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Role of Biochar in Managing The Irrigation Water Requirements of Maize Plants: The Pyramid Model Signifying the Soil Hydro-physical and Environmental Markers

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A FIELD experiment was conducted for two successive summer seasons of 2016 and 2017 to explore the effect of amending Moshtohor soil (*TypicTorriorthent* of 71.9% clay) with biochar at four different rates namely 0, 13, 26 and 39 Mg ha^{-1} on the outcome yield of maize grains grown thereon. The effect ofthis amendment was considered in relation with reduced irrigations, i.e. 60 and 80% vs. 100% water requirements (WR). The efficiency of the applied treatments were estimated using the pyramid model after considering (1) water use efficiency (WUE), (2) soil CO_2 emissions and (3) soil bulk density. Results revealed that increasing the rate of applied biochar resulted in significant improvements in both maize grain yield and soil physical characteristics. However, this amendment also increased the emission of soil CO_2. Decreasing the amount of irrigation water resulted in significant increases in water use efficiency while recorded no significant effect on the grain yield. Moreover, the reduced irrigation water requirements improved significantly soil physical properties (soil bulk density, soil aggregation, pF characteristic curves and soil hydraulic conductivity), while, at the same time, minimized the emissions of soil CO_2. Generally, the effect of biochar seemed to be more pronounced in the second growing season than in the first one. Although, the treatment of 26 Mg biochar ha^{-1} + 80% WR recorded the highest efficient indicator, yet the outcome yield was significantly lower than that occurred due to the application of 39 Mg biochar ha^{-1}+60 % WR. Moreover, the calculated efficiency indicators seemed to be comparable between these two treatments. Thus, it is recommended to use only 60% of WR on soils amended with 39 Mg biochar ha^{-1}. This treatment increased the grain yield by 1.96 fold higher than the control while saved 40% of the water requirements.

Keywords: Irrigation requirements, Managing irrigation water, Biochar, CO_2 emissions, Soil physical properties, The pyramid model

Introduction

The arable lands probably represent the largest stock of organic carbon in the terrestrial ecosystem (Singh et al., 2018). Although, organic amendments improve soil physical and chemical characteristics (Farid et al., 2014 & 2018) and consequently increase the outcome yield (Abbas et al., 2011).Yet, these amendments can also increase the emissions of the greenhouse gases (GHGs), *e.g.* CO_2 (Abdelhafez et al., 2018 and Liu et al., 2018) because of their high carbon availability to soil biota (de Souza et al., 2019). Thus, organic amendment can possess a global warming (Wu et al., 2018). On the other hand, biochar is a promising organic amendment, which is produced from the pyrolysis under limited oxygen conditions (Alghamdi, 2018). This amendment can shift soil biota towards low C turnover bacteria taxa (Zheng et al., 2018) thus, reduces the emissions of greenhouse gases GHGs (Awad et al., 2018). This might take place probably through decreasing the bioavailability of dissolved organic carbon (DOC) via sorption on biochar surfaces (Sheng and Zhu, 2018); and therefore, it persists in soils for long time periods (Singh et al., 2012, Fang et al., 2018 and Gabriel et al., 2018).

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Rice is One of the most important crops worldwide which represents the stable food for more than 50% of the world population (Van Nguyen et al., 2006). In Egypt, it is an important field crop (Elmoghazy and Elshenawy, 2018); however, the residual straw and husk signify a serious problem for the farmers (Ragab et al., 2018, Daiem et al., 2018 and El-Chaghaby et al., 2018). Around three teragrams of these residues remain unutilized annually in Egypt (Abdelhady et al., 2014). Moreover, the Egyptian farmers burn these residues in open fields (Hassan et al., 2014); thus, increasing the emissions of greenhouse gases (GHGs) (Sing et al., 2016). This might, in turn, increase the temperature (Gaihre et al., 2016). On the other hand, crop production is generally affected negatively by the corresponding increases in temperature (Mahmoud, 2017). Thus, managing rice residues is the key to minimize the emissions of GHGs (Boateng et al., 2017) probably through incorporation in the production of biochar (Wei et al., 2019).

In the clayey soil, the high content of clay particles probably affect soil characteristics directly and indirectly (Sarkar et al., 2018), causing soil compaction (Churchman, 2018) and probably arising many potential problems, *e.g.* low infiltration rates (Alaoui et al., 2018) beside of poor drainage and aeration conditions (Obia et al., 2018). To improve such characteristics, biochar application is recommended because of its low density, highly porous structure and grain sized distribution (Zhou et al., 2018). This amendment may rearrange the inter-aggregate pore spaces (Villagra-Mendoza and Horn, 2018) and consequently improve soil physical properties, *e.g.* soil bulk density (Obia et al., 2018) and the stability of soil aggregates (Li et al., 2018). Moreover, it minimizes the potentiality of clayey soils towards degradation with either wind or water erosion (Churchman, 2018).

Water scarcity has become one of the ambient factor affecting land sustainability, especially in the Mediterranean region (Yang & Zehnder, 2002 and Iglesias et al., 2007). Amending such arid soils with biochar can probably retain soil moisture (Fischer et al., 2019 and Günal et al., 2018); accordingly, biochar improves water use efficiencies (Fischer et al., 2019). Moreover, available soil moisture can determine the stabilization of SOM and its potentiality probably exceeds the effect of clay particles (Rasmussen et al., 2018). Under limited available moisture conditions, activities of soil biota seemed to be low (Walter, 2018). Accordingly, biochar persists in soils at relatively high concentrations (Singh et al., 2012) and this might improve soil physical characteristics. On the other hand, Abdelhafez et al. (2017) recorded a reversible equilibrium between the byproducts of the organic matter decomposers and the newly more stable buildup organic carbon components in soil. Such a mechanism might be more pronounced in the clayey soils rich in nutrients. It is then thought that adequate irrigations up to 100% water requirements (WR) might stimulate further microbial activities and this might in turn increase the buildup of organic carbon in the clayey soil (rich in nutrients), especially with the application of relatively high rates of biochar (Li et al., 2019). Moreover, these organic residues can probably represent the main factor improving soil physical characteristics. It is worthy to mention that, the microbial degradation of biochar accelerates under the Mediterranean climate conditions (de la Rosa et al., 2018). Probably, the rate of CO_2 emissions is highly dependent on soil moisture content (Hu et al., 2018). Thus, the global impacts of CO_2 emissions in addition to the water use efficiency for the grown plants should be considered in biochar related studies.

The current research aims at exploring the effect of amending a heavily clayey soil (71.9% clay) with biochar at four different rates namely 0, 13, 26 and 39 Mg ha^{-1} under reduced water requirements (WR), *i.e.* 60% and 80% of the full WR (100% WR) on the outcome yield of maize plants grown thereon. Soil bulk density, soil hydraulic conductivity, the characteristic pF curves and CO_2 emissions were also investigated during the two successive seasons of study. The net effectiveness of the applied treatments are then estimated using the pyramid model after considering soil hydro-physical and environmental indicators, *i.e.* (1) water use efficiency indicator (WUE), (2) the CO_2 emissions (CM) indicator and (3) the improvements in soil bulk density.

Materials and Methods

Site description

The current study was conducted in Moshtohor Village, Toukh, Qalubiya Governorate (31° 22”26” E and 30° 36”02” N), 20 meters above the sea level. The area of study is considered among the semi-arid regions. The average temperature in summer is 27.4°C and in winter is 12.9°C. The meteorological characteristics of the area of study are shown in Table 1.

