



Biochar Amendment Alleviates the Combined Effects of Salinity and Drought Stress on Water Productivity, Yield and Quality Traits of Sugar Beet (*Beta vulgaris* L.)

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Abstract

Salinity and drought are two commonly occurring major threats to agricultural yields worldwide, including sugar beet production. Therefore, this work aimed to determine the effectiveness of biochar amendment in improving soil health and alleviating the combined effects induced by salinity and drought on morphological, physiological and biochemical responses of sugar beet plants. Two field studies were established at the experimental farm of Fayoum University, Egypt over two successive winter seasons (2019/2020 and 2020/2021). The experiments were carried out in a split-split plot design with triplicate including three factors: 1) soil salinity, with two levels of EC_e ($< 4 \text{ dS m}^{-1}$ as control and 10 dS m^{-1}) as main-plot factor; 2) deficit irrigation regimes (I_{100} , I_{80} , and I_{60}) representing 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively as sub-plot factor; and 3) biochar amendment with three application levels (B_0 as control, B_{10} , and B_{20}) corresponding to 0, 10, and 20 t ha^{-1} , respectively as sub-sub plot factor. Drought and salinity stress induced significant reduction in growth attributes, relative water content, membrane stability, relative chlorophyll content (SPAD), yield and yield components of sugar beet plants. Meanwhile, the contents of sucrose, proline, Na, K, α amino-N were substantially increased with increasing stress severity. The application of biochar amendment improved the soil physical and chemical properties, resulting in better morphological, physiological and biochemical responses of saline-drought stressed sugar beet plants. Biochar at level (B_{20}) produced the highest values of root yield (95.02 t ha^{-1}) and sugar yield (20.24 t ha^{-1}) for full irrigated sugar beet plants in non-saline soil. Moreover, the application of biochar enhanced water productivity for drought and saline stressed sugar beet plants. Biochar amendment could be effectively used as a helpful agro-management strategy in alleviating the detrimental impacts of salinity and water stress on sugar beet plants, improving soil quality and enhancing water productivity to ensure water sustainability and food security, especially in areas of limited water supply.

Keywords Biochar · Salinity stress · Deficit irrigation · Water productivity · Sugar beet

1 Introduction

Sugar beet (*Beta vulgaris* L.) is recognized as an important industrial crop worldwide, ranking second in sugar production after sugarcane (Subrahmanyeswari and Gantait 2022). In Egypt, sugar beet cultivation accounted for a considerable portion of overall sugar yield, generating 1.42×10^6 tons of sugar, which represented 62.1% of the sum sugar production (Abdelwahab et al. 2022). The juice extracted

from sugar beet is particularly rich in sucrose. Moreover, sugar beet provides a variety of value-added byproducts that can be utilized in the manufacturing of eco-friendly chemical compounds and biodegradable polymer materials. These byproducts include biogas, lactic acid and bioethanol (Tomaszewska et al. 2018). The remaining parts of the sugar beet plant, including the tops with or without crowns, can be left in the field as green fertilizer or used for animal feed as ensilage. Furthermore, sugar beet pulp, along with molasses, is extensively used as a livestock feed supplement, as it is processed into high-fiber dietary food additives (Dygas et al. 2023). However, the production of sugar beet faces considerable challenges induced by abiotic stresses like salinity and drought (Shabbir et al. 2022; Yolcu et al. 2022).

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Salinity and drought stand as the predominant abiotic stresses that greatly hinder agricultural yields on a global scale (Ma et al. 2020). Under such unfavorable environmental conditions, ensuring the growth and productivity of crops emerges as a primary challenge in modern agriculture. The detrimental impacts of drought and salinity on agriculture are further exacerbated by the scars of water resources, climate changes and rising food demand (Seleiman et al. 2021; Ullah et al. 2021). These factors have emerged as critical limitations of reduced crop productivity and, consequently, food security, intensifying the urgency for the agricultural sector to adopt more efficient water management practices.

Over the past fifty years, land salinization has emerged as a significant constraint in agriculture (Dewi et al. 2022; Hayat et al. 2020). Currently, around 33% of the world's cultivable land experiences salinization, resulting in substantial decreases in agricultural productivity (Devkota et al. 2022). Elevated salt concentrations have adverse impact on the physiological and biochemical functions of plants, which limiting the growth and development of both root and aerial systems (Ran et al. 2021; Shahid et al. 2020). The presence of salts induces two forms of stress in plants, namely osmotic and ionic stress (Khare and Jain 2021). The decrease in water potential due to elevated soil salinity levels leading to a decline in water absorption by plant roots (González et al. 2021). Simultaneously, the high accumulation of Na^+ and Cl^- ions in plant cells leads to toxicity and nutritional imbalances (dos Santos et al. 2022). Water deficit arises when the water demand of a plant cannot be adequately met, whether due to insufficient precipitation or irrigation, leading to disruptions in the plant's optimal functioning (i.e. impaired growth, reduced photosynthesis rate and decreased stomatal conductance (dos Santos et al. 2022). Notably, drought stress causes significant reductions in crop productivity, this may refer to impaired performance of various photosynthesis-related traits (Zhang et al. 2020).

Plants experience osmotic stress as a result of drought and/or salt stress, leading to restricted cell extension and expansion, ultimately hindering plant growth (Zhao et al. 2021). Furthermore, drought and salt stress trigger oxidative stress in plants by stimulating the production reactive oxygen species (ROS) (Kesawat et al. 2023). Under environmental stress, their concentration rises, leading to stomatal closure which in turn minimize water loss (Hasanuzzaman et al. 2021). This increased level of ROS in plant tissues leads to oxidative damage to proteins, membrane lipids and nucleic acids (Juan et al. 2021; Ozturk et al. 2021). According to (Awadalla et al. 2021) sugar beet demonstrates significant tolerance to water stress, displaying slight variations in agronomic traits between well-irrigated and mildly drought-affected plants. Nevertheless, (Mahmoud et al. 2018) revealed a noteworthy rise in the sucrose content of sugar beet when subjected to limited water availability.

However, enhancing the water status of the plant leads to improvements in plant growth characteristics, SPAD value, chlorophyll fluorescence and irrigation productivity (Ibrahim et al. 2022; Ma et al. 2020). Interestingly, it is worth to mention that, plants under adverse conditions to regulate their water balance, have developed a range of adaptation mechanisms at various levels, including morphological, anatomical, physiological and biochemical responses (Abdou et al. 2022; Kapoor et al. 2020; Saddhe et al. 2021).

