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ORIGINAL PAPER

Co-composted Poultry Litter Biochar Enhanced Soil Quality and Eggplant Productivity Under Different Irrigation Regimes

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Abstract
The use of biochar has mostly moderate-positive to negative yield effects. However, integrating biochar with compost considerably enhanced biochar's positive effects on crops. This study aimed to investigate the potential effects of co-composted poultry litter biochar incorporation under deficit irrigation on eggplant's growth and productivity grown in salt-affected soil. Summer and fall season field experiments were conducted during 2016/2017. Three levels of co-composted biochar (CB) (0, 5, and 10 t ha^{-1}) were used as a soil amendment combined with three irrigation levels (100, 80, and 60% of ETc). CB ameliorated the negative effects of water stress on eggplants, showing increased yield and irrigation water use efficiency (IWUE). This mainly due to the positive effect of CB on soil properties (i.e., bulk density, hydraulic conductivity, electrical conductivity, pH, useful pores%, water-holding pores%, available water, fine capillary pores%, and soil biota). The results showed that CB increased stomatal conductance, relative chlorophyll content (SPAD), and the photosynthetic efficiency of water-stressed eggplant at 80% ETc and consequently improved eggplant growth (i.e., leaf area, leaf number per plant, dry matter, stem diameter) and productivity. In summer and fall seasons, the highest fruit yields were recorded under full irrigation (28.3 t ha^{-1}) and 10 t ha^{-1} of CB (27.8 t ha^{-1}). Soil supplemented with 5 or 10 t ha^{-1} of CB increased IWUE by 31.6 and 64.1%, respectively, compared to CB-untreated soil. Adding 10 t ha^{-1} of CB under irrigation with 80% ETc increased fruit yield by 37% and IWUE by 69% in relation to full irrigation and CB-untreated soil. CB may be recommended as a soil amendment for vegetable crops such as eggplant to overcome the negative effects of water stress.

Keywords Co-composted biochar · Soil quality · Chlorophyll fluorescence · Eggplant · Plant water status · Yield · Irrigation water use efficiency

1 Introduction

Eggplant (*Solanum melongena* L.) is considered as one of the most important vegetable crops classical commodity in Egypt for both local consumption and exportation. Fruits of eggplant contain a considerable amount of protein, carbohydrates, and vitamins (Mahmoud 2000). Egypt is one of the important eggplant productivity countries in the world and has an eggplant area and production of 48,253 ha and 1.3 million Mg, which accounts for 1.8% and 1.53% of those in the world, respectively (FAOSTAT 2019).

Worldwide, freshwater resources are scarce, leading to a need for re-evaluating the current strategies of water use. Climate change suggests a future increase in aridity and the frequency of extreme events, such as lower rainfall, longer drought periods, and higher temperatures, in many areas of the earth. As of late, the water available to the agricultural sector is declining worldwide due to the rapid growth of the population, the greater increase in drought caused by climate change, and other human activities that will mean an increase in the irrigated agricultural areas, consequently increasing water demands (World Bank 2006). This scenario is leading to increasing demand for irrigation water, reducing crop yields, limiting the sustainability of irrigated crops, and increasing the irrigation water price (Abd El-Mageed and Semida 2015;

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World Bank 2006). Deficit irrigation (DI) is a sustainable practice for water-saving by reducing the irrigation water application either during a particular period or throughout the whole growing season (Pereira et al. 2002). DI was proposed to increase water use efficiency by reducing irrigation water added or reducing the number of irrigation events (Kirda 2002). Numerous research evidence has shown that the water deficit succeeded in maximizing crop productivity without a severe decline in yield (Abd El-Mageed et al. 2019; Geerts and Raes 2009; Mahfouz et al. 2020; Semida et al. 2017).

Eggplant require frequent irrigation and uniform soil moisture to achieve higher yield, while water stress may cause falling flowers and small fruits (Yazar et al. 2018) and reduction of eggplant growth, tissue water content, and chlorophyll content (Plazas et al. 2019), as well as reduction of the marketable fruit yield of eggplant (Darko et al. 2019). Recently, Díaz-Pérez and Eaton (2015) mentioned that eggplant behaved as moderate tolerance to drought stress. However, in arid and semiarid regions including Egypt, where higher irrigation water requirements are synchronized with salt-alkaline soils, it is difficult to apply deficit irrigation, particularly at a severe level without yield reduction.

In recent years, a lot of attention has been paid to the development of sustainable agriculture. To mitigate abiotic stresses such as salt stress, drought, and heavy metal effects on plants, some strategies have been used, including soil amendments (Abd El–Mageed et al. 2017; Rady et al. 2016; Semida et al. 2015).

Compost of various materials and organic fertilizers has been widely used to improve soil properties and increase crop yields (Diacono and Montemurro 2010; Hussain et al. 2020; Lakhdar et al. 2010; Tejada et al. 2006). It improves soil physicochemical and biological characteristics and provides the plant with essential nutrients (Ditta et al. 2015, 2018b). However, the effect of compost is unstable in the medium and long term, which requires regular addition of compost for considerable improvement of the soil organic matter (Bass et al. 2016). More recently, as a soil conditioner in agriculture, supplementation of biochar substances was attempted, and their positive impacts on saline soil structure and plant growth and yield were reported (Akhtar et al. 2015; Calvo et al. 2014). In these reports, it has been concluded that application of biochar in proper concentrations can overcome the adverse effects of water deficit and soil salinity, improve fertility and the structure of the soil, and enhance plant and root growth and plant productivity under normal or soil salinity stress conditions. The favorable effects of biochar on productivity are thought to include high specific surface area, increases in cation exchange capacity (CEC) and microporosity (Atkinson et al. 2010), increasing soil field capacity (Alburquerque et al. 2014), a decrease in bulk density, and enhancing water and nutrients retention in soils (Saifullah et al. 2018). However, the use of biochar has mostly moderate-negative to positive yield effects. Applying biochar with a high carbon to nitrogen (C/N) ratio can eventually induce nitrogen immobilization of the soil, causing N deficiency in the plant that negatively affects plant growth and yield (Semida et al. 2019; Wang et al. 2019). There are large variations in biochar, not only in the availability of nutrients and pH but also in the physical and chemical properties, which differ according to the nature of the feedstock, pyrolysis conditions, the amount of added biochar, and soil type (Saifullah et al. 2018; Semida et al. 2019). Increasing the electrical conductivity and pH of the soil has been observed under soil amended biochar (Alburquerque et al. 2014; Bass et al. 2016; Ullah et al. 2020), which would be unsuitable to apply under salt-alkaline soil. Furthermore, in most cases, biochar has a lower nutrient content for the plant (Trupiano et al. 2017), whereas CB could be a promising soil amendment that could not only overcome the low nutrients of biochar but also regulates the nutrients released from the compost (Antonangelo et al. 2021).

Oxidation of biochar particles alters their physiochemical properties (called aging or weathering process), and without oxidation, biochar loses its ability to increase CEC, nutrient retention, and thus soil fertility (Cheng et al. 2008; Wang et al. 2019). Composting of biochar with an organic substance has been shown to facilitate natural oxidation by increasing the oxidation surface of biochar, accelerating the composting process, as well as enhancing fertility and carbon sequestration capacity (Sanchez-Monedero et al. 2018). Using biochar-compost mixtures has positive synergetic effects as in stimulating the microbiological activity and increasing the soil water-holding capacity along with enhancing micro-aeration and reducing the nutrient loss by leaching (Wang et al. 2019). Moreover, adding biochar during composting acts as a bulking agent and adjusts the C/N ratio (Kammann et al. 2015). Besides, increasing the CEC and retention of nutrients, composting was found to modify biochar structure and pores which increased the biochar micropores resulting in a larger surface area and increased the surface absorption capacity (Sanchez-Monedero et al. 2018). Thus, combined application of biochar and compost amendment in soil could increase the potential benefits for plant growth and increase crop yield. Kammann et al. (2015) found that the addition of co-composted biochar to poor sandy soil exhibited higher water-holding capacity by 15% compared to untreated production of fresh biochar. According to Mensah and Frimpong (2018), combined application of compost and biochar with 2% (*w*/w) in pots increased the dry matter yield, plant height, and number of leaves of two maize cultivars.