Surface soil samples (0-30 cm) were collected from the investigated area prior to each growing season, air dried, cursed, sieved to pass through a 2mm sieve and then analyzed for their chemical and physical characteristics as outlined by Sparks et al. (1996) and Klute (1986). This soil is classified as *Typic Torriorthent*. Chemical and particle size distribution of the investigated soil are presented in Table 2.

Biochar preparation

Rice straw was collected from a farm at Moshtohor Village, air-dried, cut into small pieces (about 10 cm long) and then converted to

TABLE 1. Meteorological data of the investigated area

	Temperature (°C)		Relative humidity (%)		Rainfall (mm)		Wind speed (km h^{-1})	
	2016	2017	2016	2017	2016	2017	2016	2017
April	20.1	25.4	58.0	62.0	0.0	0.0	7.2	4.6
May	24.9	30.3	62.0	64.0	0.0	0.0	5.1	4.3
June	25. 8	29.7	65.0	71.0	0.0	0.0	4.1	4.8
July	28. 5	33.4	73.0	75.0	0.0	0.0	2.4	2.9
August	28.9	34.5	760	77.0	0.0	0.0	1.6	3.3
September	28.0	29.7	66.0	68.0	0.0	0.0	2.2	2.2
October	26.7	27.9	67.0	69.0	2.9	1.8	2.5	2.3
Mean	26.1	30.1	66.7	69.4	2.9	1.8	3.6	3.5

Source:Meteorological Station, Faculty of Agriculture, Moshtohor, Benha University.

TABLE 2. Chemical properties and particle size distribution of the (0-30 cm) layer of the studied soil

Parameter	pH	EC dSm^{-1}	SOC gkg^{-1}	CaCO3 gkg^{-1}	Particle size distribution, %			Texture (USDA)	Available nutrients, mg kg^{-1}		
					Sand	Silt	Clay		N	P	K
Season 2016	7.7	0.9	8.4	3.2	5.6	22.5	71.9	Clay	21.0	8.7	114.9
Season 2017	7.6	1.1	8.6	3.1					19.7	9.1	120.2

pH was determined in 1:2.5 soil:water suspension, EC was measured in the saturation paste extract.

TABLE 3. Main characteristics of the biochar under study

	pH	EC	Organic matter	Organic carbon	Total nutrients			Bulk density	Ash	C:N ratio
					N	P	K			
Parameter		dS m^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	Mg m^{-3}	%	
Value	7.83	2.52	453.1	202.36	11.0	7.8	21.9	0.345	45.32	18.40

Note: pH and EC were determined in biochar: water suspension (1:10).

biochar through low continuous pyrolysis process at 450 - 500 °C for 30 minutes according to Lu et al. (2014).Main properties of the produced biochar are given in Table 3.

The field study

A field experiment was conducted in Moshtohor Village for two successive summer seasons, *i.e.* 2016 and 2017. The experimental design was a split-plot one with three replicates. The main plot represents the irrigation treatments, *i.e.* irrigation with 5975 m^3 ha^{-1} (100% of the water requirements (WR), (2) irrigation with 4780 m^3 ha^{-1} (80% WR) and (3) irrigation with 3585 m^3 ha^{-1} (60% WR). The quantities of the irrigation water were estimated properly per plot through an accurate portable water pump connected to a meter of 0.1 liter sensitivity. The inlet of water was connected to portable irrigation pump through 4 inch hose ended with plunger (coated with a filter screen) and laid in the feeder canal, whereas the accurate assigned quantity of water per plot was delivered through another 2 inch hose laid out in each experimental unit.

The sub-plots represent biochar applications at 4 different rates i.e. zero, 13, 26 and 39 Mg biochar ha^{-1}. The experimental plot was 10.5m^2 (3 m long and 3.5 m width) with three replicates for each treatment. All plots were planted with maize (*Zea mays* L.cv. Hybrid 168) on July during the two summer seasons on ridges of 70 cm width and 25 cm distance between hills. All plots received the recommended doses of NPK fertilizers according to the Egyptian Ministry of Agriculture i.e. 286 kg N ha^{-1} as ammonium sulphate (20.6 % N), 31 kg P ha^{-1} as calcium super phosphate (6.6% P) and 47kg K ha^{-1} as potassium sulfate (40% K).Twenty days after planting, maize plants were thinned to one plant per hill (57, 360 plants ha^{-1}). The common agricultural practices were followed as recommended according to the local conditions. Plants were harvested on October afterwards maize seed yield was estimated.

Grain yield and water use efficiency were calculated using the following equations:

Grain yield (Mg ha^{-1}) = Weight of grains/ear × No. ear/plant ×No. of plants/ ha Eq. 1

Water use efficiency was calculated according to McClymont et al. (2019) as follows:

Water use efficiency (Mg/ m^3) = Grain yield / Seasonal consumptive use Eq. 2

Soil sampling and analysis

Soil bulk density (BD) was determined on undisturbed soil samples using a steel ring of 100 cm^3. The contents of soil water retained at 0.01,0.1, 0.33 bar (field capacity), 0.66, 1 and 15 bar(wilting point) were determined on undisturbed soil samples using pressure plate. Available water capacity (AWC) was then calculated as the difference between water retained at 0.33 and 15 bars. The soil cores were sampled by the cylinders to measure the saturated hydraulic conductivity (Ks) in the laboratory using the constant-head method according to Klute (1986). Water- stable aggregates were assessed by a wet-sieving method (Cambardella and Elliott, 1994). The classes of water- stable aggregates were classified into large macro-aggregates (>2 mm φ), macro-aggregates (2 - 1 mm φ), small macro-aggregates (1- 0.25 mm φ) and micro-aggregates (< 0.25 mm φ) expressed as g 100 g^{-1} of dry soil according to Wormann and Shapiro (2008).

The emissions of CO_2 were estimated according to Antoun and Jensen (1979) as follows: soil portions equivalent to 20 grams (60% water holding capacity) were placed in a hollowed glass stopper fitting into a 500 mL Erlenmeyer flask and then kept by a loose filling of glass-wool where 25 mL of 0.05 *N* Ba $(OH)_2$ solution were placed in the flask before replacement of the stopper. The flasks were incubated at 30°C for 24 hr and then titrated against 0.05 *N* HCl. Analysis for C and N took place by gas chromatography on a Hewlett – Packard 185 according to Goh and Stevenson (1971).

Data analysis

The obtained data were statistically analyzed using PASW Statistics software through the analysis of variance (ANOVA) and Dunken Test at 0.05 probability level. The soil organic carbon (SOC) stocks were calculated according to Yigini and Panago (2016) as follows:

SOC stock = (SOC × Bs x d) Eq. 3

where SOC_{stock} represents soil organic carbon stock in Mg ha^{-1}, *SOC* is the percentage of soil organic carbon (%), *Bs* is soil bulk density ($Mg \cdot m^{-3}$) and *d* is the depth of soil sampling, *i.e.* 30 cm.

The efficiency factor is also considered in this study using the pyramid model after considering soil hydro-physical and environmental indicators as follows

Efficiency indicators= $f_{WUE} \div (f_{Bs} \times f_{CE})$ Eq. 4

f_{WUE} : water use efficiency indicator (the higher… the better), f_{Bs} : the improvements in soil bulk density (the lower ….the better), f_{CE}: the emissions of CO_2 (the lower…. the better). This model assumes that: (1) the impacts of different indicators are equal in estimating the efficiency factor, (2) these indicators are calculated by dividing the outcome values recorded for each treatment by the control one, (3) plants and soil that did not receive biochar and irrigated with 100% WR are assumed to be the control ones.