Organic amendments, including compost, biochar, farm-yard manure and poultry manure, have been widely utilized as eco-friendly solutions to enhance soil quality and crop productivity (Gaudutis et al. 2023; Su et al. 2022). Certainly, the utilization of organic amendments results in the enhancement of the organic carbon stock, improving the soil cation exchange capacity, which in turn improves the soil nutrient retention capacity, consequently enhances the soil fertility for crop production (Abdou et al. 2023; Rashmi et al. 2023). Moreover, the decomposition of organic materials enhances the release of nutrient elements in the soil (Gerke 2022). Among these organic materials, biochar, as a promising soil amendment, demonstrates high potential in enhancing soil health and fertility. Biochar, a carbon-rich substance acquired through the thermochemical transformation of biomass under conditions of limited oxygen (Saranvanan and Kumar 2022). Different types of lignocellulosic materials, including plant residues, animal manure, food waste, sludge, etc. can be converted into biochar through processes such as pyrolysis, hydrothermal carbonization, or gasification (Low and Yee 2021). Typically, biochar exhibits a porous structure, an alkaline pH, and a significant amount of carbon content (Tomczyk et al. 2020). Amending soil with biochar leads to an increase in soil carbon content, reduction in nutrient leaching (Banik et al. 2021; Hossain et al. 2020), improvement in soil fertility, microbial activity, nutrient uptake and plant growth (Alkharabsheh et al. 2021). These positive effects of biochar can be attributed to the enhancement of soil physicochemical properties, such as soil bulk density, soil moisture content, soil pH, cation exchange capacity, electrical conductivity, organic carbon content, nutrient availability and enzyme activity (Ghorbani et al. 2022; Ndede et al. 2022; Singh et al. 2022).

Numerous studies have been done to examine the individual effects of salinity and drought on sugar beet plant growth and yield (Bouras et al. 2021; Ghaffari et al. 2021; Karagöz et al. 2018; Lebrun et al. 2022; Mansuri et al. 2018). However, worldwide, there are limited studies that focused on understanding how sugar beet plants respond to the simultaneous stress of both salinity and drought. Furthermore, the existing information regarding the utilization of biochar amendments to enhance sugar beet plant resilience under the adverse influences of salinity and drought conditions remains insufficient. This research hypothesizes that the

biochar-amended soil will exhibit improved physicochemical properties that will enhance the performance of sugar beet plants to withstand combined salinity and drought stress. Therefore, the aims of this investigation were to evaluate the performance of sugar plants to associated detrimental impacts of salinity and drought stresses and determine the potential of biochar amendment in mitigating the salinity-drought negative impacts on the morpho- biochemical and physiological responses of sugar beet plants.

2 Materials and Methods

2.1 Field conditions

2.1.1 Climate

This field study was established at the experimental station of the Faculty of Agriculture, Fayoum University, Egypt, situated at latitude 29°29'_N and longitude 30°91'_E. Based on (Table 1), the climate conditions at the experimental site can be described as arid, with hot summers and limited or no rainfall in winter. During the sugar beet growing season (October—April), the highest temperature of 33.0 °C was recorded in October 2020, while the lowest temperature of 8.3 °C was recorded in February 2021. The evaporation values measured by Pan evaporation corresponded to the variations in air temperature. The maximum evaporation values, 4.8 and 5.2 mm per day, were noted for October and April, respectively. Conversely, the lowest values of 1.45 and 1.55 mm per day were registered in

December and January, respectively. The monthly weather data for two seasons were provided by from the Fayoum meteorological station, Egypt.

2.1.2 Soil properties

This field-study was carried out in newly reclaimed soils, which had a sandy loam texture. The selected soils of experimental site were divided into two categories based on their salinity levels: non-saline soil with an electrical conductivity (ECe) of less than 4 dS m⁻¹, and saline soil with an ECe of 10.30 dS m⁻¹. The physical properties of the soil were measured according to (Klute and Dirksen 1986) method, and presented in (Table 2). The average values of soil bulk density (1.56 Mg m⁻³) and hydraulic conductivity (2.39 cm h⁻¹) were observed in the non-saline soil (soil depth of 0–60 cm), meanwhile, in the saline soil, the corresponding values were 1.57 Mg m⁻³ and 2.46 cm h⁻¹. The available water content at the same soil depth of 0–60 cm, averaged 11.02 and 10.60% in the non-saline and saline soils, respectively. Soil chemical analysis, was done following the method described by (Page 1982). In the non-saline soil (0–60 cm soil depth) the average values of soil pH (1:2.5 soil–water extracts) of 7.52, the content of organic matter (O.M) of 0.78%, cation exchangeable capacity (CEC) of 10.03 (cmole kg⁻¹), and CaCO₃ content of 6.63%. However, in the saline soil, the corresponding main values of these parameters: soil pH, O.M, CEC, and CaCO₃ were 7.52, 0.67%, 9.71 (cmole kg⁻¹), and 7.21% respectively, at the same soil depth of 0–60 cm.

Table 1 Climatic condition at the experimental site during sugar beet cultivation seasons (2019–2020 and 2020–2021)

Months	seasons	Temperature (°C)			P.E	W.S	Rainfall	R.H
		T ^{max}	T ^{min}	T ^{mean}				
Oct	2019	32.3	18.6	25.5	4.5	2.0	4.10	39
	2020	33.0	21.6	27.3	4.8	2.0	3.64	38
Nov	2019	26.2	13.4	19.8	2.3	1.9	5.31	42
	2020	28.1	15.6	21.9	2.1	1.7	5.11	40
Dec	2019	23.6	12.7	18.2	1.4	1.8	7.14	43
	2020	21.1	9.5	15.3	1.5	1.9	5.87	43
Jan	2020	21.3	9.4	15.4	1.5	2.2	8.12	42
	2021	20.4	8.5	14.5	1.6	1.9	7.20	43
Feb	2020	23.4	9.7	16.6	1.5	1.8	8.45	42
	2021	22.0	8.3	15.2	2.3	2.0	4.67	40
Mar	2020	29.4	12.7	21.1	4.0	2.1	11.3	37
	2021	26.7	12.7	19.7	3.5	2.2	6.57	38
Apr	2020	31.1	13.9	22.5	4.4	2.2	7.10	36
	2021	31.2	14.2	22.7	5.2	2.2	3.70	35

T^{max}, T^{min}, T^{mean} are temperature degree, maximum temperature, minimum temperature and mean temperature respectively; P.E.: Pan evaporation (mm day⁻¹); W.S.: wind speed (m sec⁻¹); R.H.: relative humidity%; rainfall (mm. month)