Deficit irrigation combined with co-composted biochar (CB) could be a very promising tool among the water management practices, which the CB would improve soil physicochemical properties and soil biota, as well as possibly enhancing soil-plant water relations for promoting plant performance and increase the irrigation water use efficiency (IWUE) of eggplant. This study looks forward whether the use of CB as a soil amendment could improve soil quality to mitigate the deleterious effects of water stress on eggplants. To address this, the present study aims to investigate the potential effect of CB on the soil physical and chemical properties and soil biota or in combination with water stress impacts plant water status, stomatal conductance, photosynthetic efficiency, plant growth, and productivity (yield and IWUE). These positive potential findings will enable eggplant to overcome the drought stress under salt-affected soil conditions.

2 Materials and Methods

2.1 Experimental Setup

Two field experiments were performed in two successive growing seasons: summer season (SS) and fall season (FS) of 2016, at El Fayoum province (west of the Nile at 90 km southwest of Cairo), Egypt between latitudes 29° 02′ and 29° 35′ N and longitudes 30° 23′ and 31° 05′ E. The local climate condition is classified as arid climate according to the aridity index (Ponce et al. 2000). Measurements of soil physicochemical characteristics before and after adding CB and the chemical composition of irrigation water were conducted according to Klute and Dirksen (1986) and Page et al. (1982) methods and were shown in Tables 1, 2 and 3. Available N in the soil before and after adding CB was determined by the method as described by Livens (1959). Available P in the soil before and after adding CB was extracted by 0.5 N sodium bicarbonate ($NaHCO_3$) solution at pH 8.5 as described by Olsen et al. (1954). The experiments were conducted in a randomized complete block in a split-plot design. Treatments were divided into three irrigation levels (I) and three co-composted biochar (CB). Irrigation water application was specified as a percentage of the crop evapotranspiration (ETc) representing one of the following three treatments: $I_{100\%} = 100\%$, $I_{80\%} = 80\%$, and $I_{60\%} = 60\%$ of ETc. I levels were assisted in the main plots, while the CB rates (viz., $CB_0 = 0$ t ha^{-1}, as control, $CB_1 = 5$ t ha^{-1}, and $CB_2 = 10$ t ha^{-1}) were placed in the sub-plots. One week before transplanting eggplant seedlings, the CB was incorporated into the soil. Table 4 presents the properties of the CB.

The treatments number were nine and replicated four times, making a total of 36 plots. The experimental plot area was 15 m length × 1.0 m row width (15 m^2). All irrigation treatments were separated as surrounded by a 2-m nonirrigated area. Four-week-old eggplant seedlings (cv. hybrid Casablanca®) obtained from the Ministry of Agriculture Nurseries, Fayoum, Egypt, were transplanted at a spacing of 0.3 m apart within rows. The irrigation water was supplied with a drip irrigation system with one line and one dripper per plant giving 4.0 L h^{-1}. The irrigation water salinity was 1.91 dS m^{-1}. Seedlings were transplanted on 18 March 2016 and lasted until 10 July 2016 in the summer season (SS) and again transplanted on 10 September 2016 and ended on 1 February 2017 in the fall (FS) growing season. Irrigation treatments were initiated 1 week after transplanting seedlings. The cultural, disease, and pest management practices were the same as local commercial crop production.

2.2 Co-composted Biochar Production

The used biochar was produced in a traditional charcoal kiln from poultry litter (350–450 C for 10 days). Compost

Table 1 Climatic parameters at Fayoum, Egypt, that prevailed during the growing seasons (SS) (FS) of 2016/2017

Month	$T_{min}$$^{\#}$ (°C)	T_{max} (°C)	T_{avg} (°C)	RH_{avg} (%)	U_2 ms^{-1}	E_{pan} mmd^{-1}
Summer (SS)						
March	13.41	28.01	20.71	36.03	2.15	4.12
April	15.92	33.36	24.64	39.00	2.16	5.6
May	21.43	37.36	29.39	41.68	1.90	6.49
June	23.43	39.48	31.45	42.73	1.50	8.30
July	25.07	40.92	33.07	41.22	2.00	7.50
Fall (FS)						
September	23.60	36.6	30.10	43.70	2.10	5.80
October	19.54	30.79	25.11	43.03	2.00	4.18
November	17.47	29.13	23.32	40.53	2.20	2.54
December	9.50	21.00	15.30	42.00	1.62	1.50
January	8.50	20.50	14.50	42.60	2.21	1.60

[#] T_{max}, T_{min}, and T_{avg} are average, maximum, and minimum temperatures, respectively, RH_{avg} is average relative humidity, U_2 is average wind speed, and E_{pan} is average of measured pan evaporation class A

Table 2 Physical and chemical properties of the studied soil

Particle size distribution				Bulk density (g cm^{-3})	K_{sat} (cm h^{-1})	FC (%)	WP (%)	AW (%)	pH	ECe (dS m^{-1})	CEC (cmole kg^{-1})	Organic matter (%)	$CaCO_3$ (%)	N (mg kg^{-1} soil)	P (mg kg^{-1} soil)
Silt (%)	Clay (%)	Sand (%)	Texture												
12.0	12.8	75.2	Loamy sand	1.58	2.21	20.03	10.55	9.48	7.86	6.89	11.1	1.10	3.81	58.32	4.25

K_{sat}, hydraulic conductivity; *FC*, field capacity; *WP*, wilting point; *AW*, available water; *ECe*, soil salinity; and *CEC*, cation exchange capacity

production was carried in windrows (3.5 × 1.5 m) following the guidelines of aerobic quality composting (Bernal et al. 2009). The compost input material consisted of geranium waste, soil, and mature compost. To compost windrow, 25% (v/) poultry litter biochar was added to produce the co-composted biochar. After mixing, windrows were left for 2 months with a turnover period of 5 days.

2.3 Irrigation Water Applied (IWA)

Eggplant seedlings were irrigated at 2 days intervals by different amounts of irrigation water applied. The crop water requirements (ETc) were estimated using class A pan equation (Allen et al. 1998):

$$\mathrm{ET_c} = E_{\mathrm{pan}} \times K_{\mathrm{pan}} \times K_{\mathrm{c}}$$

where ETc is the crop water requirement (mm day^{-1}), E_{pan} is the evaporation from the class A pan (mm day^{-1}), K_{pan} is the Pan coefficient (Allen et al. 1998), and K_{c} is the crop coefficient.

Irrigation water application (IWA) was determined by using the following formula:

$$\mathrm{IWA} = \frac{A \times \mathrm{ETc} \times \mathrm{Ii} \times \mathrm{Kr}}{\mathrm{Ea} \times 1000 \times (1 - \mathrm{LR})}$$

where IWA is the irrigation water applied (m^3), A is the plot area (m^2), ETc is the crop water requirements (mm day^{-1}), Ii is the irrigation intervals (day), Kr is the covering factor, Ea is the application efficiency (%), and LR is the leaching requirements.

2.4 Data Collections and Measurements

Soil water content (SWC) was monitored at 0–20 and 20–40 cm depth at 2-day intervals using digital WET sensors (Moisture Meter type HH2, Cambridge, CB5 0EJ, UK).

Six plants at the end of each season (SS and FS) were randomly taken from each experimental plot and assessed for growth characteristics. Firstly, plant height and stem diameter were recorded; then, the number of leaves plant^{-1} was counted. The total leaf area plant^{-1} was measured using a digital planimeter (Planix 7, Tamaya Technics Inc., Tokyo, Japan). After that, the plant leaves and branches were weighed and recorded their fresh weight (herein called shoots fresh weight); thereafter shoot dry weight plant^{-1} was recorded after oven-drying at 70 °C until constant weight. Every week after 50 days from transplanting, five plants of each experimental plot were used to measure the average number of fruits per plant and total yield per hectare. The harvest index (HI) was determined as a ratio of the yield of fruits divided by the aboveground biomass production on a dry mass basis.

Relative water content (RWC %) was estimated according to Hayat et al. (2007) equation:

$$\mathrm{RWC}(\%) = \left[\frac{(\mathrm{FM}-\mathrm{DM})}{(\mathrm{TM}-\mathrm{DM})}\right] \times 100$$

where FM is the fresh mass (g), TM is the turgid mass (g), and DM is the dry mass (g).