Results

Maize grain yield as affected by the application rate of biochar and the level of irrigation water

Analysis of variance reveals that maize grain yield improved significantly with increasing the rate of applied biochar (F= 52.937, $P<0.001$). Such increases were 1.37, 1.71 and 1.96 folds higher than the corresponding maize grain yield recorded for the non-amended control treatment owing to the application of biochar at rates of 13, 26 and 39 Mg ha^{-1}, respectively (Fig 1). Moreover, the maize seed yield obtained from the second growing season was significantly higher than that obtained from the first growing one (F= 10.742, $P=0.002$). On the other hand, the effect of irrigation level seemed to be insignificant on maize seed yield (F=2.192, $P=0.123$). Interactions between these factors seemed to be insignificant (F=0003 for season ×IR, F=0.038 for biochar ×season, F=0.423 for biochar ×IR).

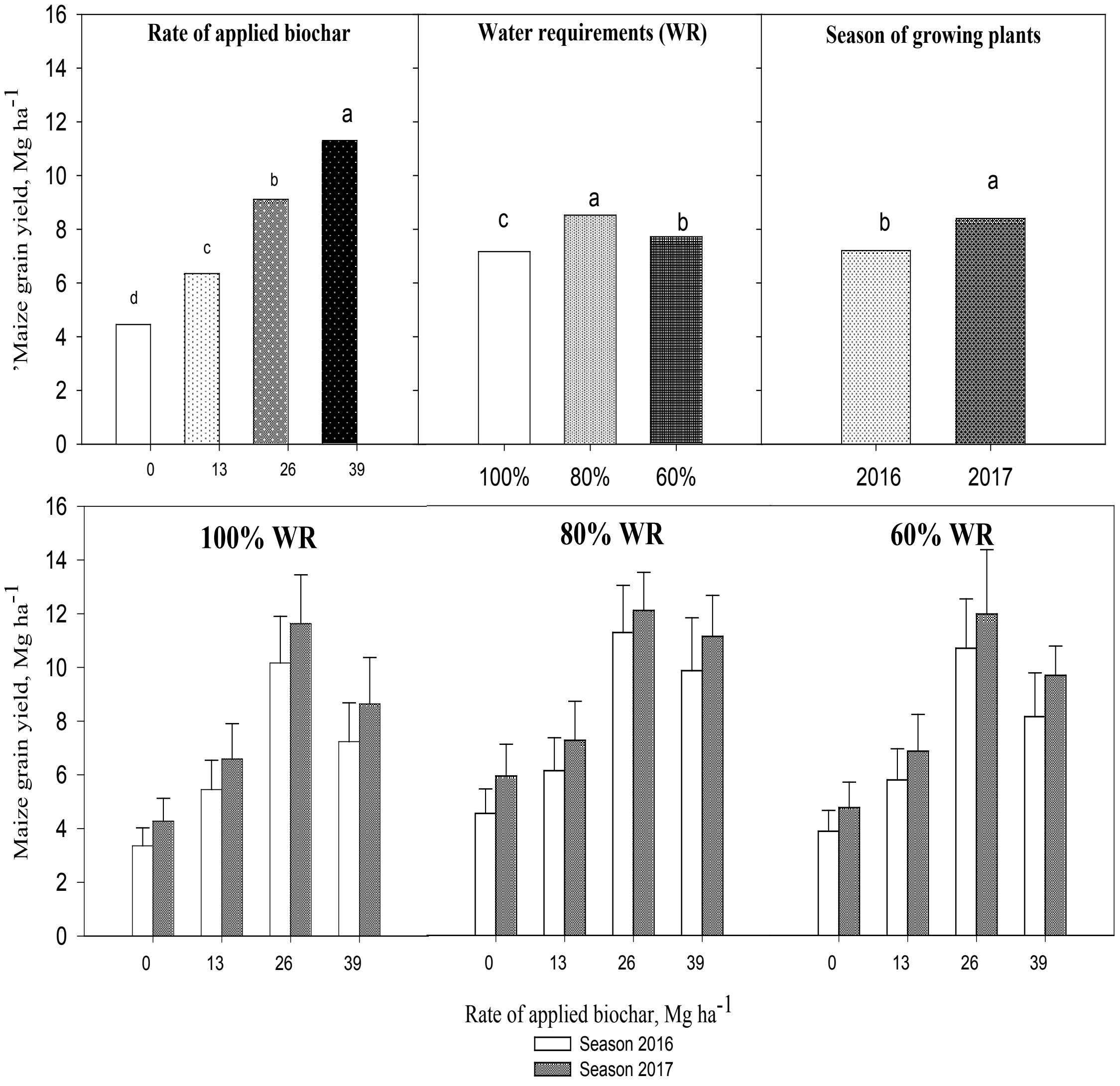

Fig. 1. Maize grain yield as affected by both the rate of applied biochar and the amount of irrigation water

Water Use efficiency as affected by the application rate of biochar and the level of irrigation water

Figure 2 confirms that amending the investigated soil with biochar improved significantly the water use efficiency of the grown plants (F= 53586, *P*<0.001). Such results seemed to be more significant with decreasing the level of irrigation water (F= 50.973, *P*<0.001). Moreover, values of WUE were more significantly higher in the second growing season than in the first one (F= 10.219, *P*=0.002). The interaction between these two factors were insignificant (F=0.183 for season ×IR, F=0.042 for biochar ×season, F=1.702 for biochar ×IR).

Impacts of biochar application rate and the irrigation level on soil physical characteristics

Bulk density as affected by the application rate of biochar and the level of irrigation water

Soil bulk density decreased significantly, at the end of each growing season, with increasing the rate of applied biochar (F =35.978, *P*<0.001). Likewise, soil bulk density decreased significantly with decreasing the amount of the applied irrigation water (F= 5.395, *P*=0.008). In this concern, decreasing WR from 100% to 80% resulted in insignificant reductions in soil bulk density; however, the corresponding variations attained due to the reduction in WR from 100% to 60% seemed to be significant (Fig. 3). On the other hand, the soil bulk density did not vary significantly with increasing the level of irrigation water during the two investigated seasons, *i.e.* F =2.054, *P*= 0.158).

Soil hydraulic conductivity as affected by the application rate of biochar and the level of irrigation water

The analysis of variance revealed that the value of soil hydraulic conductivity increased significantly with increasing the rate of applied biochar (F=38.901, *P*<0.001). The increases were 2.11, 4.31 and 512 folds (as compared to the control treatment) due to the application of biochar at rates of 13, 26 and 39 Mg ha^{-1}, respectively (Fig 4). Likewise, increasing the irrigation level increased significantly values of soil hydraulic conductivity (F=8.482, *P*=0001). Such increases seemed to be more significant and more pronounced in the second season than in the first growing one (F=5.448, *P*=0.024). On the other hand, interactions between these factors seemed to be insignificant (F=1.168 for season ×IR, F=0.931 for biochar ×season, F=0.523 for biochar ×IR)

