcome water stress. These mechanisms include recovery (plants' ability to continue growth after water stress damage; Khan et al. 2018), prevention (through physiological processes e.g. regulation of stomata to reduce water loss via transpiration; Zhang et al. 2017), tolerance (through osmotic and osmo-protective adaptation; Luo 2010) and drought escape (through regulation of the growth period to avoid water stress; Manavalan et al. 2009). Further, plants adapt to salinity by adjusting ion uptake and transport and biochemical responses (Acosta-Motos et al. 2017).

Previous studies illustrate that adding organic amendments to soil improves soil structure, and increases water-holding capacity, and plant available water (Abiven et al. 2009; Paz-Ferreiro et al. 2013; Poormansour et al. 2019). Together, these improvements result in a better environment for plant growth under water-stress conditions. One of such amendments is biochar, a carbon-rich organic material, and a by-product derived from biomass pyrolysis under high-temperature and low-oxygen conditions.

Biochar enhances the quality of soil by increasing soil pH, water-holding capacity, and cation exchange capacity (Mensah and Frimpong 2018; Rawat et al. 2019) and therefore, promotes plant growth (Videgain-Marco et al. 2020). Biochar mitigates water stress in plants by enhancing soil water availability due to its high porosity and large surface area (Razzaghi et al. 2020; Ali et al. 2017a; Agbna et al. 2017; Faloye et al. 2019). In addition, biochar improves salinity stress in plants by high transient Na^+ binding, decreasing osmotic stress, and releasing mineral nutrients into the soil solution (Akhtar et al. 2015a). It is also well documented that the growth, physiology, and yield of plants under water stresses are positively affected by biochar (Akhtar et al. 2015b).

There has been an increase in the use of biochar to enhance the yield and irrigation water use efficiency of several crops (Yang et al. 2020; Zhang et al. 2020). One crop that has received much less attention in investigations of the impact of biochar, salinity, and drought on its productivity is the faba bean. Faba bean (*Vicia faba* L.) is cultivated in more than 61 countries with a total production of 4.84 million tons of dry grain, while the cultivated area and production of faba bean in Iran are 8.2 thousand ha and 18 thousand tons, respectively (FAOSTAT 2017). Humans consume both fresh and dry seeds of faba bean due to their high nutritional value (Lizarazo et al. 2015). Faba bean also has a positive role in enhancing soil fertility through its rotation with cereal crops (Siddiqui et al. 2015). It has been shown that faba bean growth and production are significantly decreased under soil water stress (Ricciardi et al. 2001) and salinity (Bulut et al. 2011) conditions, however, the response of different cultivars to water and salinity stresses varies widely (Afzal et al., 2022; Ricciardi et al. 2001).

This work was motivated by (i) the documented ability of biochar to increase soil water availability and decrease the negative impacts of salinity, (ii) the large geographical extent and nutritional importance of faba bean, (iii) the negative impact of water and salinity stresses on faba bean yield, and (iv) the paucity of information on the potential of biochar to alleviate these stresses and increase faba bean yield. Based on the above, the objectives of this study were to investigate (i) the effect of biochar on faba bean evapotranspiration, and soil evaporation, (ii) the interaction effects of biochar, salinity, and irrigation water on faba bean yield, crop water use efficiency and seed and soil Na^+, K^+, Ca^{++} and Mg^{++} concentration and their relations.

MATERIALS and METHODS

A greenhouse experiment was performed at the Drought Research Center, Shiraz University, Shiraz, Iran. The latitude, longitude, and altitude of the research location are 29º 36´ N, 52º 32´ E, and 1810 m above mean sea level, respectively.

The soil used for the experiment was a sandy loam (clay, silt, and sand in proportions of 12%, 18%, and 70%, respectively) with organic carbon of 40%, bulk density of 1.53 g cm^{-3}, pH of 7.52 and electrical conductivity (EC) of 0.66 dS m^{-1} (EC of soil was measured in saturated extract). The applied biochar was produced through pyrolysis of wheat straw at 550°C under low oxygen conditions and had a bulk density of 0.25 g cm^{-3}, pH of 8.19, and EC of 9.30 dS m^{-1} (pH and EC of biochar were measured in 1:10 biochar: water). The nutritional characteristics of the soil and biochar are presented in Table 1. To simulate the water salinity levels, the saline water was prepared by adding 50% NaCl and 50% $CaCl_2$ (by weight) to fresh water that originally had an EC of 0.6 dS m^{-1}.

The soil and biochar were mixed thoroughly and filled into pots (22 and 30 cm diameter and height, respectively) at the treatment levels described below. Three levels of each treatment including biochar, irrigation water regime, and irrigation water salinity were applied to 108 pots under a factorial arrangement in a complete randomized design with four replications. The biochar levels were 0, 1.25, and 2.5 weight percent (denoted as B_0, $B_{1.25}$, and $B_{2.5}$, respectively) equivalent to 0, 12.5, and 25 g biochar kg^{-1} dry soil. The three irrigation levels were 100, 75, and 50 % of the crop water requirement (denoted as $I_{100\%}$, $I_{75\%}$, and $I_{50\%}$, respectively). The irrigation water salinity levels were 0.6, 4, and 8 dS m^{-1} (designated as $S_{0.6}$, S_4, and S_8, respectively). Before cultivation, the gravimetric soil water content at pot water-holding capacity (pot weight after drainages of gravimetric water) for the 0, 1.25, and 2.5 % w/w biochar treatments were 19.0, 20.9, and 23.0 % w/w, respectively.

Prior to sowing, 43.2 mg P kg^{-1} soil in the form of triple super-phosphate was added to each pot. Five seeds of faba bean (Barkat cv.) were sown in each pot and thinned to three seedlings after emergence. At the vegetative and flowering stages of faba bean, 81 mg N kg^{-1} soil in the form of urea fertilizer was applied.

To ensure good germination and full plant establishment, all pots were irrigated manually every other day to pot water-holding capacity. Application of the salinity treatments and irrigation water regimes was started 36 days after sowing (DAS). All pots were weighed every other day throughout the experiment and the amount of irrigation water for $I_{100\%}$ was determined based on the amount of water that was needed to increase the soil water content to 100% of pot water-holding capacity plus 15% as leaching fraction. In addition, the amounts of irrigation water required for $I_{75\%}$, and $I_{50\%}$ were calculated based on the amount of irrigation for $I_{100\%}$ at each biochar level. The average temperature and relative humidity in the greenhouse during the growing season were determined to be 19 °C and 57%, respectively using KLIMALOGG Pro, TFA-Germany.

