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Research Article

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Interaction effects of biochar levels, irrigation regimes, and irrigation water salinity levels on wheat II: grain and soil ions concentration and soil water retention curve

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ABSTRACT - In recent decades, the application of biochar to improve soil fertility and soil physical property and also enhance crop tolerance to abiotic stress has been proposed by researchers. Therefore, the effect of three levels of biochar (zero, 40, and 80 Mg ha^{-1}) produced from wheat straw, irrigation water salinity (0.6, 6, and 12 dS m^{-1}), and three irrigation regimes (50, 75, and 100% of crop water requirement) on wheat grain ions and soil ions concentration as well as some soil physical properties after wheat harvest were investigated under greenhouse conditions. The results showed that the Na+ and K+ concentration in soil significantly increased by application of biochar and also salinity, while application of 50% deficit irrigation significantly declined the Na+ and K+ concentration in soil. Also, the soil ECe of the highest level of biochar and salinity increased 2.1 and 1.59 times that of without biochar and salinity, respectively, while application of deficit irrigation significantly declined the soil ECe due to lower application of saline water and lower accumulation of salt. Considering the main effects of treatments, application of the highest level of biochar (80 Mg ha-1) increased the K+ concentration in grain, while application of saline water (6 and 12 dS m-1) and deficit irrigation (75% and 50 %) both declined the K+ concentration in grain. The application of biochar enhanced the soil water holding capacity. In conclusion, it is recommended to apply wheat straw biochar to increase soil fertility and increased water storage capacity in the soil. Finally, the application of non-saline biochar is suggested to prevent salinization and the destruction of agricultural soil.

INTRODUCTION

Adding amendments to soil improves soil's physical properties and provides a better environment for crops to grow and produce yield under abiotic stress (Sohi et al., 2010). In this regard, the use of crop residues as a soil amendment has been proposed (Parra et al., 2000). Nowadays, by pyrolyzing the crop residues at high temperatures and under no or limited oxygen conditions (known as biochar), long-term storage of these amendments in the soil has been provided (Zimmerman et al., 2011).

Biochar has a porous structure and contains different nutrients and therefore, is suitable for crop growth and production (Smith et al., 2010). Biochar due to its characteristics in improving soil properties (Razzaghi et al., 2020a), has been considered a protection against water stress (Novak et al., 2009). It has been shown that the application of biochar to soil improves soil physical properties such as bulk density, porosity, and water holding capacity (Hardie et al., 2014). The modification of soil's physical properties might be ascribed to the percentage of biochar application to soil (Ajayi et al., 2016). In this regard, Vaccari et al. (2011) stated that the use of biochar in agricultural soil can have many benefits in improving crop growth and yield. Also, it has been shown that biochar can alleviate water and salinity stresses (Ali and Yan, 2017).

Deficit irrigation is the application of a certain level of water either during a specific stage or throughout the crop-growing cycle (Ćosić et al., 2015) leading to a decline in crop yield and increase irrigation water use efficiency by applying less irrigation water (Pereira et al., 2002). It has been shown that the percentage effects of deficit irrigation on crop quality and yield are related to several factors such as soil and crop type, agronomic practices, and management (Rao et al., 2016; Chai et al., 2016). In an experiment, it was shown that the tomato quality and water use efficiency was increased under deficit irrigation compared to full irrigation. (Agbna et al., 2017).

Salinity has affected crop production in more than 800 million hectares, worldwide (Rengasamy, 2010). Under salinity stress conditions, the high concentrations of sodium in the soil can lead to reducing the uptake of many high-consumptive fertilizers by crops (Machado and Serralheiro, 2017). Soils that are affected by salinity, usually because of organic matter deficiencies, have a weak structure (Melero et al., 2007). Therefore, the addition of organic matter in the form of compost and biochar can enhance soil nutrients (Frimpong et al., 2021). In this regard, Akhtar et al. (2015) reported that mixing biochar with saline soil can reduce the negative effect of salinity stress on potatoes. Similarly, Thomas et al. (2013) realized the potential of biochar to absorb salt due to its negative charge and therefore, diminish the negative effect of salinity. The aim of the present study was to examine the effect of different levels of water salinity, irrigation regimes, and biochar on soil water retention curve and grain and soil ions concentration.