MSI% was measured using the method of Premachandra et al. (1990) and calculated by the following equation:

$$\mathrm{MSI}(\%) = \left[1 - \left(\frac{C1}{C2}\right)\right] \times 100$$

Table 3 Chemical composition of irrigation water

Ionic concentration (ppm)								EC[a] (dS m^{-1})	pH	SAR[b]
CO_3^{--}	HCO_3^-	SO_4^{--}	Cl^-	Mg^{++}	Ca^{++}	Na^+	K^+			
0.00	2.6	4.1	14.3	2.2	6.8	7.7	1.3	1.87	7.5	3.14

[a] *EC*, electrical conductivity; [b] *SAR*, sodium adsorption ratio

Table 4 Some characteristics of the co-composted poultry litter biochar (CB)

Characteristics	Unit	Value
Bulk density	g cm^{-3}	0.85
Electrical conductivity (EC)	dS m^{-1}	3.25
pH	–	7.34
Moisture content	%	15.60
Organic carbon	%	41.70
Ash	%	35.70
Cation exchange capacity	cmol+/kg	46.50
Macronutrients		
N	%	2.12
P	g kg^{-1}	3.02
K	g kg^{-1}	4.2
Ca	g kg^{-1}	1.37
Mg	g kg^{-1}	0.35
Na	g kg^{-1}	0.31
Micronutrients		
Zn	mg kg^{-1}	78.31
Fe	mg kg^{-1}	89.40
Mn	mg kg^{-1}	541.45
Cu	mg kg^{-1}	20.21

BD is the bulk density, MC is moisture content, and CEC is the cation exchange capacity

where MSI % is the membrane stability index, C_1 is the EC of the solution at 40 °C, and C_2 is the EC of the solution at 100 °C.

Chlorophyll a fluorescence was measured by Handy portable fluorometer (Hansatech Instruments Ltd., Kings Lynn, UK). The maximum quantum yield of PSII and F_v/fm was calculated as $F_v/fm = (F_m - F_0)/F_m$ (Maxwell and Johnson 2000). The performance index of photosynthesis based on equal absorption (PIABS) was calculated as reported by Clark et al. (2000). Stomatal conductance (g_s) was measured on fully expanded upper canopy leaves between 1400 and 1500 h with a portable photosynthetic system (CIRAS-2, PP Systems, Hitchin, UK).

The SPAD meter (SPAD-502-2900) was used to measure the relative chlorophyll content of the eggplant. The measurements of the canopy temperature were performed using a handheld infrared thermometer (Fluk 574, Everett WA, USA) at an emissivity of 0.98 and a spectral response range of 8–14 μm. Irrigation water use efficiency (IWUE) was calculated as the ratio of fruit yield (kg ha^{-1}) and irrigation water applied (m^{-3} ha^{-1}) for each irrigation level using (Jensen 1983) equation:

$$\text{IWUE} = \frac{\text{fruit yield}\ \left(\text{Kg ha}^{-1}\right)}{\text{water applied}\ \left(\text{m}^3\ \text{ha}^{-1}\right)}$$

2.5 Statistical Analysis

Statistical analysis was performed through the GLM procedure of Gen STAT (version 11, VSN International Ltd., Oxford, UK). A Duncan's multiple range test at a 5% probability ($P \leq 0.05$) level was used as a mean separation test.

3 Results

3.1 Irrigation Water Applied and Seasonal Variation

The summer season was shorter with higher maximum, minimum, and average monthly temperature than the fall season. The total growing cycle was 120 days in summer and 143 in the fall seasons. The total E_{pan} values registered during the summer season (754 mm) were 43% higher than that in the fall season (429 mm), without registration rainfall during both seasons. In the summer season, the IWA was 7242, 5794, and 4345 m^3 ha^{-1} for $I_{100\%}$, $I_{80\%}$, and $I_{60\%}$, respectively, while in the fall season it was 5604, 4483, and 3362 m^3 ha^{-1} for $I_{100\%}$, $I_{80\%}$, and $I_{60\%}$, respectively.

3.2 Physicochemical Properties and Biota of the Tested Soil in Response to Co-composted Biochar

The soil properties (i.e., physical, chemical, and biota) markedly influenced when soil amended with CB, as presented in Table 5. The application of CB to the soil significantly decreased the values of soil pH and electrical conductivity (EC) and the application of 10 t ha^{-1} of CB produced the lowest values. The soil organic matter progressively increased with the increasing CB rate. The highest available N in the soil corresponded with the highest CB rate. The application of CB significantly increased the available P in the soil. Compared to the control (CB_0), the addition of CB_1 or CB_2 decreased the bulk density and the hydraulic conductivity of the soil, where the lowest values corresponded to the application of 10 t ha^{-1} CB. Soil amended with CB showed increases of water-holding pores, useful pores, field capacity, and available water, highlighting that the addition of 10 t ha^{-1} of CB increased water-holding pores by 62.4%, useful pores by 80.2%, field capacity by 31.4%, and available water 20.5%, respectively, relative to the control. The number of bacterial cells per g of soil increased when soil was supplemented with CB (5 or 10 t ha^{-1}), and this improvement was more obvious under 10 t of CB, which increased the bacterial cells by 225% compared to the CB-untreated soil.

Table 5 Effect of co-composted poultry litter biochar (CB) application on soil physicochemical properties and soil biota after second season

CB rate ($t h^{-1}$)	ECe (dS m^{-1})	pH	OM (%)	N (mg kg^{-1} soil)	P (mg kg^{-1} soil)	Bulk density (g cm^{-3})	K_{sat}.(cm $hr.^{-1}$)	Water-holding pores (%)	Useful pores (%)	FC (%)	A.W.(%)	Number of bacteria (cell/g soil)
CBC_0	7.2a	7.60a	1.21c	52.6b	4.15b	1.59a	2.24a	11.50c	11.69c	20.89b	10.91c	2 x 10^6c
CBC_1	6.5b	7.42b	1.83b	56.1b	4.86a	1.50b	2.10b	16.07b	18.28b	25.05ab	12.78b	4.9 x10^6b
CBC_2	6.2c	7.29c	2.31a	66.3a	5.02a	1.45c	1.90c	18.68a	21.06a	27.45a	13.15a	6.5 x10^6a

ECe, soil salinity; OM, organic matter; K_{sat}, hydraulic conductivity; FC, field capacity; and AW, available water. Different letters next to mean values in each column indicate significant difference according to Duncan's multiple range test ($p \leq 0.05$)

3.3 Eggplant Water Status and Canopy-Air Temperature Responses to Co-composted Biochar Under Deficit Irrigation

Data of plant water status (RWC and MSI) and the canopy-air temperature in response to the growing season, irrigation levels, and CB are presented in Table 6. Both RWC and MSI were significantly affected by irrigation level, recording the highest values in $I_{100\%}$ but the lowest values in $I_{60\%}$. Concerning the CB effects, the RWC and MSI were increased in eggplant grown in soil amended with CB compared to those grown in untreated soil. In summer and fall seasons, the highest MSI and RWC were obtained when eggplant was subjected to irrigation at 100% of ETc and received 5 or 10 t CB, but the integrative application of irrigation at 60% of ETc and non-applied CB (CB_0) resulted in the lowest values. Application of 5 or 10 t CB to drought-stressed plants up to 20% compensated for this lack of irrigation and recorded

Table 6 Response of membrane stability index (MSI %), relative water content (RWC %), and diurnal variation in (Tc-Ta) of deficit irrigation-stressed eggplant (*Solanum melongena* L.) plants to co-composted poultry litter biochar applications under saline soil conditions

Source of variation	MSI (%)	RWC (%)	Tc-Ta	
			O'clock	
			14:00	15.00
Season (S)	NS	NS	**	**
Summer	56.34±1.81a	67.75±1.87a	−0.11±0.01b	−2.44±0.16b
Fall	57.24±1.69a	66.32±1.09a	3.75±0.17a	3.95±0.19a
Irrigation level (I)	**	**	**	**
$I_{100\%}$	61.61±1.04a	71.15±1.72a	−0.60±0.09c	−0.78±0.21c
$I_{80\%}$	58.65±1.38b	66.08±1.82b	1.91±0.32b	−0.05±0.01b
$I_{60\%}$	50.12±2.64c	63.87±1.33c	4.15±0.37a	3.08±0.41a
Co-composted biochar (CB)	**	**	**	**
CB_0	48.62±2.27c	62.40±1.27b	3.2±0.58a	2.07±0.90a
CB_1	59.79±1.29b	68.97±1.76a	1.18±0.18b	0.49±0.11b
CB_2	61.96±1.21a	69.73±1.69a	1.06±0.16b	−0.30±0.12c
I×CB	**	**	**	**
$I_{100\%}\times CB_0$	57.27±1.23b	68.68±1.29b	0.80±0.13d	−0.83±0.12d
$I_{100\%}\times CB_1$	60.82±1.21b	72.03±1.40a	−1.75±0.99f	−0.58±0.19d
$I_{100\%}\times CB_2$	66.73±1.35a	72.73±1.13a	−0.86±0.51e	−0.93±0.19d
$I_{80\%}\times CB_0$	52.11±1.64c	61.91±1.24c	2.95±0.26 b	1.63±0.11c
$I_{80\%}\times CB_1$	65.51±1.93a	68.19±1.89b	1.69±0.12 c	−0.56±0.17d
$I_{80\%}\times CB_2$	58.33±1.43b	68.16±1.84b	1.10±0.15 cd	−1.21±0.14d
$I_{60\%}\times CB_0$	36.48±2.33d	56.62±1.30d	5.94±0.24a	5.40±0.27a
$I_{60\%}\times CB_1$	53.05±1.38c	66.69±1.16b	3.59±0.35b	2.61±0.40b
$I_{60\%}\times CB_2$	60.83±1.89b	68.30±1.42b	2.94±0.29b	1.24±0.40c

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; and "ns" refers to nonsignificant difference. Different letters next to mean values in each column indicate significant difference according to Duncan's multiple range test

similar values to well-irrigated plants without CB application ($CB_0 + I_{100\%}$).