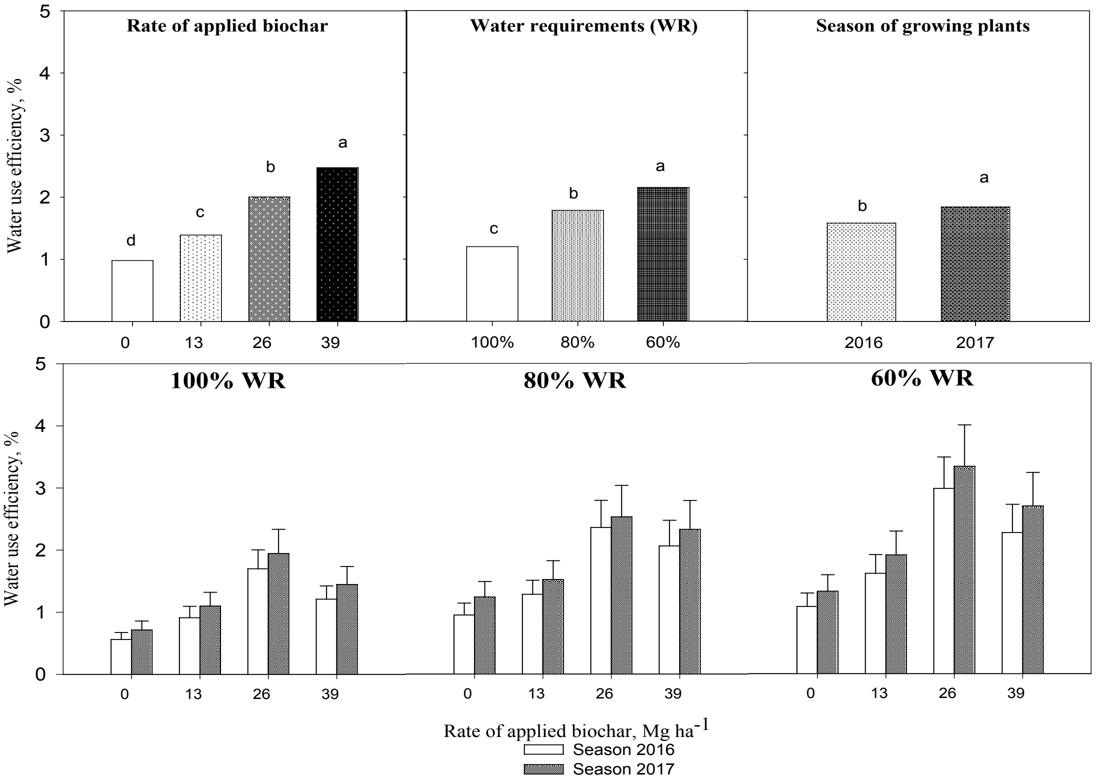

Fig. 2. Water use efficiency as affected by both the rate of applied biochar and the amount of irrigation water

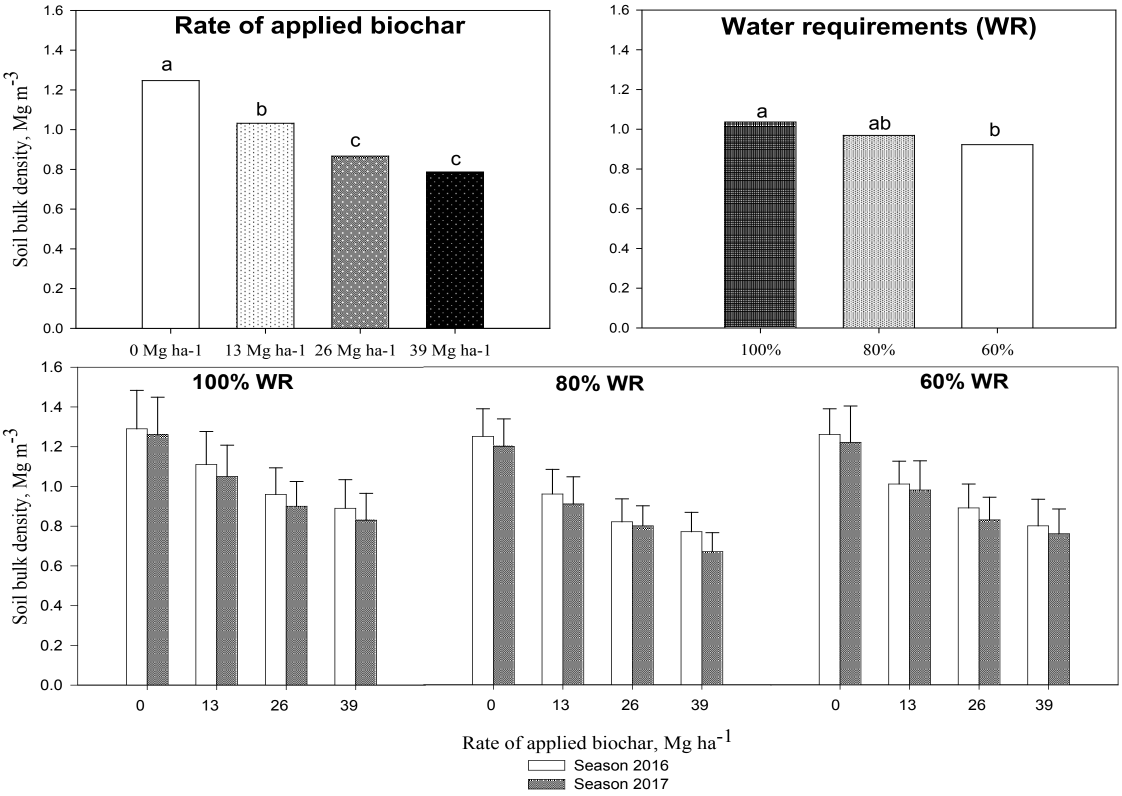

Fig. 3. Soil bulk density as affected by both the rate of applied biochar and the amount of irrigation water

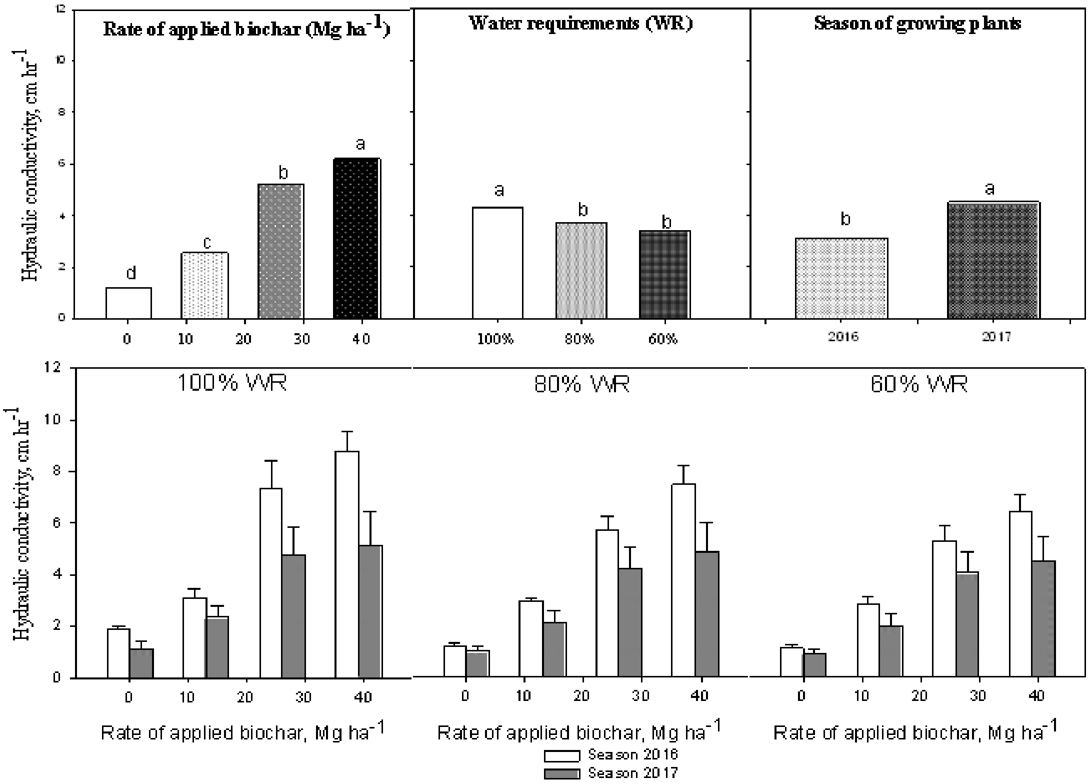

Fig. 4. Soil hydraulic conductivity as affected by both the rate of applied biochar and the amount of irrigation water