Table 2 Initial soil physico-chemical analysis of experimental site

Some initial physical characteristics of the experimental soil										
Soil type	Depth (cm)	Particle size distribution, %			Texture	ρ_b	K_{sat}	F.C	W.P	A.W
		Sand	silt	clay						
Non-saline soil	0–20	73.30	13.20	13.50	S.L	1.53	2.07	22.76	10.48	12.28
	20–40	75.50	12.30	12.20	S.L	1.55	2.14	21.41	10.28	11.13
	40–60	80.00	9.50	10.50	S.L	1.59	2.95	19.06	09.42	09.64
Saline soil	0–20	75.80	11.50	12.70	S.L	1.55	2.12	21.54	10.34	11.20
	20–40	76.60	12.50	10.90	S.L	1.58	2.43	20.43	09.87	10.56
	40–60	79.90	9.60	10.50	S.L	1.59	2.83	19.20	09.15	10.05
Some initial chemical characteristics of the experimental soil										
	depth (cm)	ECe	pH	O.M		CEC		CaCO ₃ %		
Non-saline soil	0–20	3.36	7.52	0.81		10.35		6.58		
	20–40	3.14	7.50	0.79		10.11		7.21		
	40–60	3.22	7.54	0.73		09.62		6.09		
Saline soil	0–20	10.50	7.56	0.79		10.16		7.89		
	20–40	10.21	7.51	0.65		09.64		6.21		
	40–60	10.19	7.49	0.58		09.32		7.54		

ρ_b : bulk density ($Mg\ m^{-3}$); K_{sat} : soil hydraulic conductivity ($cm\ h^{-1}$); F.C.: field capacity (%); A.W.: available water (%); ECe: Electrical conductivity (dSm^{-1}); O.M.: organic matter (%); CEC: cation exchangeable capacity ($cmole\ kg^{-1}$)

2.2 Treatments

The experimental setup followed a split-split plot design within randomized complete blocks with three factors considered: soil salinity levels, deficit irrigation treatments and application rates of biochar amendment. Each treatment combination had three replicates. The main plots were allocated for soil salinity, consisting of two levels: $<4\ dS\ m^{-1}$ (control) and $10\ dS\ m^{-1}$. Sub-main plots were designated for deficit irrigation treatments, namely I_{100} , I_{80} , and I_{60} , representing 100, 80, and 60% of crop evapotranspiration (ETc) respectively. These sub-main plots were surrounded by dikes with a width of 2 m. The sub-sub plots were used for biochar amendment application rates denoted as B_0 (control), B_{10} , and B_{20} , corresponding to 0, 10, and 20 tons per hectare respectively. The area of each sub-sub plot was $10.5\ m^2$ ($3 \times 3.5\ m$), while the area for each irrigation treatment was approximately $93\ m^2$.

2.3 Irrigation water applications

At intervals of 10 days, sugar beet plants were subjected to irrigation with varying amounts of irrigation water applied (IWA). The daily reference evapotranspiration (ETo) values were calculated using Eq. (3.1) as described by (Allen et al. 1998).

$$ET_o = E_{pan} \times K_{pan}$$

$$ET_c = ET_o \times K_c$$

Where

E_{pan} evaporation from the Class A pan ($mm\ day^{-1}$)

K_{pan} coefficient of pan evaporation

ETc crop evapotranspiration and

Kc crop coefficient.

The applied irrigation water application (IWA) (m^3/ha), in correspondence to the designed irrigation regimes, was conducted according to (Vermeiren and Jobling 1980)

$$IWA = \frac{ET_c}{Ea \times (1 - LR)} \times 10$$

Where

ETc denotes the crop evapotranspiration ($mm\ day^{-1}$)

Ea represents the irrigation application efficiency as a percentage (%)

LR Leaching requirement.

2.4 Biochar amendment

The utilized biochar amendment in this study was produced through the pyrolysis process, involving the burning of trees and plant waste in an oxygen-depleted or

oxygen-limited environment at temperatures ranging from 600 to 700 degrees. The chemical analysis of used biochar amendment is presented in (Table 3).

2.5 Plant under study

Seeds of the sugar beet (*Beta vulgaris* L., Baraca) were obtained from the Crop Research Institute, Agricultural Research Center and manually sown on October 1st in 2 consecutive winter seasons during 2 years (2019/2020 and 2020/2021). In hills the seeds were planted, with a spacing of 20 cm between each hill and a distance of 60 cm between rows. The addition of biochar amendment to the experimental soil was done manually one week prior to sowing. At 4 true leaves age, the beet plants were thinned to maintain (one plant hill⁻¹). Nitrogen fertilization was added at a rate of 109 kg N per hectare using urea (46.5%N). The nitrogen fertilizer was splitted into two equivalent doses, the 1st dose was done after thinning at the stage of 4 leaves per plant, while the 2nd dose was added one month later. Phosphorus fertilization, using super phosphate with a phosphorus content of 15.5% (P₂O₅), was performed at a rate of 70 kg P₂O₅ per hectare at sowing. Additionally, potassium fertilization was conducted after thinning using potassium sulfate with a potassium content of 48% (K₂O), was done at a rate of 60 kg K₂O per hectare. All other agronomic cultural practices, as well as disease and pest management for sugar beet, followed local commercial sugar beet production methods. In each season, the sugar beet plants were harvested after 190 days from planting.

2.6 Morphological measurements

At harvest in both seasons (190 days from planting) a random sampling of 10 guarded plants from each sub-sub plot was conducted. Root length in cm (RL) assessed with a meter-scale from the point of separation to the tip of the taproot. Leaf area per plant (LA in dm²) was measured using a digital planometer (Planix 7). Root diameter in cm (RD) was determined at the widest area of the root using a vernier caliper. Fresh weight and dry weight were measured using a digital balance.

Table 3 Characteristics of applied biochar amendment

	O.C	N %	C / N Ratio	pH	ECe	CaCO ₃ %	K	P	Moisture content (%)
value	45.10	0.90	50.11	7.80	4.10	1.35	4.90	3.40	35.30

O.C: organic carbon content %; N: Nitrogen; C/N ratio: carbon/nitrogen ratio; ECe: Electrical conductivity (dSm⁻¹); K: potassium (g kg⁻¹); P: phosphorus (g kg⁻¹)

2.7 Physiological Measurements

At 110 days from sowing, three randomly selected sugar beet plants were collected to determine plant physiological responses. leaf relative water content (LRWC%) and membrane stability index (MSI%) of fully expanded fresh leaves were determined. The (LRWC%) was determined following the method outlined in (Barrs 1968), while the MSI% was determined according to the method described by (Premachandra et al. 1990). To assess the relative chlorophyll concentration, a chlorophyll meter (SPAD502, KONICAMINOLTA. Inc., Tokyo) was used.

2.8 Osmoprotectants: Total soluble sugars and Proline contents:

The extraction and determination of total soluble sugars content (TSS; mg g⁻¹ dry weight; DW) were performed using a professional method (Irigoyen et al. 1992). The extraction was carried out with 96% ethyl alcohol, and the measurement of TSS was done by recording the absorbance at 625 nm using a UV-160A UV Visible Recording Spectrometer, Shimadzu, Japan. The estimation of proline content was conducted using a rapid colorimetric method, and the absorbance was measured at 520 nm following the procedure described by (Bates et al. 1973).