MATERIALS AND METHODS

The experiment was performed in the greenhouse of the Drought Research Center, School of Agriculture, Shiraz University during 2015–2016. The geographical coordinates of the Research Station are 52º 32´ E and 29º 36´ N, respectively, with an altitude of 1810 m above the mean sea level. The mean maximum and minimum temperatures during the growing season were 34°C and 15°C, and the maximum and minimum relative humidity were 70 % and 28 %, respectively.

Three levels of biochar, irrigation regimes, and irrigation water salinity were applied in factorial arrangements under a complete randomized design with four replicates. Three biochar levels included 0, 40, and 80 Mg ha^{-1} of biochar (equivalent to zero, 2.07, and 4.17% by weight named as B0, B2, and B4, respectively), irrigation water salinity treatments were 0.6, 6, and 12 dS m^{-1} (named as S0.6, S6, and S12, respectively) and irrigation regimes were 50, 75, and 100 % of crop water requirement (I50%, I75%, and I100%, respectively). The biochar was produced by pyrolyzing the wheat straw at a high temperature (550°C) under low oxygen conditions. The physical and chemical properties of produced biochar and the sandy loam soil (passed from a 2 mm sieve) are observed in Table 1.

Before planting and according to soil analysis, the fertilizers were determined and added to the soil. Then, the soil and biochar were mixed completely with the mentioned ratios. The pots of 20 cm in height and 21.6 cm in diameter were filled with the mixture (final pot weight of 6 kg). Ten wheat seeds (Shiraz cv.) were sown in pots (20 Feb. 2016) and the pots were fully irrigated with non-saline water (0.6 dS m-1) until complete seedling establishment was obtained. Thereafter, the seedlings were thinned to 7 plants per pot. The application of irrigation regimes and water salinity treatments was initiated 25 days after sowing (DAS) by weighing the pots every other day. The water salinity levels of 6 and 12 dS m^{-1} were prepared by dissolving the equal percent of sodium chloride (NaCl) and calcium chloride (CaCl2) in tap water. The irrigation water depth for I100% was determined based on the depth of irrigation water that was required to increase the soil water content to 100% of pot field capacity plus 15 % as leaching fraction and the depth of irrigation water for I75%, and I50% were calculated and applied based on 75 and 50 % of the depth of irrigation for I100% at each biochar levels. The pots initially were irrigated up to pot holding capacity.

Measured parameters

Sodium, Potassium, and Calcium Concentration in Wheat Grain and Soil

To measure the ions concentration in soil, the soil samples were taken after the wheat harvest (24 June 2016). The soil was first passed through a 2 mm sieve then saturation extract from all samples was prepared by using a Buchner funnel and also a suction pump. One gram of wheat grain powder was used to determine the ion concentration in the grain. Sodium and potassium concentrations in grain and soil were measured using a flame photometer (Richards, 1954). Calcium concentration in grain and soil was determined by EDTA titration (Knudsen et al., 1982).

Soil Saturated Electrical Conductivity

The soil saturated electrical conductivity (ECe) was measured in the obtained saturation extract of each treatment using an EC meter (Rhoades, 1996).

Table 1. Measured parameters of tested soil and biochar

Measured elements	Soil	Biochar
Soil texture	Sandy loam	-
EC (dS m^{-1})	0.66	9.3
Na (mg l^{-1})	2.2	1.7
K (mg l^{-1})	0.65	48
Ca (meq l^{-1})	2.0	2.3
CEC (meq 100g^{-1})	13.6	25.8
pH	7.44	8.18*
Bulk density (g cm^{-3})	1.53	0.25
θ_{FC} (cm^3 cm^{-3})	0.21	----
θ_{PWP} (cm^3 cm^{-3})	0.08	----

* PH biochar was measured in 1:10 biochar:water

Estimation of the van Genuchten Equation Parameters

The soil water retention curve is one of the important soil physical characteristics that provides the relationship between matric potential and volumetric soil water content. Three soil samples were taken from $B_0S_{0.6}I_{100\%}$, $B_2S_{0.6}I_{100\%}$, and $B_4S_{0.6}I_{100\%}$ treatments after wheat harvest. Disturbed soil samples were passed through a 2 mm sieve, and placed in of 100 cm^3 cylinder, located on a saturated pressure plate. Then the soil was saturated from the bottom. The gravimetric soil water content (θ_m) for each replicate of biochar treatment ($B_0S_{0.6}I_{100\%}$, $B_2S_{0.6}I_{100\%}$ and $B_4S_{0.6}I_{100\%}$) was determined at different suctions (0.03, 0.1, 0.3, 0.7, 1.0 and 1.5 MPa). Then, the volumetric soil water content (θ_v) was determined by multiplying the θ_m by soil bulk density (ρ_b).