Measured parameters

Actual crop evapotranspiration and soil evaporation

Actual crop evapotranspiration (ET_a) was determined by using the water balance equation (Eq. 1) as follows:

$$ET_a = I + P - D_p - R + \Delta S \quad \text{Eq. (1)}$$

where ET_a is the actual crop evapotranspiration (mm), I is the depth of irrigation water (mm), P is the depth of rainfall (mm), D_p is the drainage water (mm), R is the runoff (mm), and ΔS is the change in water content (mm). As this study was performed in the greenhouse, the depth of rainfall and runoff was considered equal to zero. Drainage water was determined by measuring the volume of water leached from each pot.

For each level of biochar, three pots were filled with the same mixture of soil and biochar, without any faba bean seed, to measure soil surface evaporation. These pots were located between the experiment's main pots. All three pots were irrigated to 100% pot water-holding capacity according to their biochar level using fresh water. The plant transpiration was calculated by subtracting soil evaporation from actual crop evapotranspiration.

Table 1. Nutritional properties of biochar and soil used in this study

Properties	Unit	Biochar	Soil
Cation exchange capacity	meq 100 g^{-1} soil	25.76	13.59
Nitrogen	%	0.25	0.02
Calcium	meq L^{-1}	2.3	2
Potassium	meq L^{-1}	67.52	0.63
Magnesium	meq L^{-1}	5.80	5.1

Crop yield

Fresh faba bean seed yield of all plants in each pot was harvested gradually when the seeds were fully ripened, while straw yield was harvested at 165 DAS. Fresh seed yield and straw yield were dried at 70 ° C for 48 h to determine their dry weight.

Crop water use efficiency (CWUE)

CWUE (kg m^{-3}) was calculated using Eq. 2 as follows:

$$CWUE = \frac{GY}{ET_a} \qquad \text{Eq. (2)}$$

where GY is the dry seed yield (kg) and ET_a is the actual plant evapotranspiration (m^3) for each treatment.

Ions concentration in soil and faba bean seeds

After harvest, 400 grams of dried soil from each treatment were taken to prepare saturated extract to determine the concentration of sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in the soil. Two grams of dried faba bean seeds from each treatment were used to determine the concentration of these elements except magnesium in the seeds. The concentration of seed Na^+ and K^+ for all treatments was determined using a flame photometer (Richards 1954), and EDTA titration was used for the determination of Ca^{2+} concentration in the soil and in the seed and Mg^{2+} concentration in the soil (Knudsen et al. 1982).

Sodium adsorption ratio (SAR)

Sodium adsorption ratio [(meq $L^{-1})^{0.5}$] was calculated based on the measured concentrations of sodium (Na^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) in the soil using Eq. 3 as follows:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad \text{Eq. (3)}$$

Soil Saturated Electrical Conductivity (ECe)

The dried soil samples from all treatments were used to prepare the saturated extract and thereafter, the soil saturated electrical conductivity (EC_e) of all treatments was measured using an EC meter (Rhoades 1996).

Statistical analysis

Statistical analysis was performed using the PROC GLM of SAS (SAS Institute Inc. 2007). All the data satisfied the normality and homogeneity of variance tests. Interaction effects between irrigation water salinity levels, irrigation water regimes, and biochar levels on the measured parameters were evaluated by analysis of variance (ANOVA). Means were compared using Duncan's Multiple Range Test (DMRT) at the 5% level of probability.

RESULTS

Irrigation water, soil evaporation, and actual evapotranspiration

The seasonal depth of applied irrigation water decreased with increasing biochar application and deficit irrigation treatment (Fig. 1). The maximum and minimum depth of irrigation water was 1098 mm in $B_0I_{100\%}$ and 486 mm in $B_{2.5}I_{50\%}$, respectively. On average for all irrigation levels, biochar reduced the irrigation water depth by 12.0%, indicating the ability of biochar to enhance water holding capacity (Fig. 1).

Application of biochar from zero to 2.5% w/w under full irrigation and no saline conditions significantly decreased irrigation water depth, soil evaporation, plant transpiration and actual crop evapotranspiration (ET_a) by 13.0, 27.5, 3.4, and 11.0 %, respectively (Fig. 2). Moreover, the application of saline irrigation water and deficit irrigation reduced crop evapotranspiration at each biochar level (Table. 2); however, no significant difference was observed between crop evapotranspiration of $B_{1.25}S_{0.6}I_{50\%}$ and $B_{1.25}S_4I_{50\%}$ and also between $B_{2.5}S_{0.6}I_{50\%}$ and $B_{2.5}S_4I_{50\%}$.

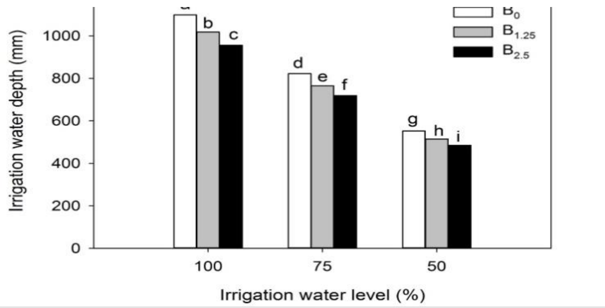

Fig. 1. Total amount of irrigation water depth for tested biochar (B_0, $B_{1.25}$, and $B_{2.5}$) and irrigation water levels (50, 75, and 100 %). Different letters indicate significant differences at a 5 % level of probability.

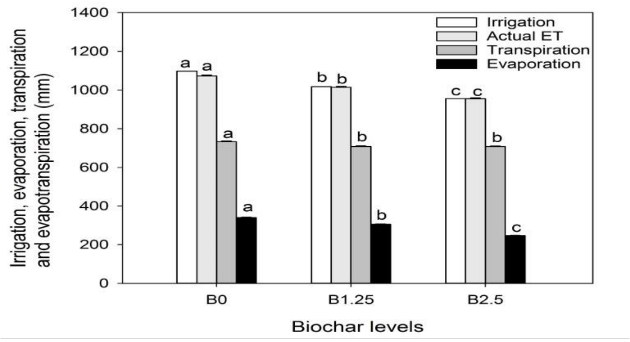

Fig. 2. Irrigation water depth, total actual evapotranspiration, plant transpiration, and soil evaporation in tested biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$) under full irrigation and 0.6 dS m^{-1} salinity level. For each trait, different letters represent significant differences at a 5 % level of probability.