2.9 Quality parameters

2.9.1 Juice impurities

The percentages of sodium and potassium were measured by flame photometer. The amount of α-amino N (using ninhydrin and hydrindantin method) was assessed as described by (Carruthers et al. 1962).

2.9.2 Juice Quality

The percentage of sucrose was measured as mentioned by (Le Docte 1927).

The calculation of juice purity percentage was performed according to the following equation: Purity % = 99.36 - [14.27 (Na% + K% + α-amino N %) / sucrose %] (Devillers 1988).

Molasses lost sugar (MLS) was expressed as the following: MLS = 0.14(Na% + K%) + 0.25 (α-amino N %) + 0.5 (Devillers 1988). Extractable sugar % = sucrose % - SM - 0.6 (De Xter et al. 1967).

2.10 Sugar Beet Yields

All sugar beet plants, including the previously sampled 10, within each experimental plot were gathered, cleaned, topped, and weighed. This was done to determine the root yield (RY ton ha⁻¹) and top yield (TY ton ha⁻¹), while the sugar yield (SY ton ha⁻¹) was calculated by multiplying the root yield by the sucrose percentage (sucrose%).

2.11 Water Productivity (WP) of Sugar Beet Crop

The water productivity was quantified as the yield of sugar beet roots (in kg) per cubic meter of water consumed. The calculation of WP values followed the equation proposed by (Jensen et al. 1983).

$$WP(\text{kgm}^{-3}) = \text{Roots yield (kg ha}^{-1}) / \text{applied irrigation water (m}^3\text{ha}^{-1})$$

2.12 Statistical analysis

Was done in split-split plot design within a randomized complete block design (RCBD), using the Genstat computer software package (version 11, VSN International Ltd., Oxford, UK). To determine significant differences among the variable means, Duncan's multiple range test was applied at a significance level of $\alpha \leq 0.05$.

3 Results

3.1 Soil properties

Results outlined in (Table 4) showed that, biochar amendment had an ameliorative effect on saline and non-saline soil properties. Soil bulk density (ρ_b) was decreased in biochar amended plots. This reduction was significant under used high levels of biochar (B_{20}) as compared with non-biochar amended plots (B_0). The decline in ρ_b was linked to a substantial increase in soil total porosity (TP). Under biochar application rate 20ton ha⁻¹, TP in saline soil was increased by 5.52% compared with control. Interestingly, the use of biochar alters pore geometry, causing a significant decrease in quickly drainable pores (QDP) which associated with a significant increase in

slowly drainable pores (SDP). QDP showed a substantial reduction by 14.23 and 20.23% in normal and saline soils respectively, meanwhile the increase in SDP under the same soil types amounted 22.13 and 34.38% respectively, in comparison with control (B_0). The soil in two experimental sites is sandy loam in texture, indicating lower water retaining capacity. Used biochar amendment showed a positive effect on water holding capacity and water movement. Comparing with non-amended soils, the fraction of water holding pores (WHP) was increased by 16.65 and 20.05% in non-saline and saline soil respectively, due

Table 4 Effect of soil amendment application levels on soil properties (in 0–20 cm soil depth)

Parameter	unit	Non- saline soil			Saline soil		
		B_0	B_{10}	B_{20}	B_0	B_{10}	B_{20}
ρ_b	Mg m ⁻³	1.53 ± 0.01a	1.52 ± 0.01ab	1.50 ± 0.02b	1.54 ± 0.01a	1.52 ± 0.01ab	1.51 ± 0.02b
K sat	cm h ⁻¹	1.99 ± 0.02a	1.84 ± 0.01b	1.53 ± 0.03c	1.89 ± 0.02a	1.76 ± 0.01b	1.64 ± 0.01c
T.P	%	42.26 ± 0.01b	42.64 ± 0.03ab	43.40 ± 0.04a	41.13 ± 0.03c	42.26 ± 0.02b	43.40 ± 0.02a
Q.D.P	%	9.56 ± 0.01a	8.94 ± 0.01b	8.20 ± 0.02c	10.28 ± 0.01a	9.11 ± 0.01b	8.20 ± 0.03c
S.D.P	%	4.88 ± 0.02c	5.54 ± 0.01b	5.96 ± 0.03a	3.84 ± 0.01c	4.39 ± 0.04b	5.16 ± 0.07a
W.H.P	%	12.13 ± 0.07c	13.27 ± 0.02b	14.15 ± 0.02a	11.57 ± 0.04c	12.68 ± 0.01b	13.89 ± 0.01a
F.c	%	22.35 ± 0.03c	23.58 ± 0.05b	24.55 ± 0.01a	21.13 ± 0.01c	22.63 ± 0.02b	23.65 ± 0.01a
A.W	%	12.13 ± 0.01c	13.27 ± 0.04b	14.15 ± 0.04a	11.57 ± 0.01c	12.68 ± 0.04b	13.89 ± 0.01a
pH		7.51 ± 0.04b	7.75 ± 0.04a	7.69 ± 0.01a	7.44 ± 0.01b	7.64 ± 0.04a	7.65 ± 0.02a
ECe	dSm ⁻¹	3.62 ± 0.02b	3.33 ± 0.01c	3.81 ± 0.01a	9.71 ± 0.01a	9.58 ± 0.02a	8.87 ± 0.01b
O.M	%	1.17 ± 0.01c	1.53 ± 0.01b	1.84 ± 0.01a	0.97 ± 0.01c	1.26 ± 0.01b	1.46 ± 0.02a
CEC	cmole kg ⁻¹	11.33 ± 0.02c	14.15 ± 0.02b	15.11 ± 0.1a	9.57 ± 0.02c	13.44 ± 0.01b	14.87 ± 0.05a