Plants grown during the summer season had a negative value of the Tc-Ta (−1.28 on average) than those recorded in the fall season (+3.85 on average). The results indicated that eggplant exposed to severe water restriction ($I_{60\%}$) had higher canopy temperature and recorded the highest Tc-Ta values, while the lowest values corresponded to fully irrigated plants ($I_{100\%}$), in both growing seasons. Data in Table 6 indicate that the difference in canopy-air temperature (Tc-Ta) was significantly influenced by CB treatments. Under the application of CB (5 or 10 t ha^{-1}), the canopy-air temperature difference (Tc-Ta) was decreased compared with CB-untreated soil.

3.4 Leaf Stomatal Conductance, SPAD, and Chlorophyll Fluorescence of Eggplants in Response to Co-composted Biochar Under Deficit Irrigation

Combined application of 5 or 10 t ha^{-1} CB with full irrigation recorded the highest stomatal conductance and SPAD values, whereas the lowest values were observed when eggplant exposed to severe water stress ($I_{60\%}$) without CB application (Fig. 1). However, CB-amended soil alleviated the negative effects of water stress on the leaf stomatal conductance and SPAD value. In this respect, the addition of 5 or 10 t ha^{-1} CB in combination with irrigation at 80% ETc increased such parameters in comparison of irrigation with 80% ETc and absence of CB and recorded similar values to fully irrigated plants untreated with CB.

The maximum quantum yield of PSII (F_v/fm), the activity of PSII reaction centers (F_v/F_0), and the photosynthetic performance index (PI) were increased as a result of soil-applied 5 or 10 t CB in combination with full irrigation. Adding 5 or 10 t of CB to drought-stressed eggplants with 20% enhanced F_v/fm, F_v/F_0, and PI and recorded similar or higher values than plants grown under full irrigation without CB application ($CB_0 + I_{100\%}$) (Fig. 2).

3.5 Eggplant Growth in Response to Co-composted Biochar Under Deficit Irrigation

Tables 7 and 8 illustrate the effects of growing seasons, irrigation level, CB, and their interaction on eggplant growth. Plants grown during the summer season had higher values of growth traits (i.e., plant height, leaves number, stem diameter, shoots fresh and dry weight, and leaf area) than those grown during the fall season. These growth parameters were decreased significantly with increasing water stress, $I_{60\%}$ resulted in decreases of plant height by 17.3%, the number of leaves per plant by 46.1%, stem diameter by 26.3%, shoot fresh weight by 49.7%, and leaf area $plant^{-1}$ by 87.2% compared to fully irrigated plants. Soil-applied 5 t or 10 t CB improved eggplant growth variants compared to CB untreated soil and CB_2 showed the highest values. The combined application of 5 t ha^{-1} CB and irrigation at 100% of ETc recorded the highest growth parameters, while the treatment $CB_0 + I_{60\%}$ showed the lowest values of growth parameters. Otherwise, water restriction with 20% in CB-treated soil with 10 t ha^{-1} ($CB_2 + I_{80\%}$) exhibited higher values than full irrigation and absence of CB ($CB_0 + I_{100\%}$).

3.6 Yield, HI, and IWUE of Eggplant in Response to Co-composted Biochar Under Deficit Irrigation

Plants grown during fall had higher HI and IWUE compared to the plants grown during the summer season (Table 8). The HI was influenced by the irrigation level, HI decreased with increasing deficit irrigation, also it was affected by CB, ranging from 0.63 (CB_0) to 0.70 (CB_2) (Table 8). Regarding the interaction between irrigation level and CB, the combined application of $I_{100\%}$ plus CB_1 recorded the highest HI, while the application of $I_{60\%}$ with CB_0 resulted in the lowest HI (Table 8). Eggplant irrigated with $I_{100\%}$ or $I_{80\%}$ produced the highest IWUE, but $I_{60\%}$ reduced the IWUE by 6.8% relative to full irrigated plants (Table 8). The results in Table 8 reported that the IWUE was markedly influenced by adding CB. Soil supplemented with 5 or 10 t ha^{-1} of CB increased the IWUE by 31.6 and 64.1%, respectively, in comparison to CB-untreated soil (CB_0). However, integrative application of 10 t ha^{-1} of CB and $I_{80\%}$ or $I_{60\%}$ led to the greatest IWUE that increased by 69% and 49%, respectively, compared to full irrigation without application of CB, while the lowest IWUE corresponded with $I_{60\%}$ without CB application. In both growing seasons, a curvilinear (polynomial of 2nd order) relationship was found between IWA and IWUE (Fig. 3a and b).

As shown in Table 9, growing season, irrigation level, and CB and their interaction had clear effects on eggplant yields and yield component. The summer season increased fruit yield by 18.9% and the number of fruits by 44.1% than those recorded when planting eggplant in fall. Sever water deficit ($I_{60\%}$) reduced the number of fruits by 38.6%, fruit length by 16.7%, fruit diameter by 16.8%, fruit weight by 13.3%, and fruit yield by 44.3% than those fully irrigated ($I_{100\%}$) that recorded the greatest values (except for fruit diameter). Responses of yield component and yields of eggplant illustrated in Table 9 reveal that all these parameters were increased with increasing CB level. Under 20% water stress, application of 10 t ha^{-1} CB increased fruit characteristics (length, diameter, and weight), fruit number, and yield by 37% compared to fully irrigated eggplants without CB application. The relationship between IWA and fruit yield or IWUE of both growing seasons were polynomial of 2nd order (Fig. 3a and b) and indicated that fruit yield was increased corresponding to increasing of the IWA, whereas IWUE was decreased with increasing the IWA.