Yield and dry matter

Decreasing irrigation water from 100% to 50% significantly reduced dry seed yield (DSY) at all biochar and salinity levels (Fig. 3 a-c). Also, an increase in salinity levels from 0.6 to 8 dS m^{-1} significantly reduced DSY. Under full irrigation, the application of biochar significantly increased DSY (Fig. 3 a-c). In addition, increasing biochar resulted in higher DSY under 75% and 50% crop water requirement and salinity level of 0.6 dS m^{-1}. At salinity level of 4 dS m^{-1} and irrigation water levels of 75% and 50%, the application of biochar reduced the DSY in comparison with that obtained in B_0. This trend was not observed for salinity level of 8 dS m^{-1} and irrigation water levels of 75%, as DSY increased by application of biochar. Maximum and minimum DSY and dry matter (DM) were observed in $B_{2.5}S_{0.6}I_{100\%}$ (14.4 g pot^{-1} and 75.6 g pot^{-1}) and $B_{1.25}S_8I_{50\%}$ (6.1 g pot^{-1} and 39.2 g pot^{-1}), respectively (Fig. 3 b-c and Table 2). However, the DM of $B_{1.25}S_8I_{50\%}$ was not significantly different from the DM of $B_{2.5}S_8I_{50\%}$ at a 5% level of probability (Table 2).

Application of saline water and lower irrigation water regimes resulted in decreasing the DM at all biochar levels (Table 2). Despite an exception in which DM was significantly increased with the application of more saline water in $B_{2.5}S_8I_{75\%}$ (52.2 g pot^{-1}) compared to $B_{2.5}S4I_{75\%}$ (48.3 g pot^{-1}). Similar to DSY, the application of biochar at a salinity level of 0.6 dS m^{-1} significantly increased DM in all irrigation water levels. Application of 1.25% and 2.5% biochar under salinity levels of 4 and 8 dS m^{-1} decreased DM in comparison with $S_{0.6}$ at the same level of biochar. (Table 2).

Crop water use efficiency

The maximum and minimum crop water use efficiency (CWUE) was obtained in $B_{2.5}S_{0.6}I_{50\%}$ (0.72 kg m^{-3}) and $B_0S_8I_{100\%}$ (0.21 kg m^{-3}), respectively (Fig. 3 d-f). At a salinity level of 0.6 dS m^{-1}, increasing biochar from zero to 2.5% w/w significantly increased CWUE in all three levels of irrigation. Moreover, increasing biochar from 0 to 2.5% w/w significantly increased CWUE in all three salinity levels under full irrigation conditions (Fig. 3 d-f). Decreasing irrigation water levels from 100 to 50%, significantly increased CWUE at all biochar and salinity levels.

Table 2. Faba bean dry matter, crop evapotranspiration, and seed ion concentration in tested treatments. Biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$), irrigation water levels ($I_{50\%}$, $I_{75\%}$, and $I_{100\%}$), and irrigation water salinity levels ($S_{0.6}$, S_4 and S_8).

Characteristics	B_0			$B_{1.25}$			$B_{2.5}$		
	$S_{0.6}$	S_4	S_8	$S_{0.6}$	S_4	S_8	$S_{0.6}$	S_4	S_8
Dry matter (g pot^{-1})									
$I_{100\%}$	66.4^{c}	56.6^{fg}	55.9^{gh}	70.4^{b}	49.67^{kl}	49.8^{kl}	75.6^{a}	54.0^{hi}	53.7^{hi}
$I_{75\%}$	59.8^{de}	50.3^{jk}	47.9^{klmn}	61.7^{d}	45.9^{mno}	47.4^{lmn}	64.9^{c}	48.3^{klm}	52.2^{ij}
$I_{50\%}$	53.6^{hi}	46.4^{mno}	44.3^{o}	53.3^{i}	49.1^{kl}	39.2^{p}	58.4^{ef}	45.6^{no}	40.8^{p}
Crop evapotranspiration (mm)									
$I_{100\%}$	1073.0^{a}	1050.1^{b}	1022.7^{c}	1013.9^{d}	998.7^{e}	852.8^{h}	954.7^{f}	945.3^{g}	794.2^{k}
$I_{75\%}$	813.3^{i}	802.3^{j}	691.7^{p}	764.1^{l}	762.9^{m}	690.1^{q}	719.0^{n}	718.4^{o}	646.6^{r}
$I_{50\%}$	549.0^{s}	548.0^{t}	468.4^{w}	514.8^{u}	514.8^{u}	387.4^{z}	485.8^{v}	485.8^{v}	434.8^{x}
Potassium concentration (g kg^{-1})									
$I_{100\%}$	11.3^{def}	10.4^{g}	9.8^{hi}	12.0^{b}	11.4^{cde}	10.5^{g}	12.4^{a}	11.6^{c}	11.1^{ef}
$I_{75\%}$	10.6^{g}	10.4^{g}	9.6^{i}	11.5^{cd}	11.0^{f}	9.9^{h}	11.9^{b}	11.1^{ef}	11.1^{ef}
$I_{50\%}$	10.5^{g}	10.0^{h}	9.8^{hi}	11.2^{def}	10.4^{g}	9.9^{hi}	11.4^{cde}	10.4^{g}	10.0^{h}
Calcium concentration (g kg^{-1})									
$I_{100\%}$	1.20^{p}	1.36^{mn}	1.89^{bc}	1.76^{efg}	1.82^{cde}	1.88^{bcd}	1.81^{def}	1.94^{b}	2.04^{a}
$I_{75\%}$	1.18^{p}	1.50^{kl}	1.79^{ef}	1.42^{m}	1.66^{hi}	1.59^{ij}	1.74^{fgh}	1.69^{gh}	1.91^{b}
$I_{50\%}$	1.08^{q}	1.29^{no}	1.56^{jk}	1.39^{m}	1.24^{op}	1.39^{m}	1.43^{lm}	1.39^{m}	1.39^{m}

* For each characteristic, means with the same letters are not significantly different at a 5% level of probability