B_0 , B_{10} and B_{20} are biochar incorporation rates (t ha⁻¹); ρ_b : bulk density; K_{sat} : soil hydraulic conductivity; T.P.: total porosity; Q.D.P.: quickly drainable pores; S.D.P.: slowly drainable pores; W.H.P.: water holding pores; F.C.: field capacity; A.W.: available water; ECe: Electrical conductivity; O.M.: organic matter; CEC: cation exchangeable capacity; All values provided in the table represent means, and those accompanied by distinct letters indicate significant differences ($p \leq 0.05$) according to Duncan's multiple range test (DMRT); *indicate significant differences at $p \leq 0.05$

to biochar application level (B_{20}). Furthermore, the implementation of biochar has significantly reduced the values of saturated hydraulic conductivity (K_{sat}) which in turn enhanced the soil's water retention capacity. In normal and saline soil, the reduction in K_{sat} amounted 23.12 and 12.23% respectively as a result of conducted biochar with 20ton ha^{-1} against control. Field capacity also showed a considerable increase by 9.84 and 11.39% under normal and saline soils respectively, owing to biochar addition with 20ton ha^{-1} versus control. Interestingly it is worth noting that, a slight increase in soil pH was observed in response of biochar application compared with control. However, the variations in pH values in correspondence of used moderate and high levels of biochar statistically were not-significant in both soil types. Organic matter content was significantly increased in normal and saline soil by 57.26 and 50.52% respectively resulted by biochar addition with 20ton ha^{-1} compared with control. In addition, the determined soil cation exchangeable capacity (CEC) in both experimental sites were significantly increased in correspondence of used biochar amendment. Respecting to soil salinity the application of biochar had an opposite effect on soil salinity. In normal soil, the addition of biochar resulted in a slight increase in soil salinity, meanwhile in saline soil, the ECe value were decreased with biochar amendment.

3.2 Growth Traits

Data involved in (Tables 5 and 6) showed inhibitory effects generated by drought and/or osmotic stress on growth performance of sugar beet plants. Growth traits [i.e. root length (RL), root fresh weight (RFW), root dry weight (RDW), top fresh weight (TFW), top dry weight (TDW), leaf area (LA) and root/top ratio (R/T)] of sugar beet plants were significantly reduced in correspondence to salinity and drought stresses. In saline soil the decrease in RL, RFW, RDW, TFW, TDW, LA and R/T were 10.78, 48.04, 11.25, 38.05, 43.92 and 19.04% respectively as compared with non-saline soil. Statistically, the data indicated non-significant differences in root diameter of sugar beet plants due to increased salinity stress. Similar to, salinity, the used deficit irrigation caused morphological disorders in sugar beet plants. Under moderate water stress condition (I_{80}), the values of RL, RD, RFW, RDW, TFW, TDW, LA and R/T were declined by 5.30, 7.11, 18.87, 33.33, 23.33, 16.31, 11.98 and 20.78%, respectively compared with full irrigation treatment. The maximum decrease was observed under water stress level (I_{60}) by 14.69, 18.23, 50.33, 56.48, 47.92, 37.59, 23.59 and 3.17% for RL, RD, RFW, RDW, TFW, TDW, LA and R/T respectively lower than adequately watered plants. Conversely, the addition of biochar had a stimulating effect on vegetative growth of stressed and normally grown sugar beet plants.

Table 5 Root morphological responses of sugar beet plants to salinity levels, deficit irrigation regimes and biochar amendment

Treatments	RL	RD	RFW	RDW
Year	NS	NS	NS	NS
2019/2020	26.42a ± 0.14	14.50a ± 0.02	2.34a ± 0.01	0.75a ± 0.01
2020/2021	26.05a ± 0.12	13.82a ± 0.04	2.31a ± 0.02	0.74a ± 0.01
Soil salinity (S)	*	NS	*	*
S ₁	27.73a ± 0.18	14.17a ± 0.01	3.06a ± 0.04	0.80a ± 0.009
S ₂	24.74b ± 0.19	14.15a ± 0.09	1.59b ± 0.03	0.71b ± 0.01
Irrigation (I)	*	*	*	*
I ₁₀₀	28.11a ± 0.24	15.47a ± 0.11	3.02a ± 0.04	1.08a ± 0.02
I ₈₀	26.62b ± 0.23	14.37b ± 0.14	2.45b ± 0.05	0.72b ± 0.01
I ₆₀	23.98c ± 0.25	12.65c ± 0.13	1.50c ± 0.01	0.47c ± 0.01
Biochar (B)	*	*	*	*
B ₀	22.89c ± 0.24	11.58c ± 0.11	1.68c ± 0.05	0.53c ± 0.02
B ₁₀	26.47b ± 0.21	14.28b ± 0.15	2.47b ± 0.03	0.74b ± 0.01
B ₂₀	29.35a ± 0.25	16.62a ± 0.12	2.83a ± 0.07	0.99a ± 0.02
S × I	*	*	*	*
S × B	*	*	*	*
I × B	*	*	*	*
S × I × B	*	*	*	*

S₁: non-saline soil (<4 dS m^{-1}); S₂: saline soil (10 dS m^{-1}); I₁₀₀, I₈₀, and I₆₀ represent 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha^{-1} , respectively; RL: root length (cm); RD: root diameter (cm); RFW: root fresh weight (Kg plant⁻¹); RDW: root dry weight (Kg plant⁻¹); All values provided in the table represent means, and those accompanied by distinct letters indicate significant differences ($p \leq 0.05$) according to Duncan's multiple range test (DMRT); * indicate significant differences at $p \leq 0.05$

Table 6 Top morphological responses of sugar beet plants to salinity levels, deficit irrigation regimes and biochar amendment

Treatments	TFW	TDW	LA	R/T ratio
Year	NS	NS	NS	NS
2019/2020	1.89a ± 0.12	1.17a ± 0.15	97.60a ± 2.29	0.64a ± 0.01
2020/2021	1.78a ± 0.14	1.14a ± 0.12	96.31a ± 1.97	0.65a ± 0.03
Soil salinity (S)	*	*	*	*
S ₁	2.26a ± 0.02	1.48a ± 0.03	107.15a ± 1.11	0.54a ± 0.01
S ₂	1.40b ± 0.03	0.83b ± 0.04	86.75b ± 1.07	0.86b ± 0.009
Irrigation (I)	*	*	*	*
I ₁₀₀	2.40a ± 0.04	1.41a ± 0.02	110.09a ± 1.54	0.77a ± 0.02
I ₈₀	1.84b ± 0.02	1.18b ± 0.02	96.90b ± 1.31	0.61b ± 0.01
I ₆₀	1.25c ± 0.01	0.88c ± 0.01	83.86c ± 1.14	0.53c ± 0.01
Biochar (B)	*	*	*	*
B ₀	1.47c ± 0.03	0.98c ± 0.009	85.81c ± 1.31	0.54c ± 0.01
B ₁₀	1.82b ± 0.02	1.11b ± 0.02	96.44b ± 1.61	0.67b ± 0.02
B ₂₀	2.20a ± 0.02	1.38a ± 0.03	108.60a ± 1.71	0.72a ± 0.04
S × I	*	*	*	*
S × B	*	*	*	*
I × B	*	*	*	*
S × I × B	*	*	*	*

