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Soil respiration, root traits and dry matter yield of sorghum (*Sorghum bicolor* L.) as affected by biochar application under different cropping patterns and irrigation method

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A b s t r a c t. This study aimed to investigate the effect of alternate furrow irrigation accompanied by biochar application within different cropping patterns on soil respiration and root traits such as root dry weight and root volume associated with the dry matter yield of sorghum (*Sorghum bicolor* L.) over a two-year period (2017 – 2018). The treatments consisted of three irrigation methods, which included every furrow irrigation, fixed furrow irrigation and alternate furrow irrigation and two cropping patterns including one-row, two-rows and three levels of biochar application including 0, 6 and 12 t ha^{-1}. Different irrigation levels had a significant effect on root morphological indices, soil respiration, and the dry matter of forage yield. Biochar application showed a significant influence on soil respiration, as the highest soil respiration was observed in the B2 and B1 treatments (0.173 and 0.171 μmol C g^{-1} soil h^{-1}, respectively), in contrast, the least was observed in the control treatment B0 (0.168 μmol C g^{-1} soil h^{-1}). Biochar application had a positive effect on root dry weight, root volume and dry matter yield due to the prevention of severe moisture loss and further yield loss.

K e y w o r d s: biochar, root dry weight, root volume, soil respiration, *Sorghum bicolor* L.

INTRODUCTION

Drought and water scarcity are two important factors affecting crop production and soil microbial activity (soil respiration). Therefore, the use of drought-resistant crops and appropriate strategies to improve water storage in the soil would appear to be essential. In many areas of the world irrigation, water is overused (Chai *et al.,* 2014), while water scarcity is one of the most critical problems in arid and semi-arid regions (Afshari *et al.,* 2020; Forouzani and Karami 2011; Moslemi *et al.,* 2011; Samarbakhsh *et al.,* 2009). However, in a climate change scenario or with the onset of drought, crops may be influenced by drought stress, and agricultural production is expected to plunge. Low-irrigation is a method for optimizing water application which improves the water utilization of plant roots in the soil. Alternate furrow irrigation is one of the ways to save water through improving water use efficiency with the least impact on reducing the production of crops and horticultural plants (Kang and Zhang; 2004; Xiao *et al*., 2015). Randhawa *et al.* (2017) examined maize biomass accumulation under water stress conditions and stated that drought stress reduced the dry matter accumulation of maize. Wu *et al.* (2015) reported that the root water uptake in maize was higher under alternate furrow irrigation conditions than regular irrigation. The hydraulic conductivity of roots indicate their water absorption capacity, which is mainly dependent on the structure, water permeability, and root surface area (Ardakani *et al.,* 2009; Hoseinzade *et al.,* 2016; Sutka *et al.,* 2011; Liu *et al.,* 2014). Plants with deep and extensive roots could also produce a higher yield under drought stress conditions (Chimungu *et al.,* 2014; Liu *et al.,* 2011).

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Sorghum is highly resistant to drought (Borrell *et al.,* 2014). The use of the appropriate cropping patterns could play an important role in maintaining soil moisture in arid and semi-arid regions. The results of the research conducted by Cox *et al.* (2006) showed the highest dry matter yield of maize in a two-row cropping pattern. The two-row cropping pattern has also been assessed in peanut crops, and it has been observed that this planting method raises the growth rate of this crop and indirectly increases the dry weight of the aerial plant parts (Kurt *et al.,* 2017). Soil texture is one of the most important soil properties that affect the degree of water and nutrient retention, permeability, drainage, ventilation, organic carbon content, buffering capacity, porosity and many mechanical properties of the soil (Akpa *et al.,* 2014).

Biochar application in the soil increases nutrient availability and water storage in the soil (Jeffery *et al.,* 2015). The results of the study performed by Brennan *et al.* (2014) showed that biochar application in the soil enhanced favourable root traits such as root density and length. Biochar application increased plant height, stem diameter, chlorophyll content, net photosynthesis and grain yield (Sun *et al.,* 2017; Masto *et al.,* 2013). Soil respiration directly correlates with temperature and negatively correlates with moisture, while biochar application and carbon sequestration decreases soil respiration severity (He *et al.,* 2016). In this study, root morphological traits, soil respiration (SR) and the relationships between these parameters and biochar application were investigated.