Soil aggregation as affected by the application rate of biochar and the level of irrigation water

Analysis of variance revealed that the different aggregate size classes were affected significantly by both the rate of applied biochar (F= 162.968, *P*<0.001 for micro-aggregates, F= 61.580, *P*<0.001 for small macro-aggregates, F=16.048, *P*=0.021 for macro-aggregates, F= 4.324, *P*=0.010 for large macro-aggregates), and the season of growing plants. It seems that the micro-aggregate classes decreased; however, insignificantly, with increasing the rate of applied biochar during both seasons of growth (Fig. 5). In case of the small macro-aggregates, these aggregates decreased significantly with the application of the highest rate of applied biochar, *i.e.* 39 Mg ha^{-1}. On the other hand, biochar applications improved significantly soil aggregation within the macro- and large macro- aggregate size classes especially with increasing the rate of applied biochar. Soil aggregation that occurred in the second growing season was significantly higher than that occurred in the first growing one (F= 52.287, *P*<0.001 for micro-aggregates, F= 13.481, *P*=0.001 for small macro-aggregates, F=5.741, *P*=0.021 for macro-aggregates, F= 11.182, *P*=0.002 for large macro-aggregates). The level of water irrigation did not affect significantly soil aggregation (F= 2.804, *P*=0.071 for micro-aggregates, F= 3.119, *P*=0.053 for small macro-aggregates, F=1.342, *P*=0.271 for macro-aggregates, F= 0.094, *P*=0.901 for large macro-aggregates). Likewise, the interactions between these three variables were of insignificant effect on soil aggregation.

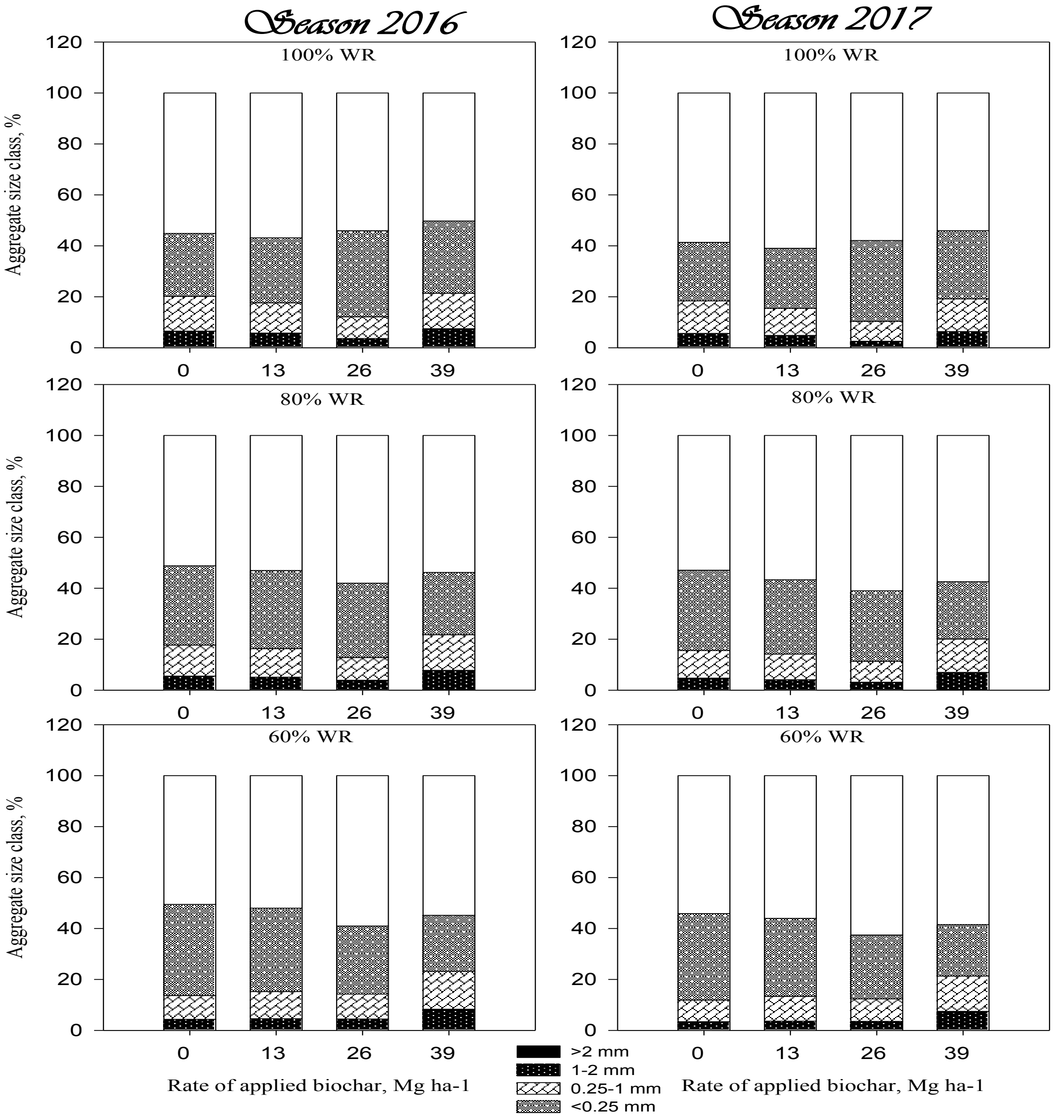

Fig. 5. Aggregate size classes as affected by both the rate of applied biochar and the amount of irrigation water

Soil-water potential as affected by the application rate of biochar and the level of irrigation water

Figure 6 reveals that the pF curves characterizing soil-water potential in the investigated heavy textured soil improved significantly with biochar application (soil retained higher moisture content), especially at its highest rate, *i.e.* 39 Mg biochar ha^{-1}. Apparently, decreasing the irrigation WR from 100 to 80% seemed to have no pronounced effect on the pF curves of the soil; however, further reductions in the irrigation level resulted in noticeable decline in the characteristic pF curve during both seasons of study.

SOC stock as affected by the application rate of biochar and the level of irrigation water

Analysis of variance reveals that SOC stock was affected significantly by the rate of applied biochar (F =74.605, P<0.001) and the level of the applied irrigation water (F =6.294, P= 0.004); however, the interaction between these two factors seemed to be insignificant (F =0.678, P= 0.668). It seems that SOC stock increased significantly in soils with increasing the rate of the applied biochar (Fig. 7). Decreasing the irrigation amount from 100% WR to 80% WR recorded significant reductions in SOC stock. On the other hand, irrigation with 60% WR recorded no significant variations in SOC stock as compared to those received either 100% WR or 80% WR. It is worthy to mention that SOC stock in soil did not vary significantly between the two studied growth seasons (F =0.691, P= 0.410).

Emissions of CO2 as affected by the application rate of biochar and the level of irrigation water

Figure 8 reveals that significant soil emissions of CO_2 increased with increasing rate of the applied biochar (F=35.304, P<0.001). Likewise, soil emissions of CO_2 increased significantly with increasing the level of water irrigation (F=10.436, P<0.001), *i.e.* the increases followed the descending order: 100% WR> 80% WR> 60% WR (Fig. 8). Generally, the emissions of CO_2 occurred in the second growing season were significantly higher than those occurred in the first growing one (F=7.772, P=0.008).