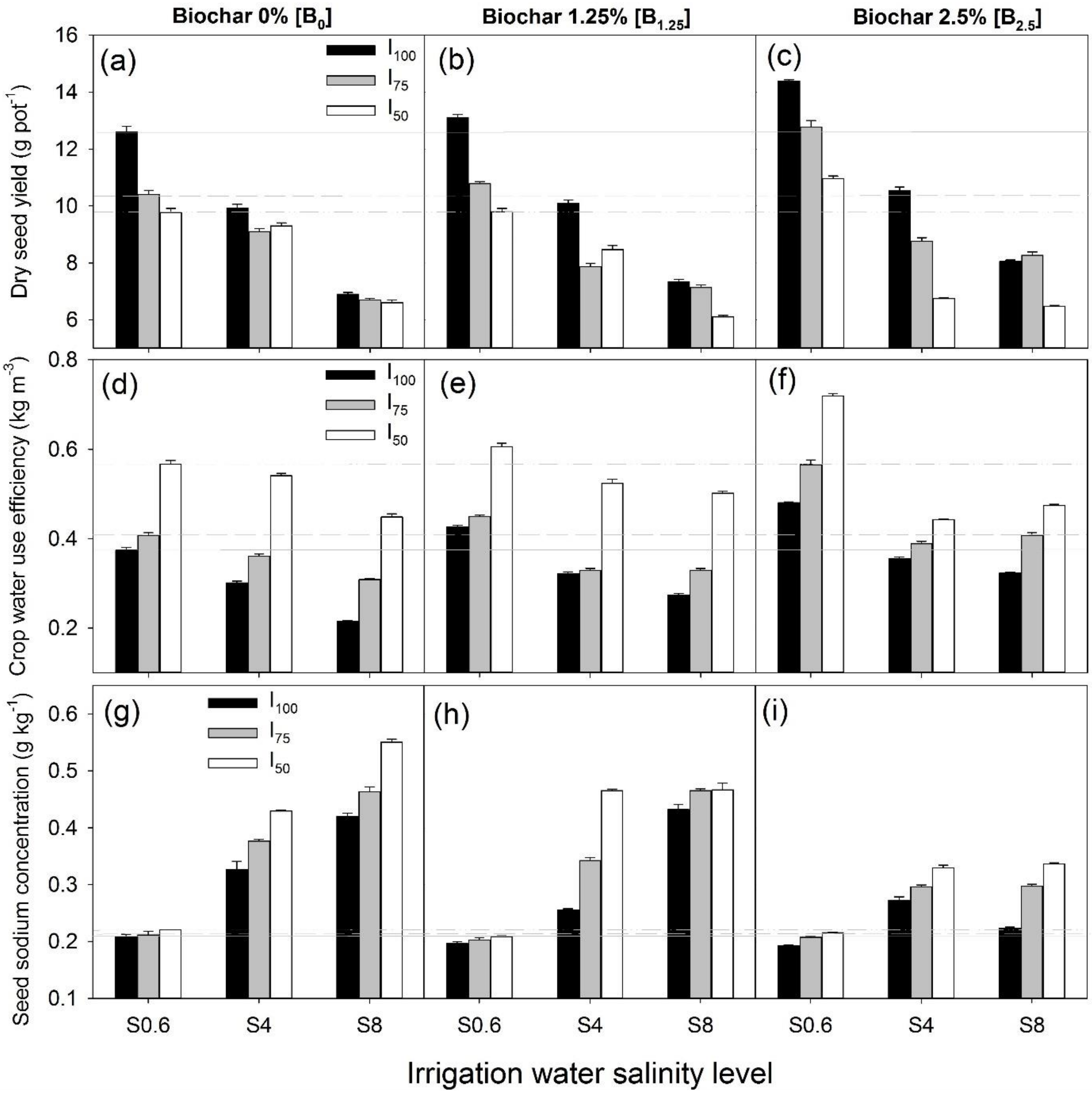

Fig. 3. Dry seed yield (a-c), crop water use efficiency (d-f), and seed sodium concentration (g-i) as affected by irrigation water regimes ($I_{50\%}$, $I_{75\%}$, and $I_{100\%}$), irrigation water salinity ($S_{0.6}$, S_4 and S_8) and biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$). The solid, dashed, and dotted lines represent the amount of each variable at $B_0S_{0.6}I_{100\%}$, $B_0S_{0.6}I_{75\%}$, and $B_0S_{0.6}I_{50\%}$, respectively, for the three irrigation regimes (I_{100}, I_{75}, and I_{50}), without biochar (B_0) and low salinity irrigation water ($S_{0.6}$)

Ion concentration in seeds

Increasing irrigation water salinity from 0.6 to 8 dS m^{-1} at each biochar and irrigation water level significantly increased the sodium concentration in seeds (Fig. 3 g-i). A similar result was observed for irrigation water levels; declining irrigation water levels from 100% to 50% at each salinity and biochar level increased the sodium concentration in seeds. Application of 2.5% w/w biochar significantly reduced seed sodium concentration in comparison with that obtained in no biochar application at each salinity and irrigation water level (Fig. 3 g-i).

Increasing salinity levels decreased potassium concentration under each biochar level and irrigation water regime (Table 2). On the other hand, increasing biochar from B_0 to $B_{2.5}$ significantly increased potassium concentration at each salinity and irrigation water level (Table 2) as used biochar had high potassium concentration (67.5 meq L^{-1}).

Increasing salinity from 0.6 dS m^{-1} to 8 dS m^{-1} significantly increased calcium concentration in seeds (except in $B_{1.25}I_{50\%}$), while the application of deficit irrigation significantly decreased calcium concentration in seeds (Table 2). Saline water was prepared by dissolving NaCl and $CaCl_2$, therefore it was enriched with Ca. This resulted in seed Ca increase in saline irrigation water. Whereas, deficit irrigation decreased the seed Ca. Maximum and minimum concentration of calcium in seeds was observed in $B_{2.5}S_8I_{100\%}$ (2.04 g kg^{-1}) and $B_0S_{0.6}I_{50\%}$ (1.08 g kg^{-1}), respectively (Table 2).

Soil chemical parameters

Increasing irrigation water salinity from 0.6 dS m^{-1} to 8 dS m^{-1} significantly increased potassium, sodium, calcium, and magnesium concentrations in soil under all biochar and irrigation water levels (Table 3). Application of tested irrigation water levels (i.e. $I_{75\%}$ and $I_{50\%}$) significantly increased sodium, calcium, and magnesium concentrations in all biochar, and irrigation water salinity levels compared to full irrigation levels except the salinity level of 0.6 dS m^{-1} in all biochar levels. Under 2.5% w/w biochar and the salinity level of 8 dS m^{-1} conditions, the application of 50% irrigation water level significantly reduced soil potassium concentration in comparison with that obtained in full irrigation. Maximum potassium concentration was observed in $B_{2.5}S_4I_{50\%}$ as the amount of 21.68 meq L^{-1}, which was 48.2 times the minimum value of potassium concentration in $B_0S_{0.6}I_{50\%}$, although no significant difference was observed in potassium concentration among irrigation water levels under 0.6 dS m^{-1} salinity and zero biochar application. The sodium and calcium concentrations in the $B_{2.5}S_8I_{50\%}$ were 19.2 and 9.4 times those corresponding element concentrations in the $B_0S_{0.6}I_{100\%}$, respectively (Table 3).

Sodium adsorption ratio (SAR) in soil after harvest varied between 1.72 (meq $L^{-1})^{0.5}$ (minimum value) in $B_{1,25}S_{0.6}I_{50\%}$ and 13.85 (meq $L^{-1})^{0.5}$ (maximum value) in $B_{1,25}S_{8.0}I_{50\%}$ (Table 3). The addition of 1.25% w/w biochar under salinity level of 8 dS m^{-1} and all irrigation water levels significantly increased SAR in comparison with those corresponding treatments obtained in B_0, but further application of biochar (to 2.5% w/w) significantly declined the SAR under salinity level of 4 and 8 dS m^{-1} and all irrigation water levels in comparison with those corresponding treatments obtained in $B_{1.25}$.