MATERIALS AND METHODS

A split-split plot arrangement based on a randomized complete block design (RCBD) was conducted with three replications during two growing seasons (Spring-Summer 2017 and Spring-Summer 2018). Three irrigation methods, which included every furrow irrigation (EFI) [I0] as a common practice in the region, fixed furrow irrigation (FFI) [I1] and alternate furrow irrigation (AFI) [I2] were allocated to the main plots, two cropping patterns were used, including one-row (sowing the sorghum seeds on one row) [P0] and two-rows (sowing the sorghum seeds on two rows) [P1] for the subplots, also, three levels of biochar application including 0 [B0], 6 [B1] and 12 [B2] t ha^{-1} to sub-sub plots. The experiments were carried out at the experimental research farm of Islamic Azad University – Karaj-Iran which is located at an altitude of 1313 m a.s.l. with the geographic coordinates of 50° 54’ longitude and 35° 28’ latitude. A normality test was performed for the collected data and then to ensure the uniformity of the treatment variations, a Bartlett’s test was performed. In this experiment, the irrigation regime, cropping pattern and biochar treatments were considered to be a fixed factor and the year was assumed to be a random factor in the combined analysis of data An analysis of variance and the prepared figures were accomplished by using SAS Ver.9 and Microsoft Excel. Mean comparisons were performed using the Tukey HSD method test at a 5% probability level.

Each replicate consisted of 18 plots, each with 4 cultivated lines of 7 m in length and 5 m in width. The space between rows was arranged to be 0.6 m and the space between the plants was planned to be 0.1 m in each row. Plant density was devised to be 166,000 plant ha^{-1} of Sorghum (*Sorghum bicolor* L.). The seeds were sown on May 15, for each of the years that were investigated. Replanting was performed after seed emergence wherever required.

Biochar was mixed with the soil 14 days before the sowing date on May 15, 2017 and May 13, 2018. Follow up irrigations were performed from seed emergence until the growth stage of 4 leaves depending on the plant’s requirements. Irrigation timing was determined using the method of Bafkar *et al*. (2017):

$$I_t = \frac{d_n}{ET_c}, \tag{1}$$

where: I_t is the irrigation cycle, d_n is the net height of the irrigation water, and ET_c is the rate of evapotranspiration of the plant.

Also, d_n was calculated from the following equation (Bafkar *et al.,* 2017):

$$d_n = (FC - PWP)\ (MAD)\ (D), \tag{2}$$

where: D is the depth of root development in centimetres, MAD – maximum allowable depletion, PWP – permanent wilting point, and FC – field capacity.

The calculation of evapotranspiration (ET_c) using the Blaney and Criddle (1964) method was performed using the following equation:

$$ET_c = \alpha + \beta\ [P\ (0.46T + 8.13)], \tag{3}$$

α and β are the climatic variables, T is the average monthly temperature (ºC), and P is a fixed variable of the day. Some of the soil properties are listed in Table 1.

The applied biochar was based on forest wood and contained 84-88% carbon, 8-10% moisture, 5.8% of pH, 950-1 100 mg g^{-1} of iodine, 150-250 mg g^{-1} of methylene blue, and 4-8% of ash.

Five plants were randomly selected from each plot in order to measure the root traits. The roots were separated from the other vegetative parts of the plant, and then the washed roots were dried in an oven at 80°C for 48 h. The root volume (RV) was measured by placing the roots in graduated cylinders and determining the rate of change in the water level.

The CO_2 efflux emitted from the potting soil, is an indicator of the biological activity of the soil which was estimated according to the method described by Hopkins (2008). Plant sampling for the measurement of carbon mineralization was performed once during each growing season and after the final harvest (115 days after sowing date).

Table 1. Soil characteristics at 0-30 cm depth range

Soil parameter	EC ($dS\ m^{-1}$)	pH	Sand	Silt	Clay	Texture	TNV	OC	Total N	P	K
				(%)				(%)		($mg\ kg^{-1}$)	
2017	5.81	7.76	49	31	20	loam	11.75	0.97	0.092	17.72	488.1
2018	5.46	7.81	55	26	19	sandy-loam	12	0.91	0.080	22.02	818.4

EC – electrical conductivity, TNV – total neutralizing value, OC – organic carbon.