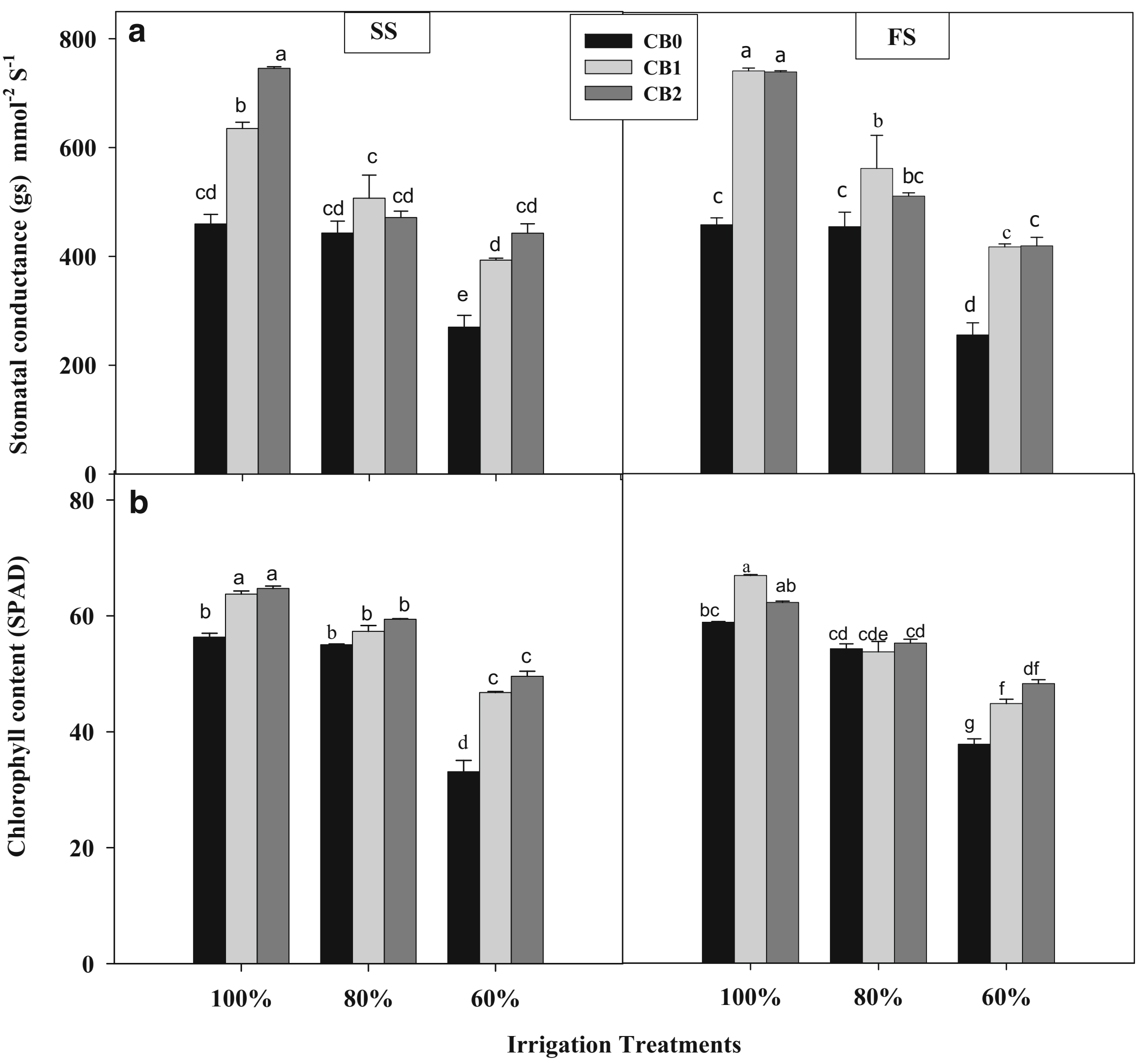

Fig. 1 Effect of co-composted poultry litter biochar (CB) as soil amendment on (**a**) stomatal conductance (*gs*) and **b** relative chlorophyll content (SPAD) of eggplant plants grown under different irrigation levels (100%, 80%, and 60% of ETc) in summer (SS) and fall (FS) seasons. Vertical bars represent means of 3 replications ± S.E ($p \leq 0.05$). Columns marked by different letters are significantly different. (CB0 = 0, CB1 = 5, and CB2 = 10 t ha^{-1})

4 Discussion

Sustainability of agronomic practices and production increases are therefore necessary if the goals of increasing food supply are to be achieved. Water stress and salinity are important factors that significantly threaten the growth and productivity of crops. Soil improvement affected by salinity is a major challenge that must be faced before plant production in these areas becomes possible. Among the proposed remediation strategies, the application of co-composted biochar (CB) to salt-affected soil with different soil moisture regimes has not been fully explored. This novel approach of integrating biochar in composting as a soil amendment boosted the beneficial effects on soil physicochemical properties and increased soil water relations and nutrient retention. These factors could make CB an important part of a water management strategy to present better conditions for improving eggplant growth and productivity under water-deficit conditions.

Our results revealed that exogenous CB application positively improved the physicochemical and soil biota of the salt-affected soil. In this study, eggplant was cultivated in saline soil with 7.2 dS m^{-1}. The ECe value of the tested soil gradually reduced up to 6.2 dS m^{-1} in soil supplemented with 10 t ha^{-1}. This reduction in the soil salinity by adding CB may be due to the presence of charged sites (e.g., COO^{-}) indicating the ability of CB to chelate cations and keep them in inactive formulas (Abd El-Mageed et al. 2018, 2019). Also, the lower EC of the CB (3.25 dS m^{-1}; Table 4) likely modulates the soil ECe. Furthermore, adding CB to saline soils could accelerate the leaching of salts and NaCl and decrease exchangeable Na^+ and the ECe value due to reducing the bulk density, increasing the porosity, and improving soil hydraulic

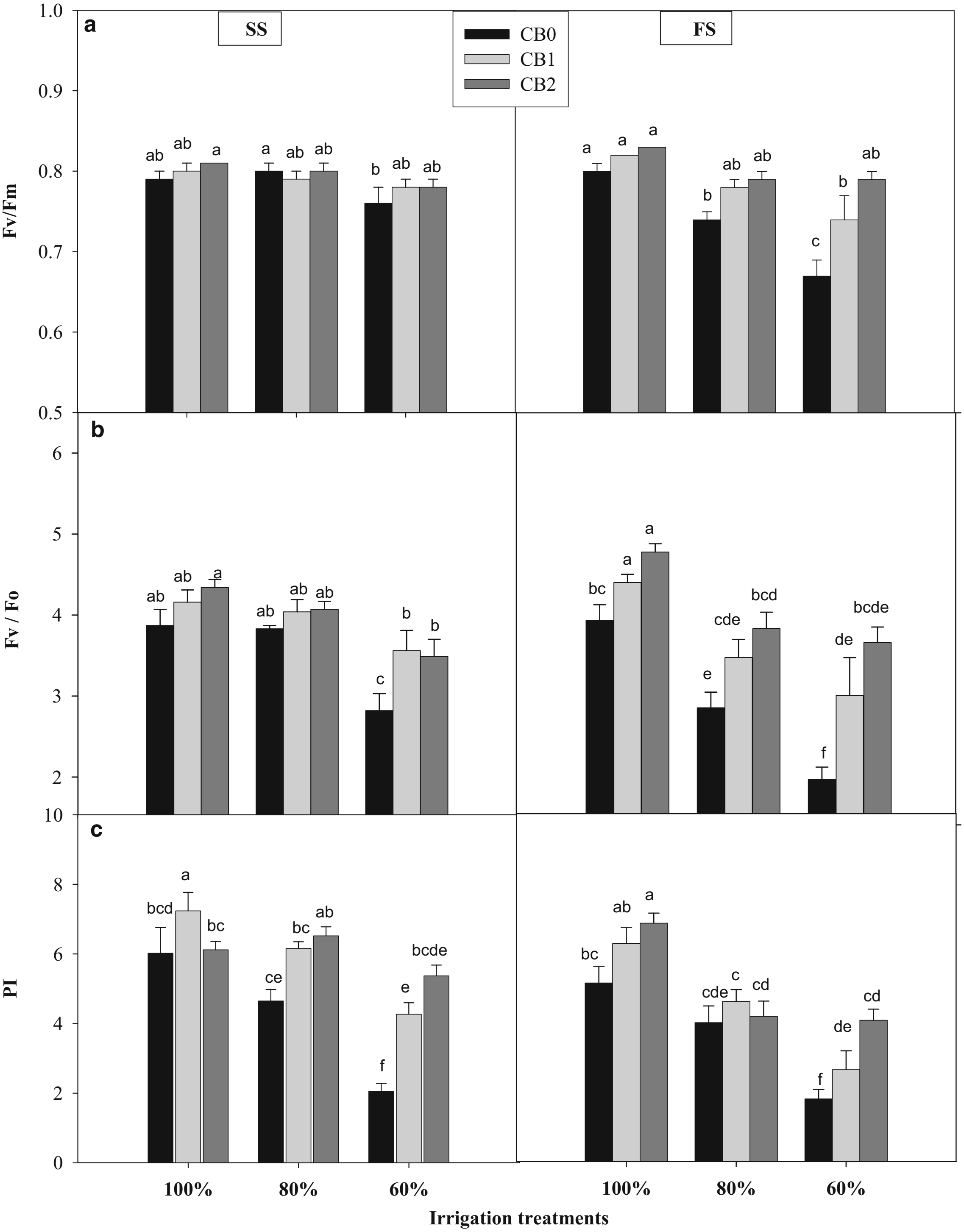

Fig. 2 Leaf eggplant chlorophyll fluorescence grown under various irrigation levels (100%, 80%, and 60% of ETc) and co-composted poultry litter biochar (CB) applications in summer (SS) and fall (FS) seasons. **a** Maximum quantum efficiency of PSII (F_v/fm); **b** potential photochemical efficiency (F_v/F_0); **c** performance index of photosynthesis (PI). Vertical bars represent means of 3 replications ± S.E ($p \leq 0.05$). Columns marked by different letters are significantly different. (CB0 = 0, CB1 = 5, and CB2 = 10 t ha^{-1})

conductivity and the construction of the soil, thus facilitating salts leaching (Diacono and Montemurro 2015; Lakhdar et al. 2010). Similarly, the pH of the tested soil decreased with increasing CB rate, which could be attributed to the higher CB's cation exchange capacity (CEC; Table 1), and increasing the soil microbial activities, which may enhance the production of active organic acids (such as volatile fatty acids) as a by-product from organic matter degradation resulting in the