Thereafter, the van Genuchten equation (van Genuchten, 1980) was used to find the relationship between soil matric potential (Ψ_m) and θ_v:

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{(1+(\alpha \times \Psi_m)^n)^m} \qquad m = 1 - \frac{1}{n} \qquad n > 1 \qquad (3)$$

where, α, n and m are shape parameters, θ_r and θ_s are residual and saturated soil water content, respectively.

Statistical analysis

The SAS software (PROC GLM, SAS Institute Inc., 2007) was used for statistical analyses. 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). Means comparison (5% level of probability) was conducted using Duncan's Multiple Range Test (DMRT).

RESULT AND DISCUSSION

Soil ions

The application of biochar increased the Na^+ concentration in soil among different levels of irrigation water and water salinity (Table 2). However, no significant difference was seen between the Na^+ concentration of B_2 and B_4 under 12 dS m^{-1} and all irrigation water regimes. The same occurred between the Na^+ concentration of B_0 and B_2 under 12 dS m^{-1} and all irrigation water regimes. In this regard, Chaudhry et al. (2016) showed that the addition of 12 Mg ha^{-1} biochar (produced from hardwood and grass) increased the soil sodium concentration. Increasing salinity from $S_{0.6}$ to S_{12} significantly enhanced the Na^+ concentration at each level of biochar and irrigation water regimes due to the existence of higher Na^+ in higher irrigation water salinity. Although the application of deficit irrigation declined the Na^+ concentration at different biochar and salinity levels, no significant difference was found in Na^+ concentration between different irrigation water levels (Table 2).

Application of biochar at each level of salinity and irrigation water levels increased soil K^+ concentration due to the high concentration of potassium in the applied biochar (Table 1). Considering the main effect of biochar, the K^+ concentration was significantly increased by 73% and 44% under B_4 and B_2 in comparison with that in B_0, respectively. In this regard, Khan et al. (2014) reported that the use of 5 Mg ha^{-1} biochar in the soil led to an increase in the soil's potassium concentration. Similar to Hamam and Negim (2014), application of 6 and 12 dS m^{-1} saline irrigation water in the current study significantly increased soil K^+ concentration by 55% and 24% in comparison with that at $S_{0.6}$, respectively. It has been already shown that salinity induces an increase in Na^+ adsorption on solid soil complex and release of K^+, leading to an increase in K^+ concentration in soil solution (Irakoze et al., 2021). Moreover, the application of 50% deficit irrigation significantly declined soil K^+ concentration by 12.6% in comparison with that in full irrigation in the current study, as it has been shown that a decline in soil moisture limited K^+ diffusivity in soil (Hu et al., 2006).

Application of B_2 and B_4 significantly increased Ca^{++} concentration in soil by 193% and 162% in comparison with that at B_0, respectively. In the current study, application of salinity increased Ca^{++} concentration in soil under all biochar and irrigation water levels, while application of deficit irrigation declined soil Ca^{++} concentration. However, no significant difference ($P< 0.05$) was found between Ca^{++} concentration of $I_{100\%}$ and $I_{75\%}$ and also between $I_{75\%}$ and $I_{50\%}$. Similarly, Major et al. (2010) indicated that the availability of Ca^{++} was higher under the presence of biochar and maize cultivation.

The soil saturated electrical conductivities (EC_e) for different treatments are shown in Table 2. Considering the main effect of treatments, increasing biochar and salinity significantly increased soil EC_e due to accumulation of salt concentration in soil, while application of deficit irrigation significantly declined soil EC_e due to lower application of saline water and salt accumulation. In this regard, Younis et al. (2015) reported that by adding 3 and 5% by weight biochar (provided from the cork), the soil EC_e was increased.

Grain ions

Table 3 shows the main and interaction effects of the treatments on grain ion concentration. The concentration of Na^+ in grain varied between 0.14 g kg^{-1} in $B_0S_{0.6}I_{50\%}$ and 0.54 g kg^{-1} in $B_0S_{0.6}I_{100\%}$ treatments. Considering the main effect of treatments, increasing the biochar application rate of 4% w/w significantly increased grain Na^+ concentration, while application of deficit irrigation declined the grain Na^+ concentration. The result of this study was in contrast to findings by Akhtar et al (2015), who showed the decline in Na^+ uptake in potatoes by application of biochar. Comparing each irrigation water and salinity levels among three levels of biochar showed that there was only a significant difference ($P< 0.05$) between the grain Na^+ concentration of $B_4S_{12}I_{50\%}$ and $B_0S_{12}I_{50\%}$ treatments and also with $B_2S_{12}I_{50\%}$ treatment, which resulted in significantly higher grain Na^+ concentration of B_4 compared to that in B_0 and B_2.