A small plastic cup which contained 20 grams soil from each treatment, one vial containing 10 mL of 2M NaOH and 10 mL of distilled water were added to the incubation jars with gastight lids (Mason Jar). The jars were then incubated in a dark room at 25°C for 10 days. The vials of NaOH were removed from the jars, 1 mL of NaOH (CO_2 was trapped in the NaOH during the incubation period) and titrated with 0.02N H_2SO_4 using a burette with 3 drops of phenolphthalein as a pH indicator after the addition of 200 µL of 1M $BaCl_2$ and 6.1 mL of 0.5M of HCl. The results are expressed in µmol C g^{-1} soil h^{-1}.

Plant shoots were harvested on two occasions. The first harvest (first cut) was performed when 10% of the plants in each plot entered into the flowering stage which was 70 days after the sowing date and the second harvest (second cut) was performed 45 days later. Plants of 2 m^2 for each plot were harvested from 5 cm above the soil surface. The harvested shoots were then dried in an oven at 80°C for 48 h.

RESULTS AND DISCUSSION

The results of the combined analysis showed that the effect of year, irrigation regime and biochar had a significant effect on root dry weight (RDW), root volume (RV), soil respiration (SR) and dry matter yield (DMY) (Table 2). The interaction effects of the irrigation regime, cropping pattern and biochar application on the RDW, RV and DMY at the first harvest were significant at a 1% probability level but had no significant effect on SR and DMY at the second harvest (Table 2). The mean comparison for the interaction effect of the irrigation regime × cropping pattern × biochar application on RDW showed that the highest RDW was observed for the I0P0B1, I0P1B2, I1P1B1, and I0P0B2 treatments (31.55, 30.74, 27.60, and 27.30 g $plant^{-1}$, respectively), and the lowest value was related to the I2P1B0 treatment (14.86 g $plant^{-1}$) (Fig. 1). For the two-row cropping pattern, plant competition decreased and this pattern provided more suitable space for root growth to absorb moisture and nutrients. In this study, it was found that biochar improved soil hydraulic and moisture properties and caused increasing root moisture uptake under water deficit conditions. Improved root growth facilitated the uptake of water and nutrients which are required by the plant. Biochar may facilitate root growth and increase crop growth and yield by reducing the soil density and increasing water availability (Obia *et al.,* 2016). Xiao *et al.* (2016) reported an increase in the root length of maize in the semi-arid region of Loess Plateau in China, due to biochar application. Biochar plays a role as a useful modifier to improve the physical and chemical properties of the soil, it is effective in maintaining soil organic matter, increasing fertilizer productivity and also increasing crop production, especially for long-term cultivated subtropical soils (Deenik *et al.,* 2010; Van Zwieten *et al.,* 2010).The mean comparison of the interaction effects of the irrigation regime × cropping pattern × biochar application on RV showed that the highest RV was observed in the I0P1B2, I1P0B2, I0P1B1, I0P0B1, I2P0B2, and I0P0B2 treatments (60.39, 60.00, 55.81, 54.42, 54.17, and 52.45 cm^3 $plant^{-1}$, respectively), and the lowest was related to the I0P1B0 and I0P0B0 treatments (28.39 and 33.17 cm^3 $plant^{-1}$, respectively) (Fig. 2). The water deficit, especially during the vegetative growth period, reduced root development and RV. Increasing RV indicates further root development which allows for improved water and nutrient absorption capacity from a larger volume of soil. Thus, it appears that biochar application and changing the cropping pattern have partially reduced the adverse effects of drought stress, improved water uptake and nutrients and thus improved root growth and volume. Abiven *et al.* (2015) showed that the maize root biomass in the plots treated by biochar were almost doubled. Amendola *et al.* (2017) stated that with biochar application to the soil, the root diameter (0.56 mm) was increased compared to the control (0.46 mm), which led to an increase in root biomass. The analysis of variance showed that the effect of the irrigation regime on SR was significant at a 5% probability level. A mean comparison showed that there were no significant differences between the irrigation treatments, although I1 was lower than I0 (0.165 and 0.168 µmol C g^{-1} soil h^{-1}, respectively) (Fig. 3). Soil moisture is one of the most important factors affecting the soil microbial population and respiration, also, other studies have shown that water in the soil increases soil microbial respiration and there is a significant positive correlation between soil moisture and soil respiration (Jiang *et al.,* 2013; Gong *et al.,* 2015). The mean comparison of SR showed that there was a significant difference between the biochar application (B1 and B2) and the control (B0) treatments, and also, the highest SR was observed for the B2 and B1 treatments (0.173 and 0.171 µmol C g^{-1} soil h^{-1}, respectively), and conversely,