The maximum saturated electrical conductivity (EC_e) was obtained in $B_{1.25}S_8I_{75\%}$ (18.12 dS m^{-1}) and the minimum value of this parameter was seen in $B_0S_{0.6}I_{100\%}$ (1.42 dS m^{-1}) (Table 3). Increasing both salinity and biochar levels resulted in increased EC_e (Table 3). Application of 50% irrigation water level increased EC_e in comparison with those obtained in $I_{100\%}$ under salinity levels of 4 and 8 dS m^{-1} and biochar levels of 0, 1.25, and 2.5% w/w, except in salinity level of 8 dS m^{-1} and 2.5% w/w biochar that EC_e was not changed significantly.

Relationship between seed and soil ion concentration

The relationship between seed and soil potassium concentration for tested biochar levels (Fig. 4 a and Table 4) showed that seed potassium concentration decreased by increasing soil potassium concentration under all biochar levels; however, the rate of decrease (according to the slope of the regression equations (Table 4) under $B_{2.5}$ was lower than B_0. Good correlations were observed between seed and soil sodium concentration (R^2 of 0.93, 0.90, and 0.74 for B_0, $B_{1.25}$, and $B_{2.5}$, respectively; Fig. 4 b and Table 4). The highest Na^+/K^+ ratio in soil under B_0 was 30 meq meq^{-1}, while by applying 2.5% w/w biochar, the ratio decreased to 5.4 meq meq^{-1} (Fig. 4 c). A similar trend was observed in seeds as lower Na^+/K^+ ratios were obtained under higher biochar application.

Table 3. Soil chemical parameters as affected by biochar (B_0, $B_{1.25}$, and $B_{2.5}$), irrigation water ($I_{50\%}$, $I_{75\%}$, and $I_{100\%}$), and water salinity ($S_{0.6}$, S_4 and S_8) treatments

Characteristics	B_0			$B_{1.25}$			$B_{2.5}$		
	$S_{0.6}$	S_4	S_8	$S_{0.6}$	S_4	S_8	$S_{0.6}$	S_4	S_8
Potassium (meq L^{-1})									
$I_{100\%}$	0.69^{n*}	1.81^{m}	2.60^{lm}	7.23^{i}	9.49^{h}	15.83^{d}	15.87^{d}	20.12^{b}	19.95^{b}
$I_{75\%}$	0.59^{n}	2.01^{m}	3.20^{kl}	4.89^{j}	9.22^{h}	16.19^{d}	11.92^{f}	17.82^{c}	21.97^{a}
$I_{50\%}$	0.45^{n}	3.50^{k}	3.29^{kl}	4.37^{j}	14.01^{e}	16.63^{d}	10.93^{g}	21.68^{a}	18.05^{c}
Sodium (meq L^{-1})									
$I_{100\%}$	4.87^{m}	31.36^{l}	50.96^{i}	5.79^{m}	46.67^{j}	63.67^{g}	5.88^{m}	40.33^{k}	60.00^{h}
$I_{75\%}$	4.07^{m}	59.13^{h}	69.07^{f}	4.08^{m}	61.08^{gh}	97.67^{b}	5.19^{m}	52.17^{i}	80.00^{d}
$I_{50\%}$	3.37^{m}	64.14^{g}	76.43^{e}	3.65^{m}	82.67^{d}	105.17^{a}	4.47^{m}	68.00^{f}	93.33^{c}
Calcium (meq L^{-1})									
$I_{100\%}$	5.84^{lmn}	17.62^{j}	25.48^{g}	7.10^{klm}	19.61^{i}	22.96^{h}	8.32^{k}	35.99^{e}	35.29^{e}
$I_{75\%}$	4.81^{no}	33.22^{f}	34.53^{ef}	5.26^{mno}	25.66^{g}	35.26^{e}	7.53^{kl}	47.42^{c}	47.06^{c}
$I_{50\%}$	4.47^{o}	36.03^{e}	38.22^{d}	4.81^{no}	34.73^{ef}	37.97^{d}	6.66^{klmn}	61.00^{a}	54.90^{b}
Magnesium (meq L^{-1})									
$I_{100\%}$	4.51^{m}	19.04^{l}	30.33^{k}	5.40^{m}	28.21^{k}	38.95^{i}	5.57^{m}	37.34^{i}	55.56^{ef}
$I_{75\%}$	3.76^{m}	34.75^{j}	46.47^{g}	4.49^{m}	41.56^{h}	70.43^{c}	4.99^{m}	48.30^{g}	74.07^{b}
$I_{50\%}$	3.12^{m}	39.38^{hi}	54.67^{f}	4.17^{m}	57.36^{e}	77.38^{a}	4.76^{m}	62.96^{d}	78.00^{a}
SAR (meq $L^{-1})^{0.5}$									
$I_{100\%}$	2.14^{lmn}	7.32^{j}	9.65^{h}	2.31^{l}	9.54^{h}	11.44^{d}	2.23^{lm}	6.66^{k}	8.90^{i}
$I_{75\%}$	1.96^{lmn}	10.14^{g}	10.85^{ef}	1.85^{mn}	10.53^{fg}	13.43^{b}	2.07^{lmn}	7.54^{j}	10.28^{g}
$I_{50\%}$	1.86^{mn}	10.44^{g}	11.22^{de}	1.72^{n}	12.18^{c}	13.85^{a}	1.87^{mn}	8.64^{i}	11.45^{d}
EC_e (dS m^{-1})									
$I_{100\%}$	1.42^{n}	7.57^{i}	7.29^{i}	4.31^{l}	8.77^{h}	10.32^{e}	5.91^{jk}	7.83^{i}	14.09^{c}
$I_{75\%}$	2.11^{m}	8.96^{h}	7.68^{i}	4.36^{l}	9.62^{g}	18.12^{a}	6.36^{j}	9.62^{g}	14.82^{b}
$I_{50\%}$	2.08^{m}	9.56^{g}	10.21^{ef}	3.91^{l}	9.69^{fg}	14.11^{c}	5.42^{k}	11.96^{d}	14.08^{c}

* For each characteristic, means with the same letters are not significantly different at 5% level of probability