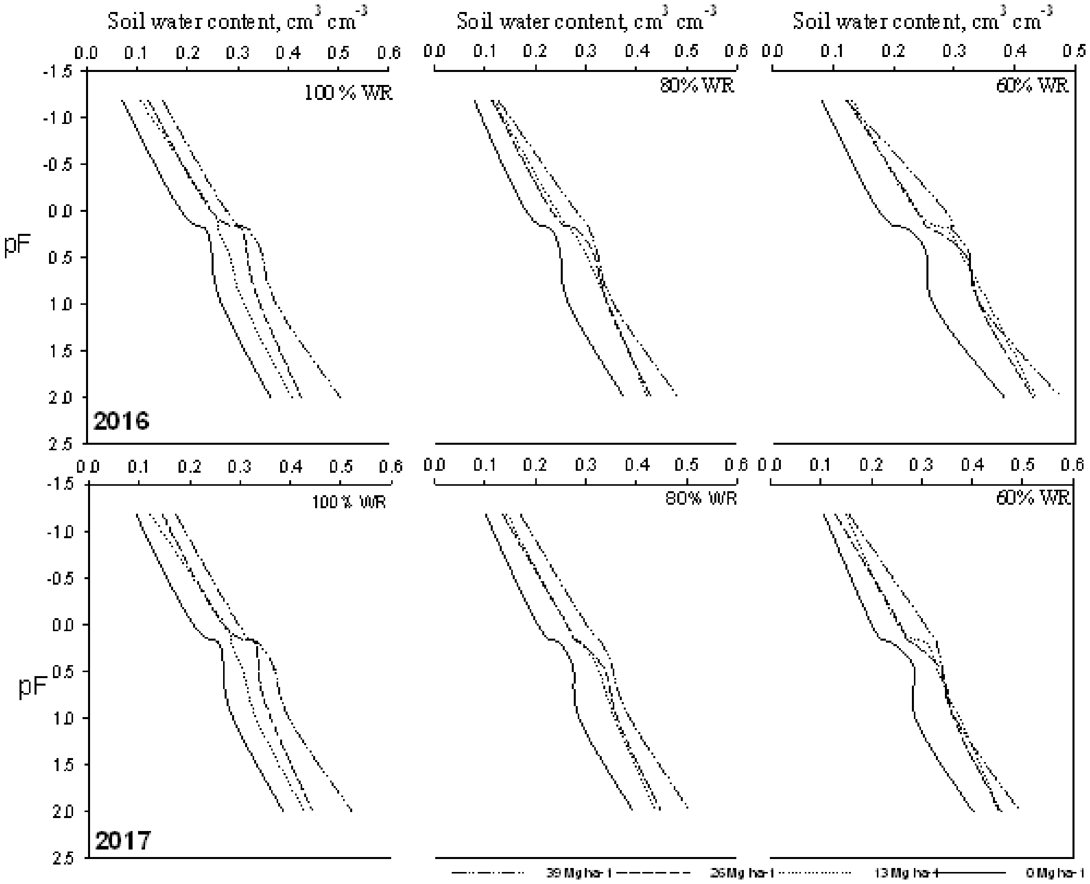

Fig. 6. Soil moisture characteristic curves as affected by both the rate of applied biochar and the amount of irrigation water

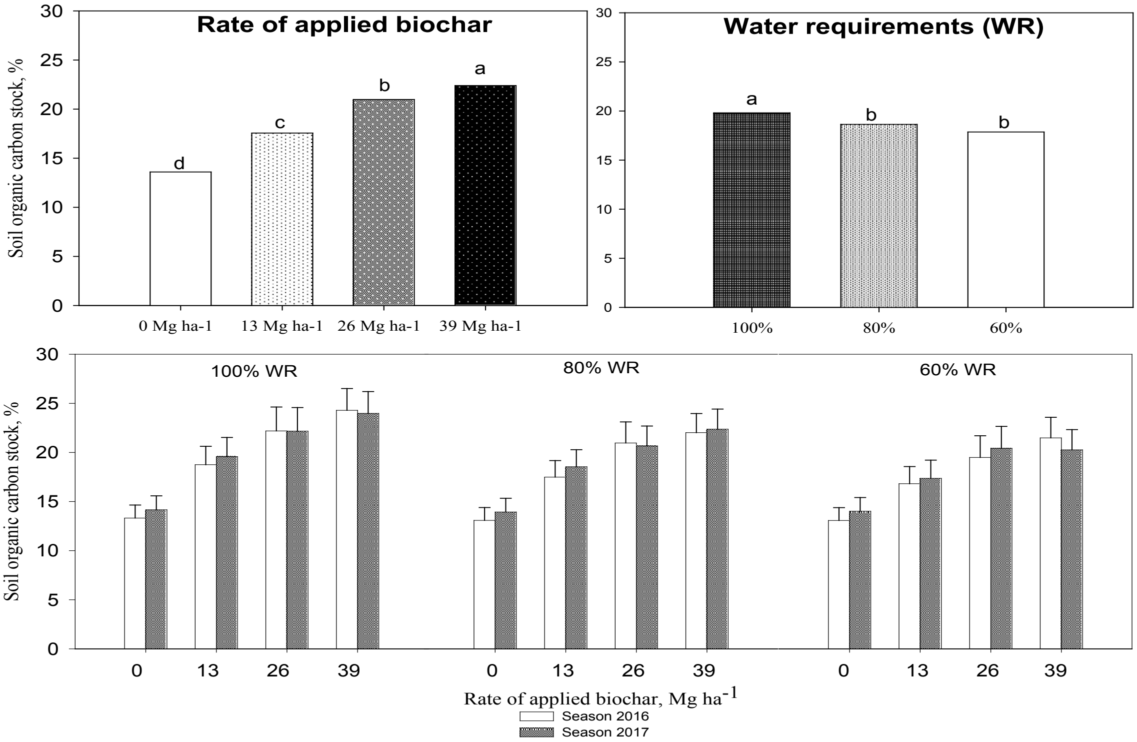

Fig. 7. Soil organic carbon (SOCs) stock as affected by both the rate of applied biochar and the amount of irrigation water