Table 2. Analysis of variances of the effects of the experimental factors on root traits (DRW, RV), soil respiration (SR) and dry matter yield (DMY) of forage sorghum during 2017 and 2018

S.O. V	df	DRW (g plant^{-1})	RV (cm^3 plant^{-1})	SR (µ mol C g^{-1} soil h^{-1})	DMY (kg ha^{-1})	
					First harvest	Second harvest
Year	1	4394^{**}	76284^{**}	32×10^{-3}**	2.6×10^{7}**	1.14×10^{8}*
R (Year)	4	23.57	9.8	22×10^{-6}	8.37×10^{5}	3.69×10^{6}
Irrigation regiment (I)	2	120^{*}	277^{*}	12×10^{-5} *	2.68×10^{8}**	1.83×10^{8}**
I × Year	2	90.68^{*}	260^{*}	$40 \times 10^{-6\ ns}$	$2.19 \times 10^{6\ ns}$	3.92×10^{7}**
Error main plots	8	10.27	24.3	11×10^{-6}	5.58×10^{6}	2.37×10^{6}
Cropping pattern (P)	1	191^{*}	5.2^{ns}	$18 \times 10^{-6\ ns}$	2.64×10^{7}**	1.58×10^{7}*
P × Year	1	25.1^{ns}	227^{*}	$33 \times 10^{-7\ ns}$	4.26×10^{7}*	$3.13 \times 10^{6\ ns}$
P × I	2	38.1^{ns}	82.1^{ns}	$60 \times 10^{-6\ ns}$	$1.48 \times 10^{7\ ns}$	$1.61 \times 10^{7\ ns}$
P × I × Year	1	28.8^{ns}	6.2^{ns}	$84 \times 10^{-6\ ns}$	$2.38 \times 10^{6\ ns}$	$8.75 \times 10^{5\ ns}$
Error sub plots	12	11.44	22.3	14×10^{-6}	3.10×10^{6}	1.17 × 106
Biochar (B)	2	244^{**}	2141^{**}	20×10^{-5}**	1.61×10^{6} ns	3.09×10^{6}*
B × Year	2	200^{**}	477^{**}	99×10^{-6}*	2.74×10^{6} ns	1.33×10^{7}**
B × I	4	9.08^{ns}	481^{**}	$33 \times 10^{-6\ ns}$	1.11×10^{7}**	3.53×10^{6}**
B × I × Year	4	4.54^{ns}	976^{**}	$95 \times 10^{-7\ ns}$	1.56×10^{7}**	2.15×10^{6}**
B × P	2	79.8^{**}	223^{*}	$45 \times 10^{-6\ ns}$	3.14×10^{6} ns	$6.45 \times 10^{5\ ns}$
B × P × Year	2	36.1^{*}	226^{*}	$50 \times 10^{-6\ ns}$	2.55×10^{7}**	7.23×10^{6}**
B × P × I	4	94.4^{**}	307^{**}	24×10^{-6ns}	6.90×10^{6} *	$4.01 \times 10^{5\ ns}$
B × P × I × Year	4	72.7^{**}	329^{**}	$32 \times 10^{-6\ ns}$	5.90×10^{6} *	$9.50 \times 10^{5\ ns}$
Error	48	4.89	34.6	13×10^{-6}	1.22×10^{6}	4.10×10^{5}
CV (%)	-	8.96	12.51	2.08	9.01	12.17

Significant at: *$p \leq 0.05$, **$p \leq 0.01$, ns – non-significant.