A similar trend was observed for K^+ concentration in grain as the addition of 4 % w/w biochar increased grain K^+ concentration by 14% in comparison with that at B_0, while no significant difference ($P< 0.05$) was observed between K^+ concentration of B_0 and B_2. In this regard, Badr et al. (2015) stated that by application of 4 Mg ha^{-1} of biochar, the uptake of K^+ in wheat increased significantly. The concentration of K^+ in applied biochar was high (48 mg l^{-1}) in comparison with that in soil (Table 1), leading to an increase in the availability of K^+ in soil and therefore, higher K^+ uptake under higher application of biochar as stated by Rezaie et al. (2019).

Application of saline water and deficit irrigation in the current study significantly (P< 0.05) decreased K^+ concentration in wheat grain. Similar to Shabala and Cuin (2008) and Spano and Bottega (2016), the K^+ uptake declined under salinity conditions, which is due to an increase in Na^+ concentration and the competition between ions during root water uptake.

The effect of biochar, salinity and deficit irrigation on grain Ca^{++} concentration was similar to Na^+ concentration. The increase in Ca^{++} concentration might be due to the fact the saline water was prepared with a mixture of NaCl and $CaCl_2$. The decrease in grain ions concentration under deficit irrigation was due to lower depth of applied water and lower soil matric potential (more negative) leading to lower Ca^{++} uptake by root as shown by Razzaghi et al. (2014).

Relationship between soil and grain ions concentration for different biochar rates

It is shown in Fig. 1 a-c that by increasing soil Na^+ concentration, the grain Na^+ concentration was also increased under all biochar levels. However, the relationships between sodium concentration in soil and grain improved with the higher application of biochar according to R^2=0.93 (Fig. 1 a-c). Also, increasing the intercepts of the equations between grain and soil Na^+ concentration, confirmed that biochar improves the uptake of ions from root due to an increase in surface area of soil particles, soil porosity, and holding higher nutrients (Alkharabsheh et al., 2021). Unlike Na+, the application of biochar did not improve the relationship between K^+ in soil and grain, as the amount of K^+ in soil was enough (260 mg kg^{-1} in soil solution, as reported by Najafi-Ghiri et al. (2011)) and the increase in soil K^+ concentration under biochar application did not improve the uptake of K+ by grain (Fig. 1 d-f). Although the application of high levels of biochar increased both soil and grain K^+ concentration (Tables 2 and 3), the K^+ concentration in grain declined under both salinity and water stress due to competition between Na^+ and K^+ uptake. In line with Na^+, the relationship between soil and grain Na^+/K^+ ratio increased by application of biochar (R^2=0.76 under B_0 and R^2=0.91 under B_4) (Fig. 1 g-i). Increasing soil Ca^{++} concentration increased grain Ca^{++} concentration, however, the relationship between soil and grain Ca^{++} concentration was not improved by the higher application of biochar (R^2=0.68 under B_0 and R^2=0.64 under B_4), which might be due to similar Ca^{++} concentration in soil and biochar (Fig. 1 j-l).

Table 2. Soil ion concentrations and soil saturated electrical conductivity (EC_e, dS m^{-1}) for different irrigation water, irrigation water salinity, and biochar levels