S₁: non-saline soil (<4 dS m⁻¹); S₂: saline soil (10 dS m⁻¹); I₁₀₀, I₈₀, and I₆₀ represent 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha⁻¹, respectively; TFW: top fresh weight (kg plant⁻¹); TDW: top dry weight (kg plant⁻¹); LA: leaf area (dm²); R/T: root/top ratio; All values provided in the table represent means, and those accompanied by distinct letters indicate significant differences ($p \leq 0.05$) according to Duncan's multiple range test (DMRT); * indicate significant differences at $p \leq 0.05$

The increase in plant growth corresponded with the higher levels of biochar application. Accordingly, the use of biochar levels B₁₀ and B₂₀ resulted increase in RL by (15.64 and 28.22%), RD by (23.32 and 43.52%), RFW by (47.02 and 68.45%), RDW by (39.02 and 86.79%), TFW by (23.81 and 49.66%), TDW by (13.27 and 40.82%), LA by (12.39 and 26.56%) and R/T by (24.07 and 33.33%) respectively, higher than non-biochar amended plants (control plots). Moreover, it is important to highlight that the interaction among the applied treatments demonstrated a positive impact of biochar amendment, particularly at a rate of 20 t ha⁻¹ on growth performance of sugar beet plants which cultivated in normal soil and received irrigation at level (I₁₀₀). Meanwhile, the lowest values of growth parameters were given with increasing the degree of soil salinity and drought stress, especially for non-biochar amended plants.

3.3 Physiological Response

The present investigation revealed considerable impacts on the physiological responses of sugar beet in relation to the applied experimental treatments, including salinity stress, drought stress, and biochar amendment, as well as their interactions. Leaf relative content (LRWC) (Fig. 1a), membrane stability index (MSI%) (Fig. 1b) and relative chlorophyll content (SPAD) (Fig. 1c) were reduced by 8.96, 4.72

and 7.10% respectively in correspondence to increased levels of soil salinity. Similarly, water stress negatively affected these traits. As compared with full irrigation, the reduction in LRWC, MSI and SPAD amounted 8.96, 5.91 and 14.67% respectively under severe water stress level (I₆₀). In contrast the use of biochar mitigated the adverse effects of salinity and drought and enhanced the plant physiological responses. Enriching the soil with a high level of biochar amendment (B₂₀) contributed to a significant increase in LRWC, MSI and SPAD by 5.94, 5.71, 8.87% respectively over control plots. Furthermore, the greatest values of LRWC, MSI% and SPAD) are given for sugar beet plants that treated with (I₁₀₀ × B₂₀) in non-saline soil. Conversely, beet plants exposed to (S₂ × I₆₀ × B₀) produced the lowest values of these physiological parameters.

3.4 The Accumulation of Osmoprotectants

The adverse conditions created by drought and salinity stresses triggered sugar beet plants to enhance the levels of some substances in their roots including total soluble sugar and sucrose as well as proline content in their leaves. Total soluble sugar (TSS, (mg g⁻¹ dry weight of root beet)) showed a significant increase as water stress increased (Fig. 2a). Compared with full irrigation, TSS was increased by 10.05 and 19.68% in response of increasing drought stress

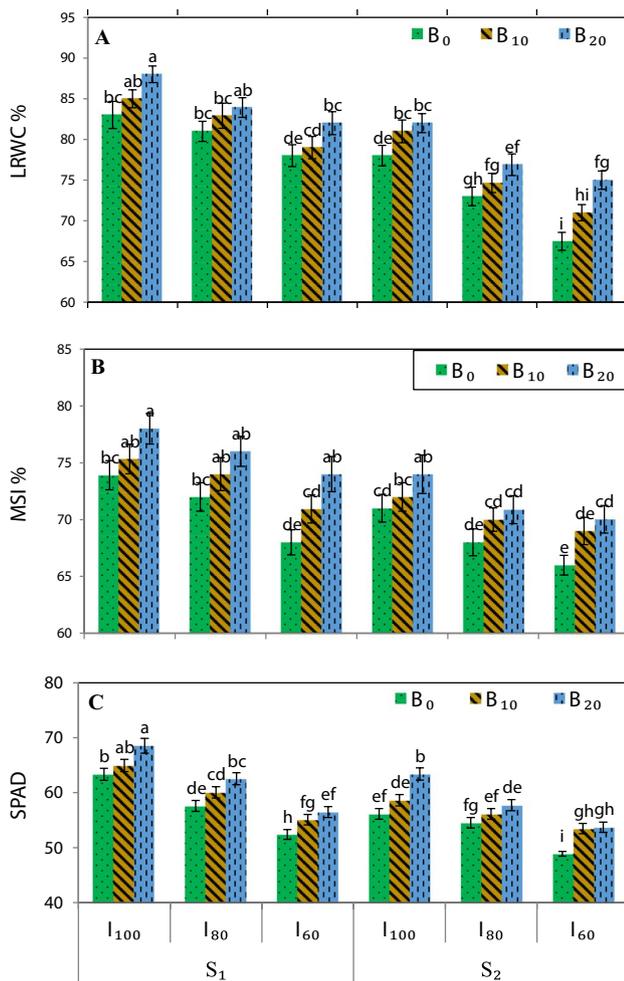


Fig. 1 The influence of soil salinity levels, water stress regimes and biochar incorporation rates on (a) leaf relative water content (LRWC), (b) membrane stability index (MSI) and (c) relative chlorophyll content (SPAD) of sugar beet plants. S₁, non-saline soil (<4 dS m⁻¹); S₂, saline soil (10 dS m⁻¹); I₁₀₀, I₈₀, and I₆₀ represents 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha⁻¹, respectively; Columns marked with the same letter are not significantly different ($p \leq 0.05$) according to Duncan's multiple range test (DMRT)

levels to (I₈₀) and (I₆₀) respectively. Salinity also induced a significant increase by 27.61% in TSS compared with control. The addition of biochar enhanced the accumulation of TSS in roots of sugar beet plants. The addition of biochar with 10 and 20 ton ha⁻¹ resulted significant increase in TSS by 12.09 and 24.04% respectively over control (B₀). The percentage of sucrose showed its highest value for biochar-amended sugar beet plants at level of (B₂₀) and subjected to severe drought level (I₆₀) in saline soil (Fig. 2b). However, the lowest value of sucrose was measured in combined treatment (S₁ × I₁₀₀ × B₀). Saline stress stimulated the accumulation of sucrose in beet roots, leading to a significant increase by 16.33% compared with non-saline soil (S₁). Similar trend