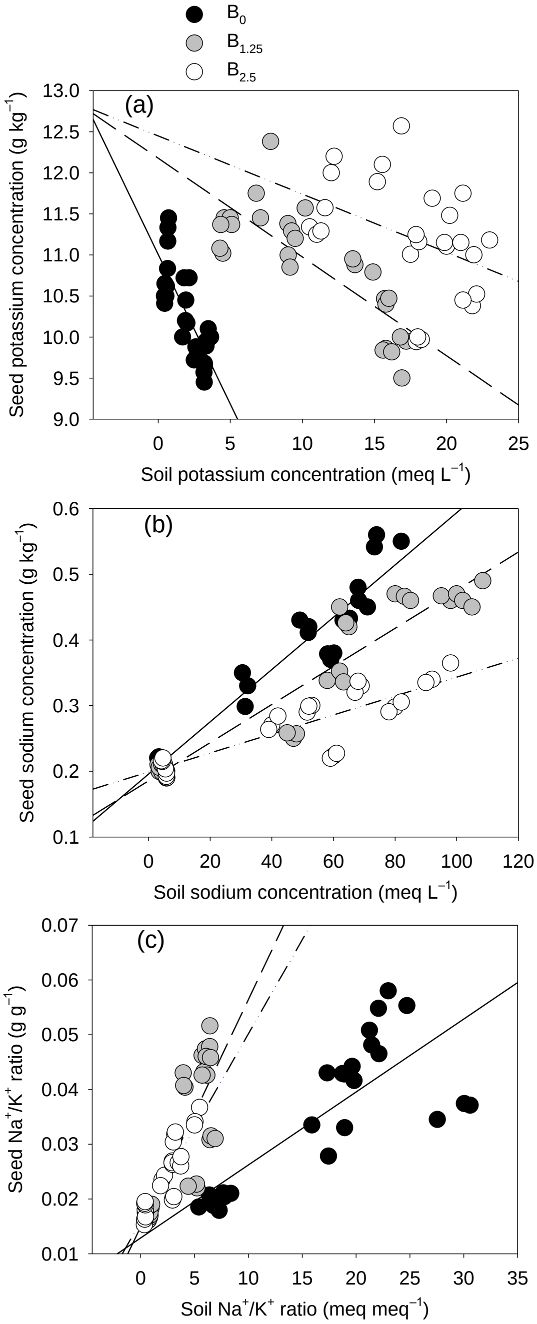

Fig. 4. Relationships between the (a) seed and soil potassium concentrations, (b) seed and soil sodium concentrations, and (c) seed and soil Na^+/K^+ ratios for three tested biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$)

Yield-salinity function

Increasing relative EC_e ($EC_e/EC_{e\text{-}0}$: ratio of EC_e of any treatments to EC_e of $B_0S_{0.6}I_{100\%}$) decreased the relative yield (Y/Y_0: ratio of yield of any treatments to yield of $B_0S_{0.6}I_{100\%}$) (Fig. 5), however, the application of 2.5% w/w biochar increased Y/Y_0 to greater than 1.0 for $EC_e/EC_{e\text{-}0} \leq 3.8$ dS m^{-1}. The 50% yield reduction (Y/Y_0 equal to 0.5) was observed at $EC_e/EC_{e\text{-}0}$ of 9.3, 11.7 and 11.0 for B_0, $B_{1.25}$ and $B_{2.5}$, respectively (Fig. 5).

Fig. 6 provided the relationship between relative dry seed yield (Y_0 in Fig. 6 is the average of dry seed yield under 0.6 dS m^{-1} salinity level at each irrigation water level and each biochar level) and soil saturated electrical conductivity for different irrigation levels and biochar levels. At zero biochar, the application of 50% of full irrigation increased the threshold value (Table 5) and decreased the slope of yield reduction in comparison with that obtained under 100% irrigation water. Under full irrigation conditions, the plants continued to take up more water and hence, more ions (such as Na+) resulted in increasing the slope of yield reduction and declining the threshold of soil-saturated electrical conductivity. Increasing biochar rates under different water regimes increased the threshold of saturated electrical conductivity in comparison with that obtained in B_0. Under biochar levels of 2.5%, the slope of yield reduction increased by application of 50% of full irrigation in comparison with that obtained under full irrigation (Table 5), however, this trend was not observed at B_0 and $B_{1.25}$

DISCUSSION

In the current study, the addition of biochar declined irrigation water depth, limited soil evaporation, and decreased actual evapotranspiration by enhancing soil porosity and water permeability, thus improving the soil water holding capacity. Also, water stress treatments in the current study reduced crop evapotranspiration due to lowered soil water potential at each biochar level. Similar results were reported by Wong et al. (2017) and Akhtar et al. (2015a). Ibrahim et al. (2017) showed that the application of 15 g kg^{-1} conocarpus biochar (produced at 400 °C) lowered cumulative evaporation by 17% compared to that of the control (no application of biochar). Similarly, Xu et al. (2016) indicated that the application of 5% w/w biochar effectively reduced soil evaporation. Moreover, the application of 2% w/w biochar (softwood pellets produced at 550°C) to sandy loam soil significantly reduced (21% lower) evapotranspiration of maize in comparison with that obtained in the control treatment (Wang et al. 2018).

In this study, the application of water stress treatments decreased the DSY and DM at all biochar levels, however, the addition of biochar to soil increased DSY and DM under all irrigation water regimes and 0.6 dS m^{-1} salinity. Similarly, Agbna et al. (2017) and Faloye et al. (2019) indicated that biochar can enhance yield under low irrigation water levels due to its capacity to retain soil water and therefore, mitigate water stress. An increase in soil salinity to 4 dS m^{-1} in the current study prevented biochar from positively influencing DSY under 50% deficit irrigation treatments. However, a further increase in salinity to 8 dS m^{-1} caused DSY to increase when combined with biochar under irrigation water levels of 75%, which could be due to the availability of more nutrients in soil under higher biochar levels. Similar to this study, the application of saline irrigation water (10 dS m^{-1}) and straw biochar at the rate of 10 and 20 Mg ha^{-1} significantly increased wheat grain yield by 8.6 and 8.4%, respectively, in comparison with that obtained in

Table 4. Relationship between seed and soil concentrations of potassium and sodium and Na^+/K^+ ratio in seed and soil for tested biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$)

Characteristics	B_0		$B_{1.25}$		$B_{2.5}$	
	Regression equation	R^2	Regression equation	R^2	Regression equation	R^2
Seed and soil potassium concentration	y=-0.36x+11.01*	0.62	y=-0.12x+12.18	0.65	y=-0.07x+12.45	0.16
Seed and soil sodium concentration	y=0.004+0.20	0.93	y=0.003x+0.18	0.90	y=0.001x+0.20	0.74
Na^{+}/K^+ ratio in seed and soil	y=0.001x+0.013	0.62	y=0.001x+0.015	0.63	y=0.003x+0.016	0.78