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}
Na^+ (meq lit^{-1})	$I_{100\%}$	4.1^{gh*}	45^{def}	90^{b}	10.6^{fgh}	52^{d}	97^{ab}	16^{f}	64^{c}	108^{a}
	$I_{75\%}$	3.2^{gh}	41^{e}	88^{b}	8.53^{g}	50^{d}	93^{abc}	14^{fg}	64^{c}	107^{a}
	$I_{50\%}$	2.2^{h}	39^{e}	85^{bc}	8.07^{g}	48^{de}	89^{b}	13^{fg}	62^{cd}	105^{ab}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		44.1(C)	52.5(B)	59.4(A)	8.6(C)	37.4(B)	95.7(A)	58.9(A)	52.08(B)	50.1(C)
K^+ (meq lit^{-1})	$I_{100\%}$	0.4^{g}	0.45^{g}	0.66^{g}	21^{f}	27^{e}	34^{d}	35^{cd}	43^{bc}	52^{a}
	$I_{75\%}$	0.34^{gh}	0.4^{g}	0.59^{g}	19^{fg}	25^{ef}	31.9^{def}	34^{d}	40^{c}	50^{ab}
	$I_{50\%}$	0.27^{h}	0.36^{gh}	0.53^{g}	17^{fgh}	22^{efg}	30.1^{def}	33^{de}	38^{cd}	46^{b}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		0.56(C)	25.2(B)	41.2(A)	17.7(C)	21.9(B)	27.4(A)	23.8(A)	22.3(AB)	20.8(B)
Ca^{++} (meq lit^{-1})	$I_{100\%}$	2.8^{j}	18^{g}	29^{f}	9^{i}	49^{d}	61^{a}	14^{h}	54^{bcd}	55^{bc}
	$I_{75\%}$	2.6^{jk}	17^{g}	28^{fg}	8.4^{ij}	49^{d}	57^{b}	13^{hi}	52^{cd}	53^{c}
	$I_{50\%}$	2.3^{k}	16^{gh}	28^{fg}	7.7^{ij}	47^{de}	55^{bc}	12^{hi}	49^{de}	53^{c}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		13.9(C)	40.7(A)	36.4(B)	7.9(C)	39(B)	46.2(A)	32.4(A)	31.1(AB)	29.5(B)
EC_e (dS m^{-1})	$I_{100\%}$	1.0^{h}	3.8^{g}	7.6^{cd}	6.8^{d}	7.8^{c}	8.2^{bc}	9.2^{ab}	9.4^{ab}	9.9^{a}
	$I_{75\%}$	0.85^{h}	3.5^{g}	7.4^{cd}	5.7^{f}	7.3^{cde}	7.9^{c}	8.7^{b}	8.9^{b}	9.6^{a}
	$I_{50\%}$	0.69^{i}	3.2^{gh}	7.1^{cde}	5^{fg}	6.8^{d}	7.1^{cde}	7.9^{c}	8.1^{bc}	8.8^{b}
	Main effect	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
		3.9(c)	6.9(B)	8.1(A)	5.09(C)	6.5(B)	8.1(A)	7.07(A)	6.58(B)	6.07(C)

* Small and capital letters represent 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

Table 3. Grain ion concentrations under different irrigation water, irrigation water salinity, and biochar levels

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}
Na^+ (g Kg^{-1})	$I_{100\%}$	0.19^{ef*}	0.35^{bcd}	0.54^{a}	0.23^{def}	0.36^{bcd}	0.44^{ab}	0.25^{de}	0.36^{bcd}	0.48^{a}
	$I_{75\%}$	0.18^{efg}	0.28^{cde}	0.41^{b}	0.19^{ef}	0.24^{de}	0.38^{bc}	0.24^{de}	0.31^{cd}	0.44^{ab}
	$I_{50\%}$	0.14^{f}	0.27^{cde}	0.30^{cde}	0.16^{efg}	0.24^{de}	0.32^{c}	0.19^{ef}	0.29^{cde}	0.41^{b}
	Main	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
	effect	0.29(B)	0.28(B)	0.33(A)	0.19(C)	0.3(B)	0.41(A)	0.35(A)	0.29(B)	0.25(C)
K^+ (g Kg^{-1})	$I_{100\%}$	5.22^{cde}	5^{cdef}	5.5^{bc}	5.68^{b}	5.17^{cde}	5.02^{cdef}	6.25^{a}	6.42^{a}	5.43^{cd}
	$I_{75\%}$	5.07^{cdef}	4.71^{de}	5.14^{cde}	4.82^{d}	4.52^{def}	4.57^{def}	5.55^{c}	5.39^{cd}	4.39^{d}
	$I_{50\%}$	4.83^{d}	4.65^{de}	4.51^{def}	4.4^{def}	4.18^{ef}	4.09^{f}	4.45^{def}	4.72^{de}	4.13^{ef}
	Main	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
	effect	4.56(B)	4.7(B)	5.2(A)	5.1(A)	4.9(B)	4.3(C)	5.4(A)	4.9(B)	4.4(C)
Ca^{++} (g Kg^{-1})	$I_{100\%}$	1.08^{ef}	1.26^{cd}	1.63^{b}	1.19^{de}	1.35^{c}	1.69^{b}	1.26^{cd}	1.48^{bcd}	1.91^{a}
	$I_{75\%}$	0.86^{fg}	1.13^{def}	1.33^{c}	1.17^{de}	1.22^{cde}	1.52^{bc}	1.22^{cde}	1.48^{bcd}	1.67^{b}
	$I_{50\%}$	0.61^{g}	0.95^{efg}	1.31^{c}	1.02^{ef}	1.14^{def}	1.47^{bcd}	1.17^{de}	1.27^{cd}	1.50^{bc}
	Main	B_0	B_2	B_4	$S_{0.6}$	S_6	S_{12}	$I_{100\%}$	$I_{75\%}$	$I_{50\%}$
	effect	1.12(C)	1.3(B)	1.44(A)	1.06(C)	1.25(B)	1.55(A)	2.53(A)	1.28(B)	1.16(B)