Table 7 Response of plant growth of deficit irrigation-stressed eggplant (*Solanum melongena* L.) plants to co-composted poultry litter biochar applications under saline soil conditions

Source of variation	Plant height (cm)	Leaves No.	Stem diameter (cm)	Shoot fresh weight (g)
Season (S)	*	*	*	*
Summer	84.62±1.46a	168.44±6.67a	1.88±0.04a	433.10±21.52a
Fall	64.44±1.44b	132.51±8.59b	1.43±0.05b	334.30±15.38b
Irrigation level (I)	**	**	**	**
$I_{100\%}$	80.57±1.86a	190.50±8.70a	1.94±0.06a	440.80±27.04a
$I_{80\%}$	76.40±2.91b	157.70±8.19b	1.59±0.06b	344.10±27.32b
$I_{60\%}$	66.60±2.14c	103.20±5.35c	1.44±0.05c	217.29±16.21c
Co-composted biochar (CB)	**	**	**	**
CB_0	67.10±2.77c	118.50±9.02c	1.43±0.07c	252.90±22.36c
CB_1	75.202.10b	158.50±11.34b	1.68±0.06b	356.29±26.3b
CB_2	81.30±2.12a	174.50±6.16a	1.85±0.06a	393.00±23.92a
I×CB	**	**	**	**
$I_{100\%}\times CB_0$	75.00±4.00b	140.50±12.7c	1.69±0.12d	353.90±31.75d
$I_{100\%}\times CB_1$	83.30±2.97a	235.90±7.35a	1.99±0.06b	536.00±35.22a
$I_{100\%}\times CB_2$	83.40±1.89a	194.90±2.81b	2.13±0.07a	432.40±25.97c
$I_{80\%}\times CB_0$	69.90±5.49c	139.80±9.88c	1.41±0.10f	263.70±26.33 g
$I_{80\%}\times CB_1$	73.70±3.49b	139.50±7.20c	1.58±0.07e	312.00±34.22e
$I_{80\%}\times CB_2$	85.60±4.98a	193.90±8.68b	1.79±0.11c	456.40±29.36b
$I_{60\%}\times CB_0$	56.40±2.77d	75.10±3.15e	1.19±0.05 g	141.10±11.75i
$I_{60\%}\times CB_1$	68.60±3.03c	100.00±7.07d	1.48±0.07f	220.50±24.59 h
$I_{60\%}\times CB_2$	74.90±2.81b	134.60±4.25c	1.63±0.08de	290.20±23.69f

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; and "ns" refers to nonsignificant difference. Different letters next to mean values in each column indicate significant difference according to Duncan's multiple range test

soil's pH values decreasing in compost plus biochar than without biochar (Wei et al. 2014; Zeb et al. 2018). Furthermore, the increased microbial activities contribute to the degradation of organic N and the production of ammonia/ammonium that may be absorbed by negatively charged surfaces of biochar, causing a slight reduction of soil pH (Antonangelo et al. 2021). The soil analysis exhibited higher available N and P in soil-amended CB, especially with a high CB rate. Biochar-amended compost increased available N than sole biochar due to increase charged surface and absorption of N (Antonangelo et al. 2021). Increasing P availability in soil-amended CB may be attributed to the production of chelating agents like organic acids and enzymes through increasing microbial activities that have an important role in the mineralization of P in CB (Ditta et al. 2018a, b).

Increased CB in soil, in turn, increased their bulk density that can be ascribed to the pronounced content of organic colloidal particles that play an effective role in the redistribution of pore size pattern in soil. Our findings are in accordance with that observed by Abd El-Mageed et al. (2018) who stated that the bulk density was very related to the properties of the solid phase and pore size distribution in the soil. This reduction in soil bulk density was associated with increases in the water-holding pores and the useful pores (Table 5) indicating that the CB-induced soil micropores increased capillary potential.

CB-amended soil significantly increased favorable soil properties, namely organic matter content, water-holding pores, useful pores, available water, and field capacity. Given that CB a highly organic carbon and porosity material, supplying CB may induce soil aggregation (Obia et al. 2016) and set up interstitial space resulting in more micropores (Abd El-Mageed et al. 2020a, b), increasing water-holding pores and useful pores. These factors could be contributed to increasing the soil water retention capacity (Diacono and Montemurro 2010), hence increased available water content of salt-affected soil, which could enhance eggplant growth and yields. Compared to CB-treated soil, the untreated soil with CB showed higher bulk density and lower water-holding pores, useful pores, available water content, and field capacity. These findings are in line with those documented by Agegnehu et al. (2017) and Teodoro et al. (2020). The CB could modify the soil biological communities due to the CB being a highly porous material that allows it to absorb soluble organic matter and inorganic nutrients or that CB improves the physical and chemical properties of the soil,

Table 8 Response of shoot dry weight, leaf area, harvest index (HI) and irrigation water efficiency (IWUE) of deficit irrigation-stressed eggplant (*Solanum melongena* L.) plants to co-composted poultry litter biochar applications under saline soil conditions

Source of variation	Shoot dry weight (g)	Leaf area/plant (dm^2)	HI	IWUE ($Kg\ m^{-3}$)
Season (S)	*	**	*	*
Summer	134.31±6.86a	49.99±3.06a	0.63±0.01b	4.19±0.10b
Fall	100.73±3.88b	31.99±2.26b	0.72±0.01a	4.42±0.10a
Irrigation level (I)	*	**	**	**
$I_{100\%}$	126.55±6.36a	55.76±3.14a	0.70±0.01a	4.42±0.12a
$I_{80\%}$	96.29±5.36b	42.91±3.57b	0.67±0.01b	4.37±0.14a
$I_{60\%}$	59.23±3.36c	24.31±1.22c	0.65±0.01c	4.12±0.12b
Co-composted biochar (CB)	*	**	**	**
CB_0	68.96±3.31c	30.07±2.86c	0.63±0.02c	3.26±0.04c
CB_1	100.59±5.32b	44.20±3.94b	0.69±0.01b	4.29±0.04b
CB_2	112.52±4.94a	48.71±3.32a	0.70±0.01a	5.35±0.06a
I×CB	**	**	**	**
$I_{100\%}$ X CB_0	94.33±7.29d	41.13±2.06c	0.66±0.03d	3.36±0.17 g
$I_{100\%}$ X CB_1	151.21±5.77a	69.15±3.67a	0.73±0.01a	4.53±0.15d
$I_{100\%}$ X CB_2	134.10±5.02b	56.99±1.24b	0.72±0.01b	5.36±0.17b
$I_{80\%}$ X CB_0	73.62±2.82 g	31.61±3.13d	0.62±0.03f	3.36±0.15 g
$I_{80\%}$ X CB_1	89.43±5.07e	38.86±4.58c	0.70±0.02c	4.06±0.16f
$I_{80\%}$ X CB_2	125.83±10.2c	58.28±7.08b	0.70±0.02c	5.68±0.18a
$I_{60\%}$ X CB_0	38.94±4.49i	17.48±1.31f	0.62±0.03f	3.05±0.18 h
$I_{60\%}$ X CB_1	61.12±5.04 h	24.58±0.88e	0.64±0.01e	4.29±0.16e
$I_{60\%}$ X CB_2	77.63±5.5f	30.86±1.46d	0.69±0.02c	5.02±0.10c

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; and "ns" refers to nonsignificant difference. Different letters next to mean values in each column indicate significant difference according to Duncan's multiple range test

providing favorable habitat for microorganisms (Agegnehu et al. 2017; Gomez et al. 2014), increasing the number of bacterial cells (Table 5).