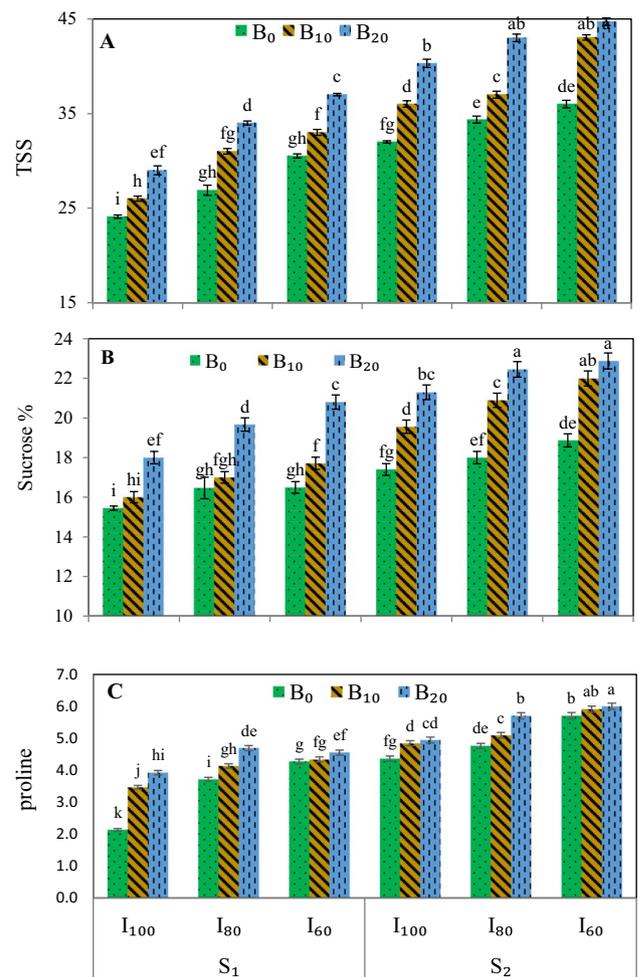


Fig. 2 The influence of soil salinity levels, water stress regimes and biochar incorporation rates on (a) Total soluble sugar (TSS) (mg g⁻¹ dry weight of root beet), (b) sucrose (%) and (c) proline (mg g⁻¹ dry weight of leaves) of sugar beet plants. S₁, non-saline soil (<4 dS m⁻¹); S₂, saline soil (10 dS m⁻¹); I₁₀₀, I₈₀, and I₆₀ represents 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha⁻¹, respectively. Columns marked with the same letter are not significantly different ($p \leq 0.05$) according to Duncan's multiple range test (DMRT)

was also observed under drought stress. The applied deficit irrigation induced significant increase in sucrose% by 6.29 and 10.25% for moderate (I₈₀) and intense drought stress (I₆₀) respectively compared with well irrigated sugar beet plants (I₁₀₀). Biochar amendment had apposite effect on sucrose accumulation in roots of sugar beet plants. In this regard, the applied biochar at moderate and high levels contributed to a substantial increase by 10.19 and 21.82% respectively over control (B₀). Interestingly, it is worth noting that, the determined proline in leaves of sugar beet plants showed significant differences due to applied treatments (Fig. 2c). As increased levels of applied water stress, the

values of accumulated proline (mg g^{-1} dry weight of root leaves) have been increased by 18.64 for (I_{80}) and 29.92% for (I_{60}) higher than control. Similar reaction was also detected in response to salinity stress, which raised the content of proline by 34.24% compared with its level under non-saline condition. The addition of biochar played a stimulating effect on proline accumulation in plant leaves. The increments in proline content in correspondence of used biochar amendment with 10 and 20 ton ha^{-1} amounted 11.29 and 19.43% respectively, over control (B_0).

3.5 Qualitative Parameters of Sugar Yield

The content of Na, K, α -amino N are classified as impurity components that significantly influence the quality of

produced sugar. As the amounts of these traits increased the higher sugar in molasses is lost, which in turn causing reduction in sugar extractability. The concentration of Na^+ (Fig. 3a), K^+ (Fig. 3b) and α -amino N (Fig. 3c) were significantly increased under stress conditions. This increase in Na^+ ($\text{meq}/100$ g of root beet), K^+ ($\text{meq}/100$ g of root beet) and α amino N ($\text{meq}/100$ g of root beet) in saline soils amounted 46.01, 20.83 and 29.77% compared with non-saline soil. Respecting to the influence of drought stress on sugar impurity characters, it was observed that, the restricted water application at (I_{60}), resulted in substantial increase in levels of Na^+ , K^+ and α -amino N by 8.39, 17.45 and 22.00% higher than control (I_{100}). As average in both saline and non-saline soils, the addition of biochar amendment (10 t ha^{-1}) alters the accumulation of these components in roots