* Small and capital letters represent 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.

The positive intercept of the equations between grain and soil ions concentration indicated that the wheat root apart from absorbing ions from the soil solution could absorb the ions from soil particles. The intercept of the linear equation was lower in B_o since Ca^{++} adsorption on soil particles was low in B_o. This value was increased in B_2 and B_4 due to an increase in Ca^{++} addition by biochar.

Soil water retention curve

Soil water retention curves (WRC) for different levels of biochar treatments ($B_0S_{0.6}I_{100\%}$, $B_2S_{0.6}I_{100\%}$, and $B_4S_{0.6}I_{100\%}$) are shown in Fig 2. The results showed that the addition of biochar caused an increase in soil water at each soil matric potential suction. However, at high soil water suction, the volumetric soil water content of $B_2S_{0.6}I_{100\%}$ and $B_4S_{0.6}I_{100\%}$ treatments were closer to each other (Fig. 2). Biochar due to its high porosity and water and nutrient holding capacity could be used as an organic amendment to improve soil quality (Razzaghi et al., 2020b), especially in sandy soil (Alghamdi et al., 2020).

The van Genuchten equation was fitted between applied soil suction and measured soil volumetric water content of different biochar rates (Table 4). Similar to Li et al. (2021), the soil volumetric water content at saturation, field capacity, permanent wilting point, and residual water content in the current study was increased by the application of biochar. This trend was also observed for total available water (TAW, θ_{FC}-θ_{PWP}). Application of 80 ($B_4S_{0.6}I_{100\%}$) and 40 ($B_2S_{0.6}I_{100\%}$) Mg ha^{-1} biochar increased TAW by 36% and 24% in comparison with that at B_0. Saturated soil volumetric water content (θ_s) of 0.41 (cm^3 cm^{-3}) was observed in $B_4S_{0.6}I_{100\%}$ treatment, while the θ_s for $B_0S_{0.6}I_{100\%}$ treatment was 0.32 cm^3 cm^{-3} as the lowest value. The latter result was obtained due to an increase in soil porosity and holding more water by application of biochar. Similar result was also observed by Zhou et al. (2019). The α parameter (the inverse of the air entry potential) of 0.44 cm^{-1} for $B_4S_{0.6}I_{100\%}$ treatment was lower than those of other treatments, while, $B_4S_{0.6}I_{100\%}$ treatment had the highest value of the n parameter (the slope of the soil WRC) as 2.01.