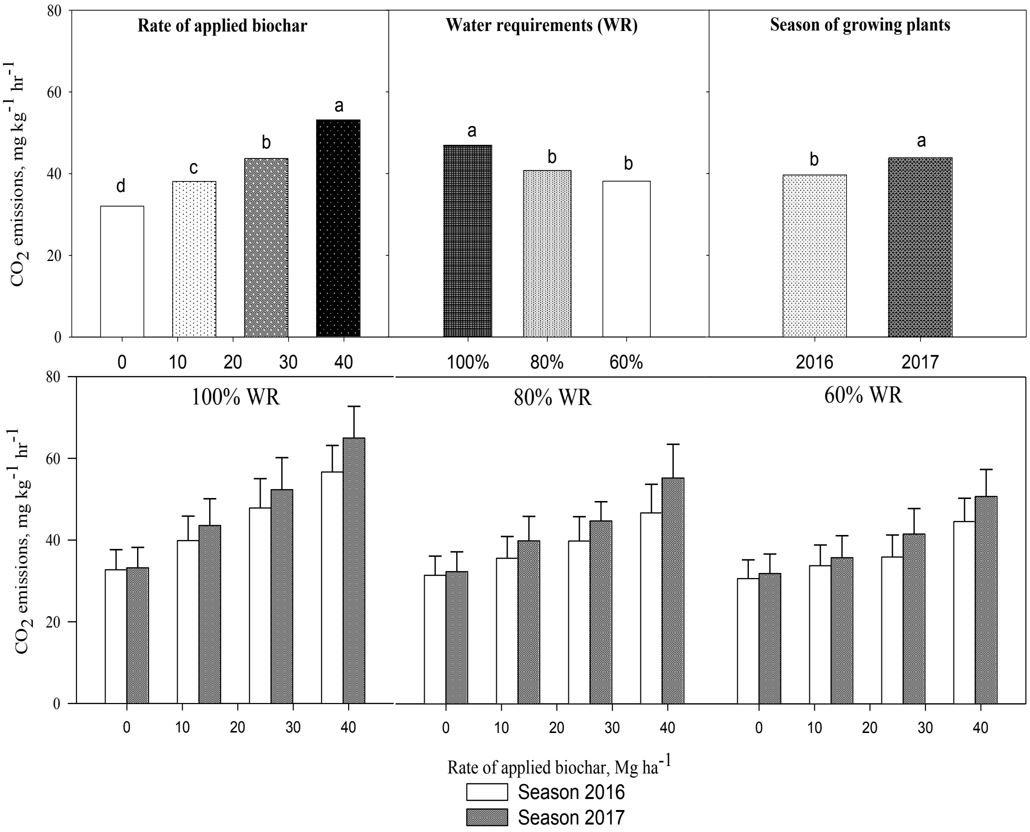

Fig. 8. Carbon dioxide emissions (mg kg^{-1} h^{-1}) as affected by both the rate of applied biochar and the amount of irrigation water

The net effect of applied biochar under the applied reduced irrigations on soil productivity, soil sustainability and its environmental impacts

The efficiency index was calculated to evaluate the competence of the investigated treatments on increasing soil productivity while maximizing the usage of the available resources and, at the same time, maintaining the environment (Fig. 9). In this concern, amending the clayey soil with biochar at a rate of 26 Mg ha^{-1} recorded the highest efficiency index especially under 60% WR. This efficiency seemed also to be somehow comparable to the corresponding one obtained due to the application of 39 Mg biochar ha^{-1} under 60% WR. On the other hand, the efficiency of the applied biochar did not vary widely with increasing the rate of applied biochar under 100% WR

Discussion

Effect of biochar on soil physical characteristics and plant grown thereon.

Application of biochar to the clayey soil increased significantly soil aggregation especially within the large macro- and macro- aggregates. Probably, the energy and nutrients released upon decomposition of the applied organic matter stimulated the activities of soil biota (Lehmann and Kleber, 2015; Kleber et al., 2015). These microbes initiated the formation of organo–mineral complexes in soil (Lal, 2016 and Sarkar et al., 2018) to be used as micro-habitat (Totsche et al., 2018). Microbes can store organic C within the macro- aggregates (Wang et al., 2017); thus, promote the formation of soil aggregates (Pronk et al., 2017 and Sarkar et al., 2018).

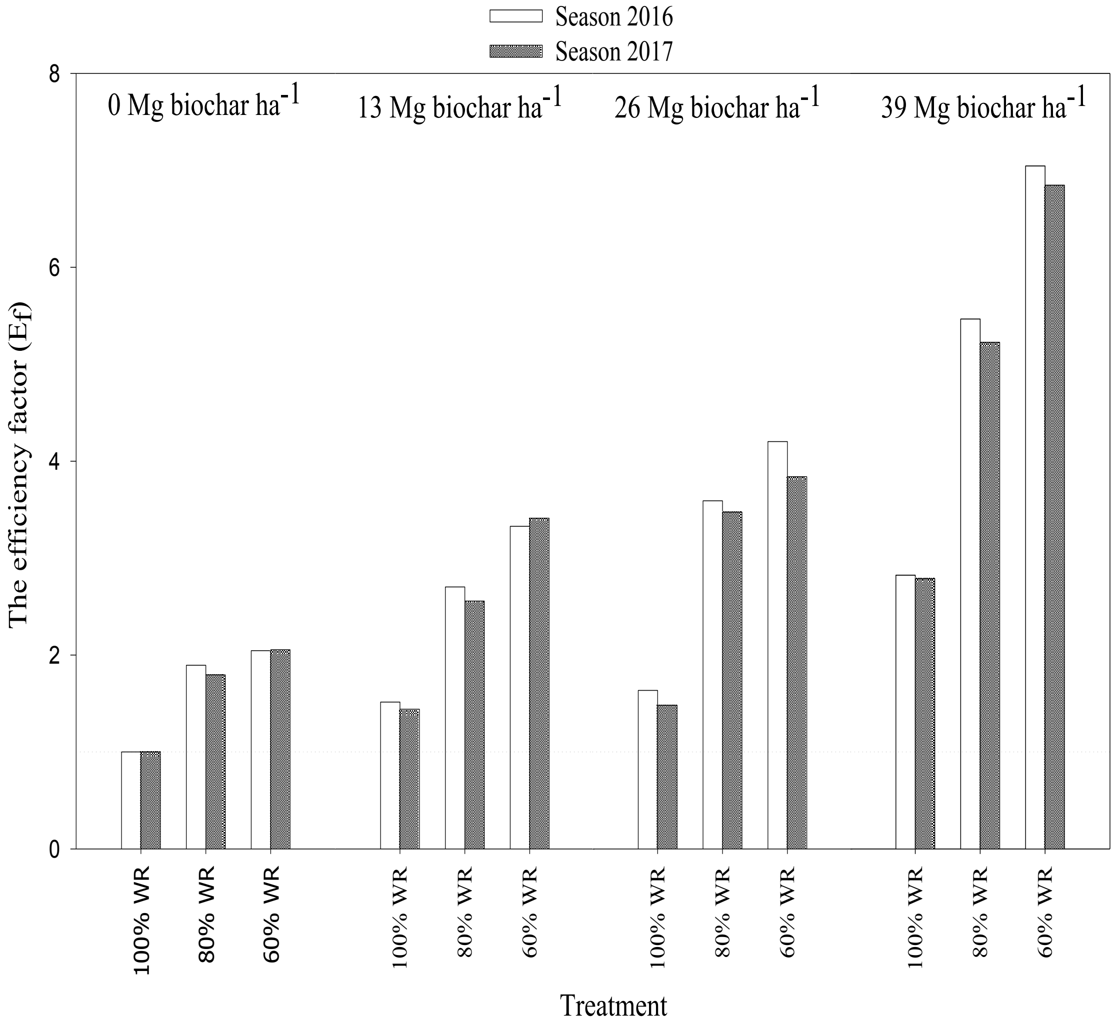

Fig. 9. The efficiency indexes (Ei) of the investigated treatments as affected by both the rate of applied biochar and the amount of irrigation water