CB alleviates the impact of drought stress in plants, either by decreasing plant exposure to such stress or modulating plant stress responses (Abd El-Mageed et al. 2020a, b). Our results reveal that CB-amended saline soil thought to improved soil health/quality, in the sense that improved the soil's physical, chemical, and biological properties. This improvement of soil quality could enhance plant growth and productivity. The addition of CB (5 or 10 t ha^{-1}) to plants grown with full irrigation produced the maximum values of eggplant water status (RWC and MSI), SPAD value, and stomatal conductance. Our results exhibited that application of CB (5 or 10 t ha^{-1}) to drought-stressed eggplant with 20% alleviated the negative effects of water stress, thereby enhancing leaf cell integrity (MSI) and cell turgor (RWC). These findings may be linked to the ameliorative effect of CB on improving soil physicochemical attributes and soil water status (Table 5) that likely mediated enhancement of root elongation that could increase water and nutrients uptake. Our results revealed that the application of CB plays an important role in stabilizing membrane integrity and maintaining the cell turgor of eggplant leaves under water stress. In this respect, increases in tissue RWC and MSI as metabolically available water, enabling to maintain tissue health and may reflect on the metabolic processes in eggplant under drought stress.

This study exhibited that eggplant irrigated with 60% ETc and untreated with CB produced a reduction of eggplant water status, SPAD value, and stomatal conductance, indicating the negative effects of water stress on eggplant. An earlier plant response to drought stress is stomatal closure through hormonal signals (mainly ABA), resulting in the reduction of stomatal conductance, modifying the plant water status (MSI and RWC) that diminishes plant growth (Abdelkhalik et al. 2020; Costa et al. 2007). Our results are in line with those reported by Abd El-Mageed et al. (2016) and Abdelkhalik et al. (2019a, b, c), who stated that reduction of soil water content was associated with decreases in RWC and MSI. Along with the reduction of SPAD value, water restriction reduced the chlorophyll a fluorescence (in terms of F_v/fm, F_v/F_0, and PI(, indicating the damage in the light-harvesting complex and a reduction in the photochemical efficiency of PSII in drought-stressed eggplants (Melo et al. 2017). The decrease in photosynthetic apparatus in response to water stress has also been observed by Habibi (2012), Abd El-

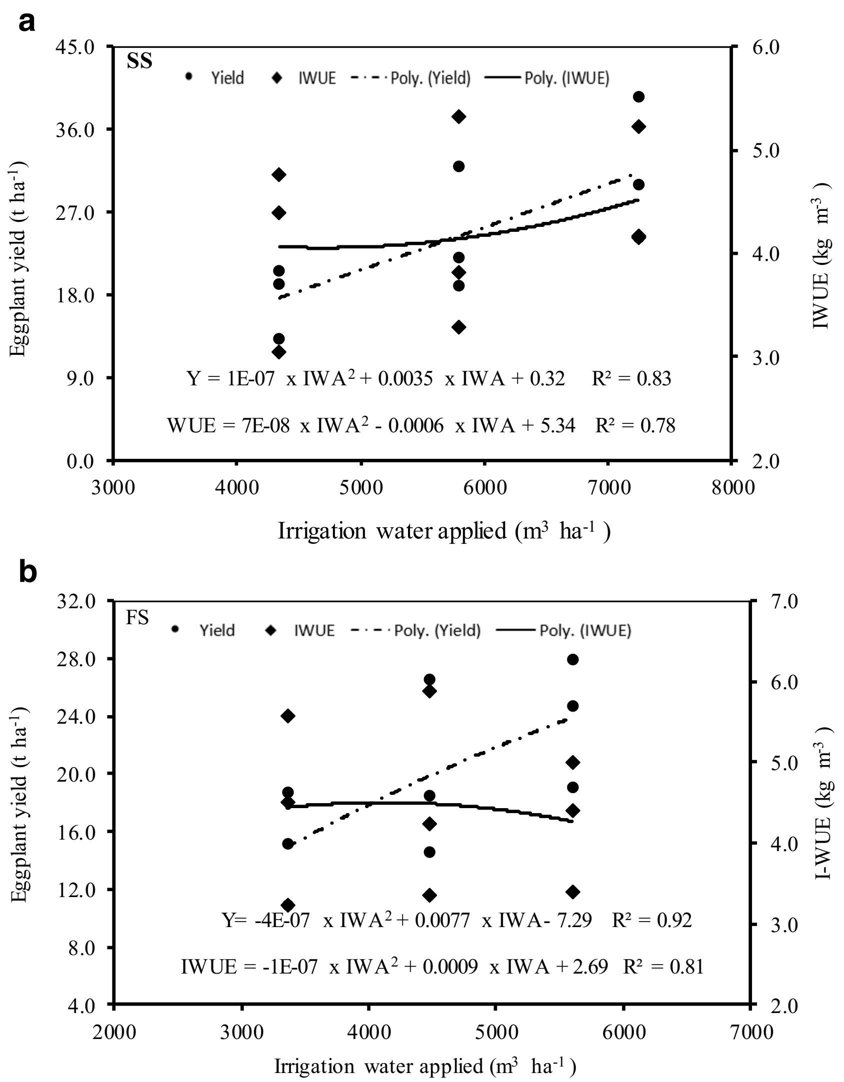

Fig. 3 **a** Regression analysis between irrigation water use efficiency (IWUE), irrigation water applied, and yield of eggplant in summer (SS) season. **b** Regression analysis between irrigation water use efficiency (IWUE), irrigation water applied, and yield of eggplant in fall (FS) season

Mageed and Semida (2015), and Abdelkhalik et al. (2019a), who reported a significant correlation between F_v/fm and stomatal conductance, which confirmed the idea that stomatal closure lowered availability of carbon dioxide for dark reactions may be one of the mechanisms of photoinhibition in water-stressed leaves. Contrariwise, CB-amended saline soil improved the stomatal conductance, SPAD value, and chlorophyll fluorescence efficiency of drought-stressed eggplant leaves at 80% ETc. These improvements may be related to maintaining cell membrane integrity and water content of water-stressed eggplant leaves by CB application (since improved soil physical and chemical properties) for increasing the stomatal conductance, chlorophyll content, and photosynthetic efficiency.

The difference between the temperature of the plant canopy and the air temperature (Tc-Ta) is deemed as an indicator of the plant water status under water stress (Kirkham 2014). Drought stress induces leaf stomatal closure resulting in the reduction of transpiration where the plant is unable to cool their leaves surface and allowing sunlit leaves to increase the temperature above ambient air temperature (Duffková 2006; Kirkham 2014), increasing the canopy-air temperature differential (Tc-Ta) of water-stressed eggplant (Table 6). In this study, the canopy-air temperature of eggplant may increase 8–9 °C in summer and 1–2 °C (Tc-Ta) in fall under severe water stress ($I_{60\%}$) compared to full irrigation. Likewise, eggplant grown under CB-amended soil decreased the canopy-air temperature difference by 2–4 °C in summer and 0.5–2 °C in fall in comparison to plants grown without CB. These findings may be attributed to increases in the field capacity and available water content by application of CB. This finding is in agreement with those obtained in sorghum under water stress and application of compost by Abd El-Mageed et al. (2018).

All studied parameters were significantly affected by the growing season, which could be attributed to different climate conditions among both seasons (Abd El-Mageed and Semida 2015). Plant water status (RWC and MSI), stomatal conductance, relative chlorophyll content (SPAD), and chlorophyll

Table 9 Response of fruit yield and fruit quality of deficit irrigation-stressed eggplant (*Solanum melongena* L.) plants to co-composted poultry litter biochar applications under saline soil conditions