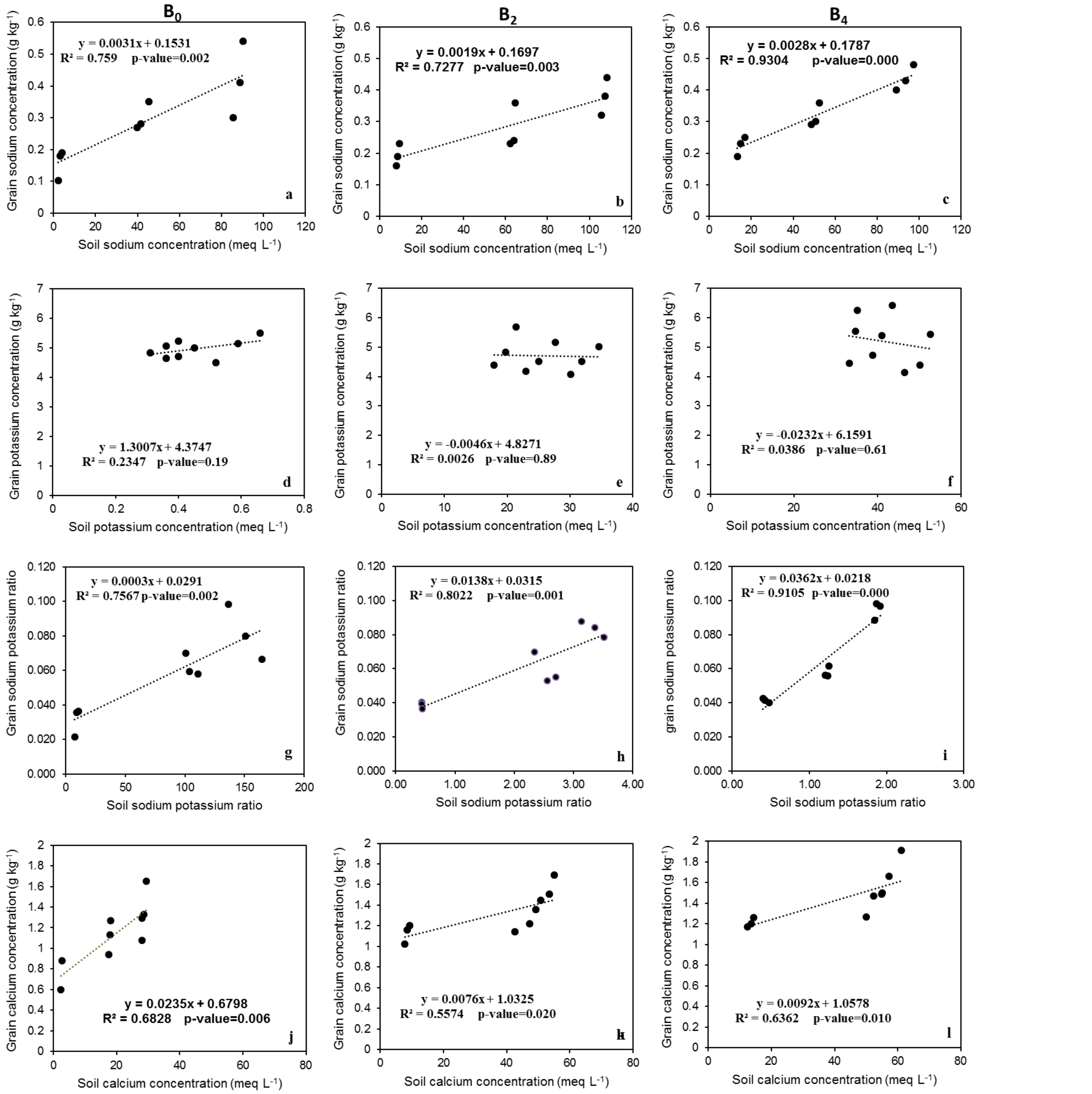

Fig. 1. Relationships between the (a-c) grain and soil sodium concentrations, (d-f) grain and soil potassium concentrations, (g-i) grain and soil Na^+/K^+ ratio, and (j-l) grain and soil calcium concentrations for three biochar levels.

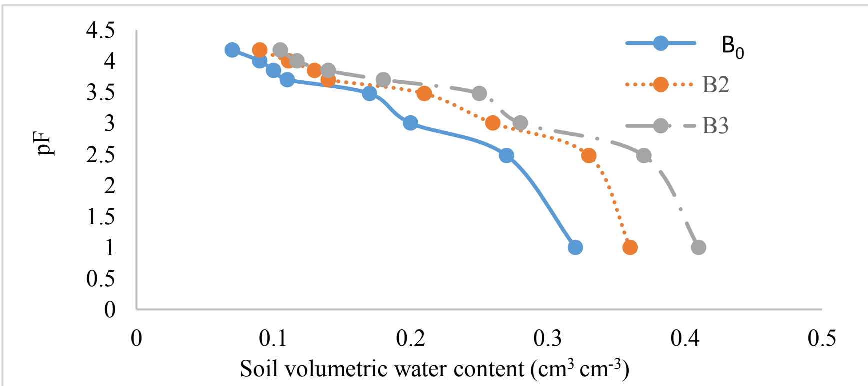

Fig. 2. Soil water retention curve at different levels of biochar

Table 4. The van Genuchten equation parameters

Treatments	θ_{FC} (cm^3 cm^{-3})	θ_{PWP} (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	Θ_r (cm^3 cm^{-3})	α (cm^{-1})	n	TAW (cm^3 cm^{-3})
$B_0S_{0.6}I_{100\%}$	0.261	0.079	0.32	0.016	0.65	1.60	0.25
$B_2S_{0.6}I_{100\%}$	0.330	0.090	0.36	0.010	0.61	1.67	0.31
$B_4S_{0.6}I_{100\%}$	0.374	0.105	0.41	0.052	0.44	2.1	0.34