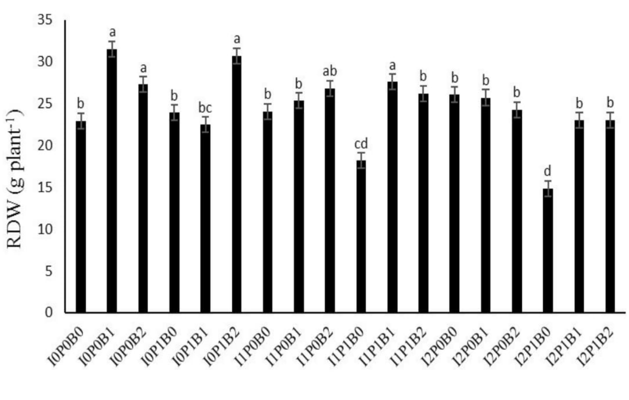

Fig. 1. Mean comparison of root dry weight (RDW) in cropping seasons of 2017 and 2018. I0 – every furrow irrigation (EFI), I1– fixed furrow irrigation (FFI), I2 – alternate furrow irrigation (AFI), P0 – one-row cropping pattern, P1 – two-rows cropping pattern; B0 – 0, B1 – 6, B2 – 12 t ha^{-1} of biochar. Columns with at least one common alphabet, according to the Tukey's HSD test, have no significant difference at the 5% level.

the lowest value was observed in the control treatment (0.168 µmol C g^{-1} soil h^{-1}) (Fig. 4). Microbial respiration is closely related to soil organic carbon. Increasing the levels of carbon in the soil provides nutrients for microorganisms, which increases their metabolism activity and also results in increased CO_2 emissions. The application of biochar in the soil increased the level of organic carbon, reduced soil density and increased maize yield which means that biochar, as a soil modifier, simultaneously increased the yield and reduced greenhouse gas emissions (Zhang *et al.,* 2012). The results of the study by Sagrilo *et al.* (2014) showed that with the use of biochar, the amount of carbon released into the soil was increased. In another experiment conducted by Liu *et al.* (2016), the results showed that the use of biochar did not affect soil respiration. It seems that biochar reduces greenhouse gas emissions, but due to the source of biomass and the biochar production process, it may have a different effect. As the results shown in Fig. 4 demonstrate, biochar had a positive effect on reducing CO_2 emissions. A mean comparison of the interaction effects of the irrigation regime × cropping pattern × biochar application

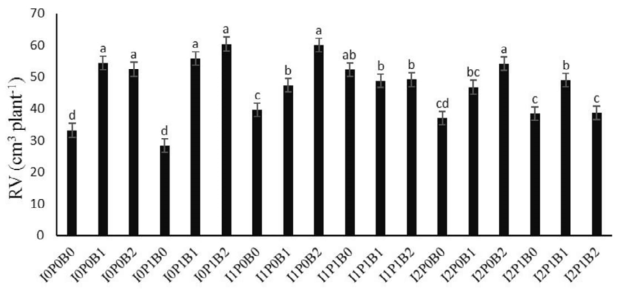

Fig. 2. Mean comparison of root volume (RV) in cropping seasons of 2017 and 2018. Explanation as in Fig. 1.

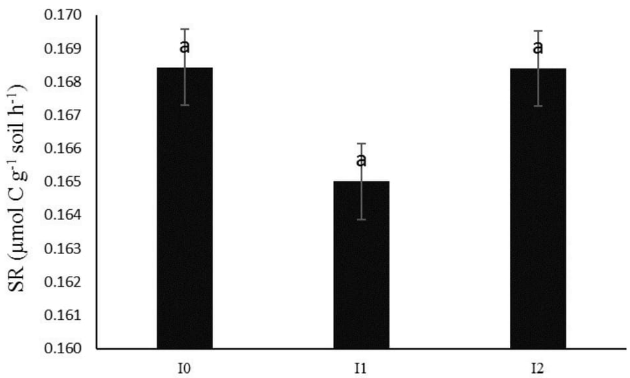

Fig. 3. Mean comparison of soil respiration (SR) [C mineralization rate] in cropping seasons of 2017 and 2018. I0 – every furrow irrigation (EFI), I1– fixed furrow irrigation (FFI), I2 – alternate furrow irrigation (AFI). Other explanations as in Fig. 1.