Source of variation	# of fruits	Fruit length (cm)	Fruit diameter (cm)	Fruit weight (g)	Yield (t ha^{-1})
Season (S)	*	NS	NS	*	*
Summer	23.61±0.91a	12.34±0.18a	3.01±0.38a	42.98±1.36b	24.45±0.92a
Fall	13.19±0.24b	12.78±0.20a	2.99±0.54a	57.96±1.10a	19.82±0.65b
Irrigation level (I)	*	*	*	*	*
$I_{100\%}$	22.67±1.23a	13.67±0.0.17a	3.16±0.23b	53.16±2.18a	28.29±0.94a
$I_{80\%}$	18.61±0.99b	12.61±0.16b	3.22±0.27a	52.16±2.04a	22.36±0.76b
$I_{60\%}$	13.91±0.54c	11.39±0.26c	2.63±0.68c	46.08±0.82b	15.76±0.48c
Co-Composted biochar (CB)	*	*	*	*	*
CB_0	16.24±0.96b	11.49±0.25c	2.76±0.71c	44.27±1.31c	16.69±0.59c
CB_1	19.30±1.30a	12.68±0.19b	2.99±0.41b	49.67±1.44b	22.12±0.81b
CB_2	19.69±0.87a	13.50±0.19a	3.25±0.28a	57.47±2.16a	27.60±1.02a
I×CB	**	**	**	**	**
$I_{100\%}$ X CB_0	21.17±0.169c	12.83±0.26 cd	3.01±0.51c	43.55±2.69e	21.18±0.46c
$I_{100\%}$ X CB_1	27.89±2.86a	13.67±0.21b	3.2±0.34b	48.05±3.75d	29.11±0.93b
$I_{100\%}$ X CB_2	18.94±0.78d	14.51±0.25a	3.19±0.16b	67.90±1.79a	34.58±1.36a
$I_{80\%}$ X CB_0	16.33±1.54f	12.19±0.28de	3.13±0.43bc	44.60±2.80e	17.25±0.59e
$I_{80\%}$ X CB_1	17.06±0.92ef	12.72±0.29 cd	3.14±0.29bc	52.61±1.91c	20.77±0.50c
$I_{80\%}$ X CB_2	22.44±2.19b	12.92±0.24bcd	3.38±0.43a	59.27±4.58b	29.05±0.72b
$I_{60\%}$ X CB_0	10.50±0.28 h	9.44±0.18f	2.08±0.69e	44.67±0.93e	11.63±0.19f
$I_{60\%}$ X CB_1	13.67±0.36 g	11.64±0.27e	2.60±0.25d	48.34±0.97d	16.48±0.44e
$I_{60\%}$ X CB_2	17.67±1.02e	13.08±0.34bc	3.19±0.38b	45.24±2.01e	19.18±0.42d

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; and "ns" refers to nonsignificant difference. Different letters next to mean values in each column indicate significant difference according to Duncan's multiple range test

fluorescence apparatus (F_v/fm, F_v/F_0, and PI) significantly differed between both growing seasons. Lower values of canopy-air temperature during the summer season compared to fall seasons, indicating that canopy temperature was lower than air temperature during summer and vice versa for fall season. Better growth characteristics and higher fruit yield due to increased fruit number were observed during the summer season. However, the IWUE was higher in the fall season may be due to lower IWA compared to the summer season.

In the present study, water stress indirectly hindered eggplant growth traits may be attributed to the drought-induced reduction of cell division and enlargement, resulting in the reduction of leaf area and the number of leaves, simultaneously with the reduction of stomatal conductance as well as the photosynthetic efficiency (Anjum et al. 2011; Osakabe et al. 2014). However, integrative application of CB and deficit irrigation at 80% ETc ameliorated the negative effects of water shortage on eggplant growth, showing increased plant height, number of leaves per plant, and shoot fresh and dry weight similar to those produced in fully irrigated plants untreated with CB. Also, compared to the CB untreated soil, the addition of 5 or 10 t ha^{-1} CB improved eggplant growth. The observed growth enhancement may be linked to the increased decomposition of CB and mineralization of nutrients. According to Wang et al. (2019) and Teodoro et al. (2020), CB may enhance plant growth by improving soil structure, providing nutrients, and increasing humic content, thereby increasing both nutrient and water-holding capacity and raising the available water content, in accordance of our findings. Further, the acidic effect of CB found in this research altered soil pH that could increase the availability of micronutrients for enhancing plant growth and productivity (Wang et al. 2019). In the greenhouse pot experiment, Schulz et al. (2013) found that the addition of CB improved oat growth (plant height and aboveground biomass) in both sandy and loamy soils.

In the current field study, deficit irrigation modulates the dry matter partitioning, showing that lower assimilates partitioning was directed for fruit production, thus reducing the HI in drought-stressed plants. Our results are in accordance with those reported by (Abd El-Mageed and Semida 2015; Fereres and Soriano 2007). Regarding CB, the HI increased corresponding to an increase in the CB rate, indicating that CB altered the dry matter distribution among plant organs.

Moreover, soil amended with CB produced higher fruit yield, fruit characteristics (length, diameter, and weight), and the number of fruits relative to the untreated soil. Semida et al. (2019) reported that the application of biochar decreased bulk density and increased soil field capacity, hence improving plant yield and water productivity. However, when eggplant is subjected to water stress, particularly under severe water deficit ($I_{60\%}$), the fruit yield drastically reduced that attributed to the decline of fruit weight and the number of fruits. These findings resulted from the water stress decreased tissue water content (RWC) and tissue health (MSI) and declined photosynthetic capacity and consequently hampered eggplant growth. Yazar et al. (2018) documented that the fruit yield and yield component (fruit number and mean fruit weight) of eggplant decreased as the irrigation water applied decreased up to 50% of the full irrigation under surface and subsurface drip irrigation. According to Karam et al. (2011), increasing the deficit irrigation from 80, 60, and 40% field capacity, the fruit yield of eggplant reduced by 60%. Reducing irrigation to 80% ETc for the plant grown under CB-amended soil alleviated the impact of water stress, showing an increase in the fruit yield compared with the plant grown under full irrigation without the addition of CB. In the pseudo-cereal *Chenopodium quinoa* grown in pots, growth and yield increased up to 305% as a result of co-composted biochar amended sandy-poor soil (Kammann et al. 2015).

In irrigated crops, it is necessary to maximize the IWUE, especially in dry areas. This can be done by increasing yields per unit of IWA, whereas in the water-limited area, it is more important for farmers to increase IWUE rather than the yield per unit area (Abdelkhalik et al. 2019b; Geerts and Raes 2009). In this research, the IWUE decreased in eggplant subjected to severe water stress ($I_{60\%}$) due to greater yield reduction compared to the water-saving achieved. This observation agrees with that obtained by Darko et al. (2019). In CB-amended saline soil eggplant, the IWUE value increased with the increasing addition of CB. Further, the highest IWUE was observed when combined application of 10 t ha^{-1} of CB with deficit irrigation at 80% ETc. Interestingly, to point out that application 10 t ha^{-1} of CB to eggplant grown under $I_{60\%}$ yielded similar fruit yield, provided important water-saving (40%), and increased the IWUE by 49% compared to full irrigation without application CB. Obadi et al. (2020) reported a similar finding indicating that integrated addition amendment mixture of biochar (2%) plus compost (2%) to drought-stressed sweet pepper at 80% ETc increased the IWUE by 103%. These improvements in eggplant yield, yield component, and IWUE could be attributed to the impact of CB. The CB improved the soil properties (Table 5) (i.e., bulk density, hydraulic conductivity, water-holding pores, useful pores, total porosity, available water content, and field capacity); chemical attributes (pH, ECe, organic matter); and soil biota (number of the bacterial cells). Therefore, CB improved soil-plant water relation (RWC and MSI), photosynthetic efficiency, and consequently increased plant growth. All the aforementioned factors are mainly responsible for improved crop productivity (Abd El-Mageed et al. 2020a, b; Singh et al. 2019).

Our results gave the utility of integrative application CB and irrigation at 80% of ETc for alleviating drought stress impacts on eggplant in dry-land areas. Nevertheless, the level 10 t ha^{-1} of CB may be prohibitively expensive in some regions that must be taken into consideration when considering these applications. However, in high salinity areas, the advantages may exceed the expenses, especially in crops with high economic value. Satisfactory benefits are also observed at lower rates, as this may give a reasonable other option. However, it would be interesting to evaluate in future research the long-term soil application of CB in crop rotation, also under other abiotic stress such as salinity and heavy metals.

5 Conclusions

Based on the results of this research, it can be concluded that the application of co-composted biochar alleviated the negative effects of drought-stressed eggplant cultivated in salt-alkaline soil. The study findings indicated that the co-composted biochar as a soil amendment improved soil physical properties (i.e., bulk density, hydraulic conductivity, water-holding pores, useful pores, available water content, and field capacity); chemical attributes (pH, ECe, organic matter); and soil biota (number of bacterial cells). Co-composted biochar amended soil increased leaf water content (RWC) and reduced cell membrane damage (MSI) and enhanced the efficiency of PSII; F_v/fm, F_v/F_0, and PI, and stomatal conductance, which reflected consequently in increase growth water-stressed eggplant at 80% ETc. Deficit irrigation, especially at a severe level, seriously affected eggplant growth, fruit yield, water status, and photosynthetic efficiency. The combined application of 10 t ha^{-1} co-composted biochar and water deficits at 80% of ETc produced satisfactory fruit yield and increased the irrigation water use efficiency up to 69%. Thus, it could be advisable to apply 10 t ha^{-1} co-composted biochar in combination with irrigation at 80% of ETc to maximize eggplant productivity under limited water conditions.

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Declaration

Conflict of Interest The authors declare no competing interests.

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