CONCLUSION

According to the results of this study, the addition of biochar enhanced soil fertility through increasing Ca^{++} and K^+ concentration in soil, however, the rate of increase in K^+ concentration was higher than Na^+ and Ca^{++} concentration under biochar application compared to no biochar application. In addition, ECe was increased by application of biochar and salinity, while it declined under deficit irrigation. The maximum concentration of Na^+ in grain was obtained in B0S12I100% treatment, while the maximum grain K^+ concentration was observed in B4S0.6I100% treatment. High Na^+ concentration in saline water alleviated by high K^+ in biochar application. Also, grain K^+ concentration was increased by 20% and 28 % significantly by increasing biochar from zero to B4 and under salinity levels of 0.6, 6 dS m-1, and full irrigation, respectively, showing the ability of biochar to enhance wheat tolerance to salinity. Application of biochar improved soil water holding capacity. Finally, it was concluded to apply wheat straw biochar to increase soil fertility and improve water storage capacity in the soil. It is also suggested to apply non-saline biochar to prevent soil destruction.

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مقاله علمی- پژوهشی

اثرات متقابل سطوح بیوچار، رژیم‌های آبیاری و سطوح شوری آب آبیاری بر گندم II: غلظت یون‌های دانه و خاک و منحنی نگهداشت آب خاک

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چکیده – در دهه‌های اخیر، استفاده از بیوچار برای بهبود حاصلخیزی خاک و خواص فیزیکی خاک و همچنین افزایش تحمل گیاه به تنش غیرزیستی توسط محققان پیشنهاد شده است. بنابراین تأثیر سه سطح بیوچار (صفر، ۴۰ و ۸۰ مگا گرم در هکتار) از کاه و کلش گندم ، شوری آب آبیاری (۰/۶، ۶ و ۱۲ دسی‌زیمنس بر متر) و سه رژیم آبیاری (۵۰، ۷۵ و ۱۰۰ درصد نیاز آبی گیاه) بر غلظت یون‌های دانه گندم و یون‌های خاک و همچنین برخی خصوصیات فیزیکی خاک پس از برداشت گندم در شرایط گخانه‌ای بررسی شد. نتایج نشان داد که غلظت Na^+ و K^+ در خاک با کاربرد بیوچار و همچنین شوری به طور معنی‌داری افزایش یافت، در حالی که استفاده از کم‌آبیاری ۵۰ درصد نیاز آبی گیاه باعث کاهش معنی‌دار غلظت Na^+ و K^+ در خاک شد. همچنین، EC_e خاک با بالاترین سطح بیوچار و شوری به دلیل تجمع غلظت نمک در خاک به ترتیب ۲/۱ و ۱/۵۹ برابر بدون بیوچار و بدون شوری افزایش یافت، در حالی که استفاده از کم آبیاری به دلیل کاربرد کمتر آب شور و تجمع نمک کمتر باعث کاهش معنی‌دار EC_e خاک شد. با در نظر گرفتن اثرات اصلی تیمارها، کاربرد بالاترین سطح بیوچار (۸۰ مگاگرم بر هکتار) باعث افزایش غلظت پتاسیم در دانه شد، در حالی که کاربرد آب شور (۶ و ۱۲ دسی‌زیمنس بر متر) و کم آبیاری (۷۵ و ۵۰ درصد نیاز آبی گیاه) هر دو باعث کاهش غلظت پتاسیم در دانه شدند. همچنین، استفاده از بیوچار ظرفیت نگهداری آب در خاک را بهبود بخشید. در نتیجه، استفاده از بیوچار کاه وکلش گندم برای افزایش حاصلخیزی خاک و بهبود ذخیره آب در خاک توصیه می‌شود. در نهایت استفاده از بیوچار غیر شور جهت جلوگیری از شور شدن و تخریب خاک‌های کشاورزی پیشنهاد می‌شود.