on DMY at the first harvest showed that the highest DMY were related to I0P1B0, I0P0B0, I0P1B2, and I0P0B2 treatments (16 550, 15 447, 15 148, and 14 842 kg ha^{-1}, respectively) and that the I0P1B1, I0P0B1, I1P0B2, I1P0B0 treatments had a lower intensity of dry forage yield loss (13 432, 13 395, 13 098, and 12 728 kg ha^{-1}, respectively) (Fig. 5). Biochar application reduces soil compaction and improves water retention at the wilting point and also increases water availability (Buss *et al*., 2012; Abel *et al.,* 2013). The main reason for the decreased DMY in crops under low irrigation conditions is the decrease in leaf area, which reduces the efficiency of the light received. Drought stress in wheat reduced chlorophyll content, leaf photosynthesis, spike fertility, seed number, and grain yield (Prasad *et al.*, 2011). The mean comparison of the irrigation regime for the second harvest showed that the highest DMY was related to I0 while the lowest were related to the I2 and I1 treatments (4765 and 3428 kg ha^{-1}, respectively) (Fig. 6). Low-irrigation appears to have a significantly adverse effect on sorghum DMY. Under soil water shortage conditions, the leaf water content is reduced, stomata are closed and gas exchange is limited, which reduces photosynthesis and yield (Mutava *et al.,* 2011). The mean comparisons showed

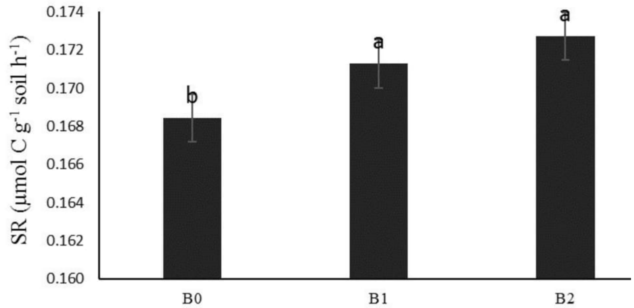

Fig. 4. Mean comparison of soil respiration (SR) [C mineralization rate] in cropping seasons of 2017 and 2018. B0 – 0, B1 – 6, B2 – 12 t ha^{-1} of biochar. Other explanations as in Fig. 1.

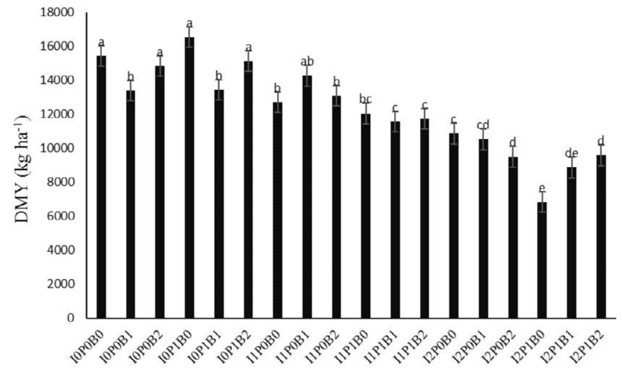

Fig. 5. Mean comparison of dry matter yield (DWY) in cropping seasons of 2017 and 2018. I0 – every furrow irrigation (EFI), I1– fixed furrow irrigation (FFI), I2 – alternate furrow irrigation (AFI), P0 – one-row cropping pattern, P1 – two-rows cropping pattern; B0 – 0, B1 – 6, B2 – 12 t ha^{-1} of biochar. Other explanations as in Fig. 1.

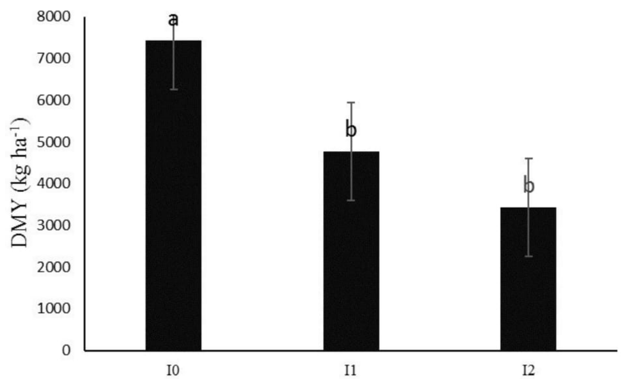

Fig. 6. Mean comparison of dry matter yield (DWY) in cropping seasons of 2017 and 2018. I0 – every furrow irrigation (EFI), I1– fixed furrow irrigation (FFI), I2 – alternate furrow irrigation (AFI). Other explanations as in Fig. 1.