Biochar also increased significantly soil-water retention. Such improvements were illustrated by the characteristic pF curves. Likewise, biochar increased soil hydraulic conductivity. Probably, clay particles seem to be more effective in formation of the different aggregate fractions than the organic carbon did (Vaezi et al., 2018); however, biochar can, on the other hand, increase the repulsive forces among the clay particles charged with the same type of charge leading to reduce soil compaction (Pilluello et al., 2018) Moreover, results obtained herein indicate that biochar is incorporated in formation of large macro- and macro- aggregates. Thus, biochar altered water infiltration (Blanco-Canqui, 2017) and consequently improved the hydraulic conductivity of the compacted clayey soil, and such increases were positively correlated with the percentage of applied biochar (Wong et al., 2018). Similar results indicated that amending soils with biochar enhanced soil biochemical, physical and hydraulic characteristics (Villagra-Mendoza and Horn, 2018 and Li et al., 2019). Integration among these factors lead to increase the water use efficiency and consequently increased production of maize seed, especially upon increasing the rate of the applied biochar, *i.e.* 39 Mg ha^{-1} vs 0 Mg ha^{-1}. On the other hand, the emissions of GHGs can represent one of the negative impacts for using such an amendment. In this concern, the emissions of CO_2 increased significantly from the soil amended with biochar especially at its highest application rate. In spite of the results which indicates that the GHGs emissions decrease in alkaline soils (Wu et al., 2018); however, the rates obtained herein presented relatively high values especially with increasing the level of irrigation water, *i.e.* 100% WR vs 60% WR. The recorded rates of carbon dioxide emissions were even higher than the corresponding ones recorded by Farid et al. (2014), *i.e.* ≈25 mg CO2 kg^{-1} h^{-1} for the application of either farmyard manure or compost at a rate of 48 Mg ha^{-1}. Accordingly, we can not support partially the findings which indicate that biochar improves C-sequestration in soil for long time periods (Singh et al., 2012) and hence decreases the GHG emissions while improving soil characteristics (Sarkar et al., 2018). Generally, the residual improvements of biochar on soil physical characteristics and the outcome yield seemed to be significantly higher in the second growing season as compared to the first growing one.

Effect of the irrigation level on soil physical characteristics and plant grown thereon

Decreasing soil moisture from 100% WR to 60% WR did not affect significantly maize grain yield. Biochar application probably minimized the negative impacts of reduced irrigations on the outcome seed yield through enhancing water holding capacity. On the other hand, reduced irrigations seemed to be an effective technique for improving the WUE.

Although, increasing the irrigation level up to 100% WR increased the emissions of CO_2 from the investigated soil as compared to the one received only 60% WR or even 80% WR; however, SOC_{stock} remained relatively higher in soils irrigated with 100% WR while decreased significantly under the reduced irrigation 80% WR. This might take place because the activities of soil biota seemed to be higher with increasing soil moisture. These microbes accelerated carbon utilization from soils (Keiluweit et al., 2015). However, high microbial populations probably utilized the intermediate byproducts of the biodegradation process and therefore retained relatively higher concentrations of SOC stock in soil. It is thought that stimulating soil microbes can increase their access to the formerly mineral-protected C-compounds (Keiluweit et al., 2015). Accordingly, the released byproducts seemed to be more incorporated in formation of soil aggregates and therefore improved significantly the physical properties of the reclaimed clayey soil. Thus, soil bulk density decreased significantly with decreasing the amount of irrigation water from 100% WR to 80% WR.

The efficiency indicator of applied biochar under reduced irrigations on maize seed production

Although, increasing the rate of applied biochar recorded significant increases in maize seed yield under reduced irrigations; yet, managing the natural resources should also be considered while evaluating the suitability of the investigated treatments to guarantee further sustainability for the available natural resources. To achieve this goal, soil hydro-physical characteristics as well as CO_2 emissions were estimated and the efficiency indicator was then calculated for the studied treatment. It seems that amending soils with biochar at its highest rate increased positively maize seed yield and at the same time saved the available water resources in the following order: 60% WR>80% WR>100%

WR. Moreover, the increases in maize seed yield owing to the application of 39 Mg biochar ha^{-1} under 80% WR seemed to be comparable to the application of the same rate under 60% WR i.e. 1.7 and 1.8 folds, respectively (compared to the reference treatment). Thus, it is recommended to amend the arable lands with 39 Mg biochar ha^{-1} to maximize grain yield under irrigation with only 60% of the water requirements. Although, the treatment 26 Mg biochar ha^{-1} + 80% WR recorded the highest efficiency indicator, ,yet the outcome yield was significantly lower than that occurred due to the application of 36 biochar Mg ha^{-1} under reduced irrigations (60 and 80% WR).

Conclusion

Amending soil with biochar at a rate of 39 Mg ha^{-1} increased significantly maize grain yield and could save up to 40% of the irrigation water requirements. Moreover, reduced irrigations guaranteed further improvements in soil physical characteristics while lowering the emissions of soil CO_2. This study supported the hypothesis indicating that adequate irrigations up to 100% WRE stimulated the activities of soil biota and this probably resulted in the buildup of organic carbon in the clayey soil; however, these results did not support the second hypothesis indicating that the buildup of organic carbon is the main factor responsible for improving soil physical characteristics.

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دور البيوشار في ادارة الاحتياجات المائية لمحصول الذرة النامي: النموذج الهرمي لتقييم خواص التربة الهيدرو-فيزيائية، والمؤشرات البيئية

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تم اجراء تجربة حقلية لموسمين صيفيين متتالين (٢٠١٦، و٢٠١٧) لدراسة جدوى استخدام البيوشار باربعة معدلات (صفر، ١٣، ٢٦، و٣٩ميجاجرام للهكتار)على زيادة محصول حبوب الذرة الشامية المتحصل عليه من أرض طينية (٧١,٩٪ طين)، وذلك تحت مستويات مختلفة من الاحتياجات المائية وهي ١٠٠٪، ٨٠٪، و٦٠٪، وتقييم كفاءة هذه المعاملات وفقا للنموذج الهرمي الذي يضع في اعتباره ما يلي: (١) كفاءة استخدام المياه، (٢) ثان اكسيد الكربون المتصاعد من التربة، و(٣) التحسن الناتج في كثافة التربة الظاهرية، وقد اظهرت النتائج أن زيادة معدل إضافة البيوشار قد انعكس ايجابيا على محصول الحبوب الناتج، كما تحسنت بعض الخواص الطبيعية للارض، ولكن يظل انبعاث ثأن اكسيد الكربون هو التحدي الذي يواجه الاستخدام المكثف للبيوشار في الاراضي، أما بخصوص تأثير الاحتياجات المائية، فقد اظهرت النتائج أنه بخفض مستوى الاحتياجات المائية، نتج عنه انخفاض ملحوظ في مقدار انبعاثات ثاني اكسيد الكربون الناتجة، كما انعكست هذه الانخفاضات في الاحتياجات المائية على زيادة كفاءة استخدام النباتات للمياه، و تحسنت الخواص الطبيعية للتربة المسمدة بالبيوشار بصورة كبيرة ، وظهرت تأثير هذه المعاملات بوضوح في الموسم الثاني مقارنة بالموسم الاول، وبعد اجراء تقييم للمعاملات باستخدام النموذج الهرمي، اوضحت النتائج أن المعاملة ٢٦ميجاجرام بيوشار/هكتار+٨٠٪ احتياجات مائية قد سجلت اعلى كفاءة مقارنة بباقي المعاملات، وعلى الرغم من ذلك، كانت المعامله ٣٩ميجاجرام بيوشار/هكتار+٦٠٪ احتياجات مائية متقاربة منها في نتائج الكفاءة المتحصل عليها، أما بخصوص محصول الحبوب الناتج، فكانت المعاملة ٣٩ميجاجرام بيوشار/هكتار+٦٠٪ احتياجات مائية هي الاكفأ، والتي سجلت زيادة كبيرة في محصول الحبوب مقارنة بالمعاملة ٢٦ميجاجرام بيوشار/هكتار+٨٠٪ احتياجات مائية، وبالتالي توصي الدراسة باستخدام ٣٩ميجاجرام بيوشار/هكتار، والتي يمكن أن توفر في الاحتياجات المائية بمقدار ٤٠٪، علاوة على قدرتها على.زيادة المحصول بمقدار ١,٩٦مرة.