* y and x represent the amount in seed and soil, respectively

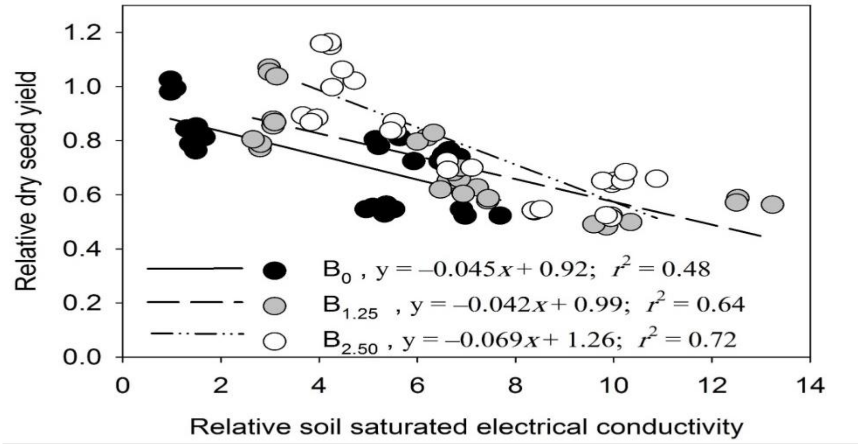

Fig 5. Relationships between the relative dry seed yield of faba bean and relative soil saturated electrical conductivity for tested biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$)

Table 5. Threshold of soil saturated electrical conductivity and slope of yield reduction for tested biochar levels (B_0, $B_{1.25}$, and $B_{2.5}$) and irrigation water regimes ($I_{50\%}$, $I_{75\%}$, and $I_{100\%}$)

Treatments	Threshold of soil saturated electrical conductivity (dS m^{-1})			Slope of yield reduction [% (dS $m^{-1})^{-1}$]		
	B_0	$B_{1.25}$	$B_{2.5}$	B_0	$B_{1.25}$	$B_{2.5}$
$I_{100\%}$	1.29	4.51	4.28	5.2	6.78	4.72
$I_{75\%}$	1.19	4.34	4.45	3.15	5.09	3.81
$I_{50\%}$	2.50	4.50	5.18	2.59	3.61	5.00

The application of saline irrigation water without biochar (Huang et al. 2019). In the same study, it was reported that yield enhancement under biochar application of 30 Mg ha^{-1} was not significant due to increased soil salinity and limited N availability.

Similar to DSY, CWUE increased by application of biochar under 0.6 dS m^{-1} salinity level and all irrigation water treatments (Fig. 3 d-f), as biochar increased the soil nutrient and water holding capacity. Consequently, the DSY increased and ET_a declined (Fig. 2), both of which were reported to have resulted in greater CWUE (Uzoma et al. 2011). In agreement with this study, the application of 2% w/w biochar (produced from softwood pellets at 550°C) lowered maize evapotranspiration by 21% and increased CWUE by 35% in comparison to the control (Wang et al. 2018). Decreasing soil water potential under deficit irrigation and salinity conditions reduced DSY and therefore, CWUE also declined (Fig. 3). In another study, it has been shown that deficit irrigation and salinity reduce plant water use efficiency, because of higher decreases in yield than the amount of water use in deficit irrigation as compared to full irrigation (Yang et al. 2019).

Sodium and potassium concentrations in seeds increased and decreased with increasing irrigation water salinity up to 8 dS/m at each level of biochar and irrigation water. (Fig. 3, Table 2). Similarly, the application of deficit irrigation increased seed sodium concentration, at each salinity and biochar level, which could be a mechanism to lower osmotic potential (more negative) to take up more water (Xi et al. 2018). Application of saline water to soil negatively affects the plant's water relations due to a reduction in soil water availability, lower osmotic potential (Munns, 2005), and higher SAR (Singh et al. 1992). Under mild water stress conditions, it has been shown that plants increase the seed's sodium concentration to decrease the seed's osmotic potential (more negative) and enhance water uptake, due to an increase in the water potential gradient as a mechanism, to resist water stress (Yue et al. 2012). Application of biochar significantly reduced seed sodium concentration due to lower water uptake, while it increased potassium concentration in seed as a result of high potassium concentration in applied biochar, resulting in salinity tolerance. Similar findings were stated by Ali et al. (2017b), Phuong et al. (2020), and Khan et al. (2020).

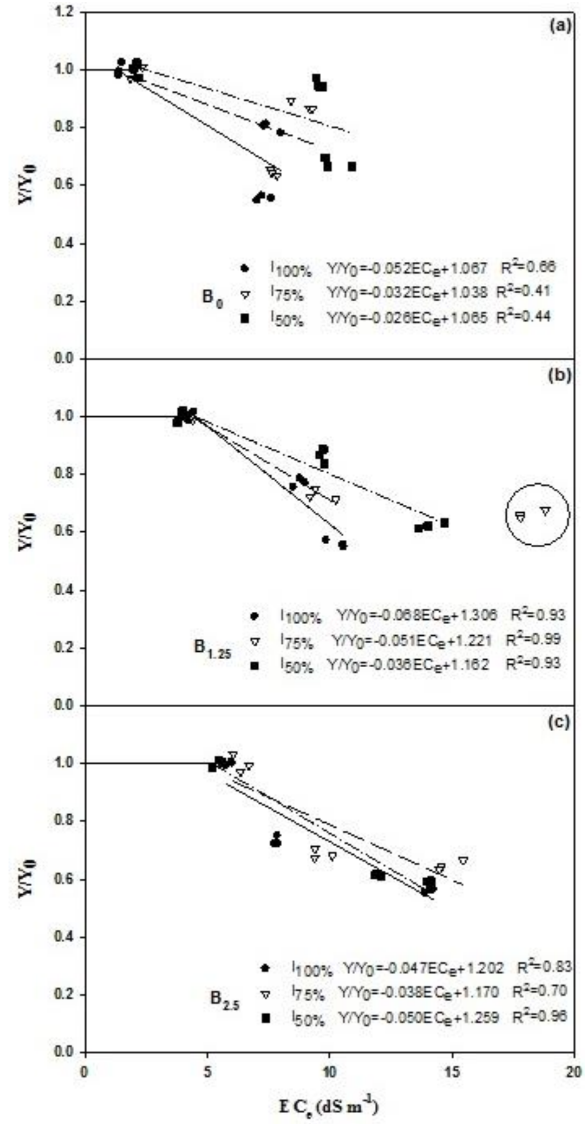

Fig 6. Relationships between relative dry seed yield (Y/Y_0) and soil saturated electrical conductivity (EC_e, dS m^{-1}) for tested irrigation levels ($I_{50\%}$, $I_{75\%}$, and $I_{100\%}$) and biochar levels of B_0 (a), $B_{1.25}$ (b) and $B_{2.5}$ (c). Y_0 is the average dry seed yield under 0.6 dS m^{-1} salinity level at each irrigation water level and each biochar level. The big circle in (b) showed the outlier data, which was not considered for regression

Sodium and potassium concentrations in seeds, increased and decreased, respectively, with increasing irrigation water salinity up to 8 dS m^{-1} at each level of biochar and irrigation water (Fig. 3, Table 2). Similarly, the application of deficit irrigation increased seed sodium concentration, at each salinity and biochar level, which could be a mechanism to lower osmotic potential (more negative) to take up more water (Xi et al. 2018). Application of saline water to soil negatively affects the plant's water relations due to a reduction in soil water availability, lower osmotic potential (Munns, 2005), and higher SAR (Singh et al. 1992). Under mild water stress conditions, it has been shown that plants increase the seed's sodium concentration to decrease the seed's osmotic potential (more negative) and enhance water uptake, due to an increase in the water potential gradient as a mechanism, to resist water stress (Yue et al. 2012). Application of biochar significantly reduced seed sodium concentration due to lower water uptake, while it increased potassium concentration in seed as a result of high potassium concentration in applied biochar, resulting in salinity tolerance. Similar findings were stated by Ali et al. (2017b), Phuong et al. (2020), and Khan et al. (2020).