that biochar application significantly improved the DMY and that the highest DMY was observed in the B2 treatment (7983 kg ha^{-1}) (Fig. 7). It seems that biochar increased DMY by providing water and nutrients to the crop. In

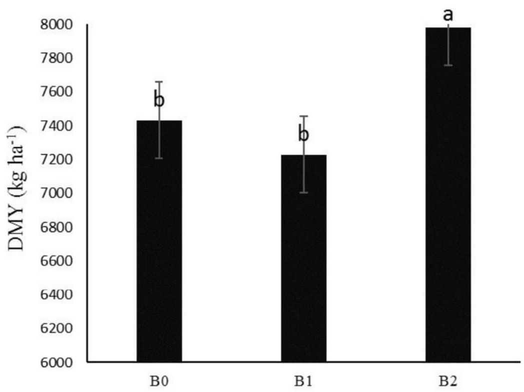

Fig. 7. Mean comparison of dry matter yield (DWY) in cropping seasons of 2017 and 2018. B0 – 0, B1 – 6, B2 – 12 t ha^{-1} of biochar. Other explanations as in Fig. 1.

most cases, biochar application improved the properties of the soil, although in some cases, its adverse effects were observed, which may be due to the insufficient application of biochar. The beneficial effects of biochar increase the availability of water (Cornelissen *et al.,* 2013; Moosavi *et al.,* 2020), thereby increasing soil moisture retention (Buss *et al.,* 2012) and improving soil chemical properties such as increasing the level of soil organic carbon, soil nitrogen and nutrient uptake (Ma *et al.,* 2016). There was no correlation between the root characteristics, SR and DMY (Table 3).

CONCLUSIONS

1.The results showed that the addition of biochar to the soil under furrow irrigation conditions and a two-row cropping pattern had a significant effect on the morphological traits of sorghum roots and increased root dry weight and root volume, but the dry matter yield declined slightly.

2. Among the interaction effects of the irrigation methods, the cropping pattern and biochar, the fixed furrow irrigation treatment with a constant two-row cropping pattern and biochar application compared to the control treatment had a better effect on these properties and reduced the limiting effects of low irrigation. Therefore, it may be stated that under fixed furrow irrigation conditions, constant stress and optimum moisture conditions existed on one side of the furrow, and the plant was able to adapt its root system better to the prevailing conditions.

3. Regarding the amount of biochar application, under the fixed furrow irrigation method and the two-row cropping pattern, biochar application could improve the root dry weight and root volume. Additionally, the application of biochar compared to non-biochar, increased soil respiration and carbon storage, while also enhancing soil quality and improving dry matter yield.

4. The results of this study showed that biochar, due to its high concentration of pores and high-water holding capacity, improved root growth under water stress conditions, and to some extent, prevented a decrease in dry matter yield.

Conflict of interest: The authors declare no conflict of interest.

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Table 3. Results of correlation constants between different cropping patterns of forage sorghum during 2017 and 2018

	RDW (g plant^{-1})	RV (cm^3 plant^{-1})	SR (μ mol C g^{-1} soil h^{-1})	DWY [harvest 1] (kg ha^{-1})
RV (cm^3 plant^{-1})	0.404^{ns}	1		
SR (μ mol C g^{-1} soil h^{-1})	0.200^{ns}	0.178^{ns}	1	
DWY [harvest 1] (kg ha^{-1})	0.482^{ns}	0.19^{ns}	-0.226^{ns}	1
DWY [harvest 2] (kg ha^{-1})	0.462^{ns}	0.092^{ns}	0.117^{ns}	0.805**

Significant at: *p ≤ 0.05, **p ≤ 0.01. RDW – root dry weight, RV – root volume, SR – soil respiration, DWY – dry weight yield; ns – non-significant.

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