Considering the relationship between the ions concentration in seed and soil (Table 4), the intercept for the equation between seed and soil potassium concentration under 2.5% w/w biochar application was higher due to the higher potassium concentration and lower Na^+/K^+ ratios. Interestingly, the significant intercept in all equations relating seed and soil potassium and sodium concentrations (Table 4) indicated that some ion absorption may be from adsorbed ions on the soil clay particles and some ions are absorbed from aqueous solutions as it has been stated by Jia et al. (2016).

The slope of the relationship between Y/Y_0 and $EC_e/EC_{e\text{-}0}$ was steeper for 2.5% w/w biochar level, as the biochar had an EC_e of 9.3 dS m^{-1} and therefore, this also increased the stresses to plants under both water stress and salinity stress conditions (Fig. 5). Deficit irrigation decreased soil water potential (more negative) and reduced the water uptake, while under full irrigation conditions, the plants continued to take up more water and hence, more ions (such as Na^+) resulted in increasing the slope of yield reduction and decline the threshold of soil saturated electrical conductivity (Fig. 6). Similar to what Rezaie et al. (2019) have reported, a higher threshold of saturated electrical conductivity under biochar application indicated that biochar can increase the plant tolerance to salinity (Tabs. 1) by increasing the potassium concentration in soil and lowering Na^+/K^+ ratios. Hillel (2000) indicated that the salinity threshold value based on the threshold-slope linear response function for faba bean is 1.6 dS m^{-1} and Katerji et al. (2003) obtained 2.8 dS m^{-1} for lysimeter experiment, while Rezaie et al. (2019) obtained salinity threshold value of 3.39 dS m^{-1} for a similar cultivar of faba bean as used in this study under no biochar and no irrigation water salinity. In this study, the salinity threshold value of 1.29 dS m^{-1} was obtained under no biochar, no irrigation water salinity, and full irrigation condition.

CONCLUSIONS

Application of biochar, by increasing soil water holding capacity, reduced the seasonal irrigation water depth and reduced the soil and crop water loss through less evaporation and evapotranspiration, respectively. Moreover, 2.5% w/w biochar application resulted in maximum dry seed yield (14.4 g pot^{-1}) and dry matter (75.6 g pot^{-1}) under 100% irrigation water level and non-saline irrigation water application. Also, the application of 2.5% w/w biochar increased crop water use efficiency to 0.72 kg m^{-3} under 50% of full irrigation water level and non-saline irrigation water application. The maximum threshold of soil-saturated electrical conductivity of 5.2 dS m^{-1} was observed in $B_{2.5}I_{50\%}$ treatment due to the absorbance of ions on the biochar surface and prevention of ion transport to the plant. Finally, cultivation of faba bean under 2.5% w/w biochar application and 100% non-saline irrigation water level is recommended for maximum faba bean production.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Mohammad Reza Bahadori-Ghasroldasht**i**, Fatemeh Razzaghi, and Ali Reza Sepaskhah. The first draft of the manuscript was written by Fatemeh Razzaghi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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برهمکنش بیوچار کاه و کلش گنـــدم بـــا آب آبیـــاری و شـــوری آب آبیاری برای بهبود راندمان مصرف آب و محصول باقلا

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واژه‌های کلیدی:

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نسبت جذب سدیم

چکیده - باقلا با وجود اینکه به طور گسترده کشت می‌شود، میزان محصول آن تحت تأثیر تنش‌های خشکی و شوری قرار دارد. بیوچار به طور بالقوه می‌تواند اثرات منفی تنش خشکی و شوری را کاهش دهد. در این تحقیق، ارزیابی اثرات متقابل بیوچار، رژیم‌های آب آبیاری و شوری آب آبیاری بر عملکرد باقلا، کارایی مصرف آب محصول (CWUE) و غلظت یون در شرایط گلخانه مورد ارزیابی قرار گرفت. تیمارها شامل صفر، ۱/۲۵ و ۲/۵ درصد وزنی بیوچار (بترتیب بعنوان تیمارهای B0، B1.25 و $B_{2.5}$)، رژیم های آبیاری (۵۰، ۷۵ و ۱۰۰ درصد نیاز آبی محصول، بترتیب بعنوان تیمارهای $I_{50\%}$، $I_{75\%}$ و $I_{100\%}$) و شوری آب آبیاری (۰/۶، ۴ و ۸ دسی‌زیمنس بر متر، بترتیب بعنوان تیمارهای $S_{0.6}$، S_4 و S_8) بود که به صورت آزمایش فاکتوریل در قالب طرح کاملاً تصادفی با چهار تکرار منظور شدند. کاربرد بیوچار ۲/۵ درصد وزنی در مقایسه با B_0 سبب کاهش ۱۱ درصدی تبخیر- تعرق واقعی شد. حداکثر محصول دانه خشک (۱۴/۴ گرم در گلدان) تحت تیمار $B_{2.5}S_{0.6}I_{100\%}$ بدست آمد. مقدار CWUE در تیمار $B_{2.5}S_8I_{50}$ ۰/۴۷کیلوگرم بر مترمکعب بدست آمد که ۱/۲۷ برابر CWUE در تیمار $B_0S_{0.6}I_{100\%}$ بود. غلظت سدیم بذر در تیمار $B_{2.5}S_8I_{50\%}$ (۰/۳۴گرم بر کیلوگرم) به طور معنی داری کمتر از غلظت سدیم بذر در تیمار $B_0S_8I_{50\%}$ (۰/۵۵ گرم بر کیلوگرم) بود. کاربرد بیوچار تحمل گیاه به شوری را افزایش داد، زیرا حداکثر آستانه هدایت الکتریکی اشباع خاک ۵/۲ دسی زیمنس بر متر در تیمار $B_{2.5}I_{50\%}$ مشاهده شد که بالاتر از ۲/۵ دسی زیمنس بر متر در تیمار $B_0I_{50\%}$ بود. در نهایت، کاشت باقلا با کاربرد ۲/۵ درصد وزنی بیوچار و آبیاری کامل با آب غیر شور برای تولید حداکثری باقلا توصیه می شود.