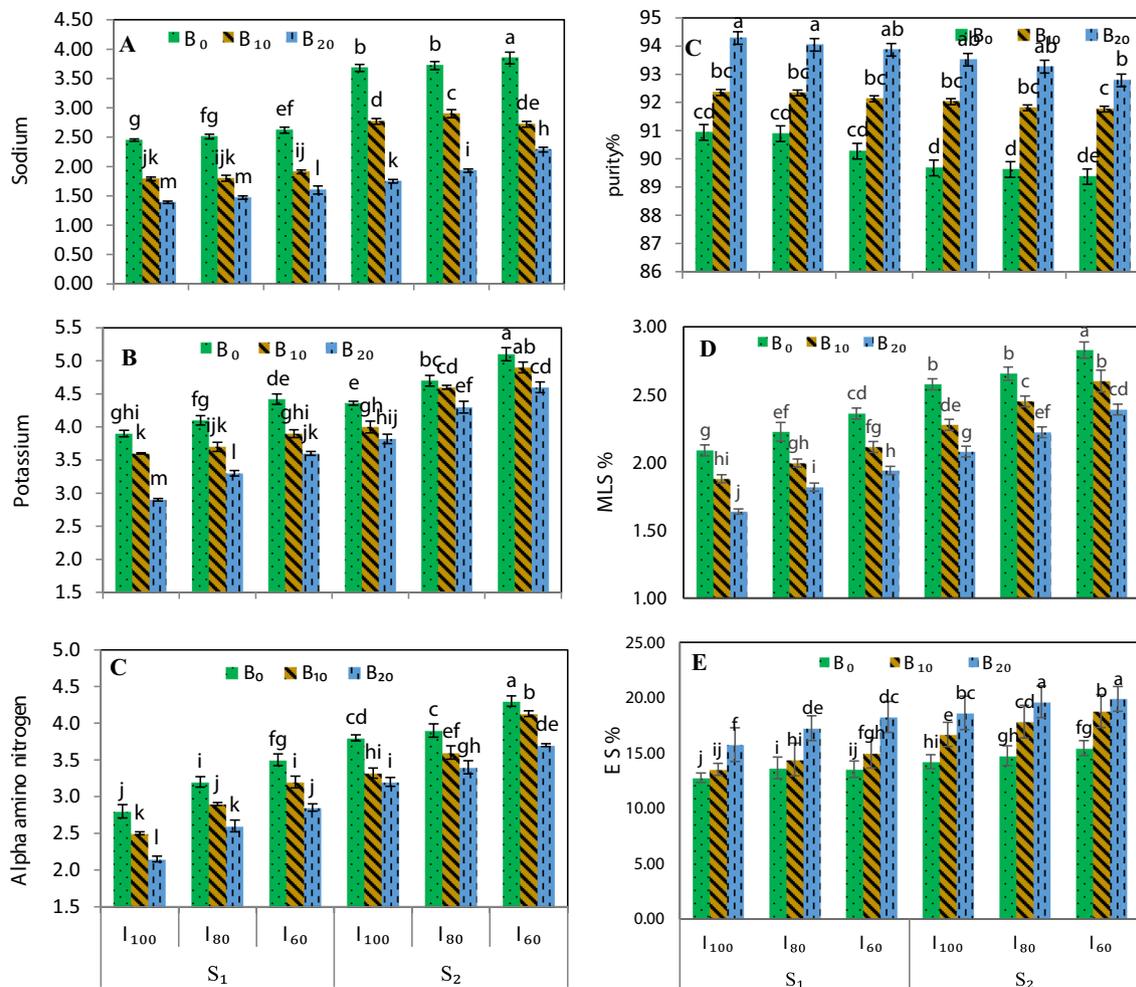


Fig. 3 The influence of soil salinity levels, water stress regimes and biochar incorporation rats on (a) the content of sodium ($\text{meq}/100$ g of root beet), (b) potassium content ($\text{meq}/100$ g of root beet), (c) α amino N ($\text{meq}/100$ g of root beet), (d) purity % (e) molasses lost sugar % (MLS) and (f) extractable sugar % (ES). S₁, non-saline soil (<4 dS m^{-1}); S₂, saline soil (10 dS m^{-1}); I₁₀₀, I₈₀, and I₆₀ repre-

sentes 100%, 80%, and 60% of crop evapotranspiration (ETc), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha^{-1} , respectively. Columns marked with the same letter are not significantly different ($\alpha \leq 0.05$) according to Duncan's multiple range test (DMRT)

of sugar beet plants, causing a significant reduction in contents of Na^+ , K^+ and α amino N by 26.23, 7.07 and 8.60% respectively relative to control (B_0). Moreover, in response of applied high level of biochar (B_{20}), the reduction in Na^+ , K^+ and α amino N amounted 44.60, 15.27 and 16.74% respectively compared with non-biochar treated plots. Interestingly, the levels of molasses lost sugar (MLS) (Fig. 3e) and extractable sugar (ES) (Fig. 3f) were increased under stress conditions. Salinity stress, increased MLS and ES by 22.24 and 16.19%. A similar finding was also detected due to drought stress. The effect of salinity on these parameters (MLS and ES) was significant, meanwhile the differences in MLS and ES induced by water stress statistically were non-significant. Unlike MLS and ES, the expressed values of purity (Fig. 3d) in response of drought and salinity stresses were decreased. Conversely, the addition of biochar amendment results considerable increase in ES and purity parameters. Biochar amendment reduced the amount of sugar that lost in molasses, which reflecting the positive impact of used soil amendment on yield qualitative parameters. The greatest value of purity (94.28%) was observed for adequately water sugar beet plant grown in non-saline soil and received biochar amendment at (20ton ha^{-1}). However, under the same biochar application rate (B_{20}), the sugar beet plants that exposed to salinity and intense drought level showed the highest values of SLM (2.39%) and ES (19.89%).

3.6 Yield Characters

Drought and salinity stresses induced detrimental effects on yield attributes of sugar beet plants. Data in (Table 7) showed gradual decrease in sugar beet productivity with increasing stress severity. The yields of sugar beet crop expressed by root yield (RY), top yield (TY) and sugar yield (SY) were significantly reduced in response to salinity and deficit water regimes. In saline soil the reduction in RY, TY and SY of sugar beet plants amounted 9.14, 9.97 and 20.42% respectively, compared with normal soil. In response to I_{80} and I_{60} the reduction in RY (16.15 and 35.82%), TY (17.20 and 34.69%) and SY (11.96 and 31.48%) respectively as compared with full irrigation regime I_{100} . However, the addition of biochar amendment achieved higher yields for stressed and non-stressed sugar beet plants, demonstrating the potential of biochar in mitigating the deleterious effect of drought and salinity. As average in two sites (saline and non-saline soils), the addition of biochar at (B_{10}) increased RY, TY and SY by 45.77, 20.52 and 61.59% respectively compared with control (B_0). Also, under high application of biochar amendment, these parameters recorded significant increase by 55.02, 23.36 and 89.37% for RY, TY and SY respectively over control. Regarding the interaction effect of used treatments, the maximum values of RY, TY and SY were detected for fully irrigated (I_{100}) sugar beet plants

Table 7 Yield responses of sugar beet plants to salinity levels, deficit irrigation regimes and biochar amendment

Treatments	RY	TY	SY
Year	NS	NS	NS
2019/2020	65.02a \pm 0.84	36.61a \pm 0.41	12.93a \pm 0.41
2020/2021	63.87a \pm 0.61	35.25a \pm 0.31	11.96a \pm 0.34
Soil salinity (S)	*	*	*
S_1	67.53a \pm 0.88	37.81a \pm 0.41	13.86a \pm 0.20
S_2	61.36b \pm 0.88	34.04b \pm 0.35	11.03b \pm 0.20
Irrigation (I)	*	*	*
I_{100}	77.95a \pm 1.10	43.44a \pm 0.52	14.55a \pm 0.31
I_{80}	65.36b \pm 1.07	35.97b \pm 0.43	12.81b \pm 0.21
I_{60}	50.03c \pm 1.06	28.37c \pm 0.32	9.97c \pm 0.25
Biochar (B)	*	*	*
B_0	48.24c \pm 1.07	31.34b \pm 0.44	8.28c \pm 0.19
B_{10}	70.32a \pm 1.08	37.77a \pm 0.51	13.38b \pm 0.25
B_{20}	74.78b \pm 1.09	38.66a \pm 0.32	15.68a \pm 0.31
S \times I	*	*	*
S \times B	*	*	*
I \times B	*	*	*
S \times I \times B	*	*	*

S_1 : non-saline soil (<4 dS m^{-1}); S_2 : saline soil (10 dS m^{-1}); I_{100} , I_{80} , and I_{60} represent 100%, 80%, and 60% of crop evapotranspiration (ETc), respectively; B_0 , B_{10} , and B_{20} are biochar incorporation levels by 0, 10, and 20 t ha^{-1} , respectively; RY: root yield (t ha^{-1}); TY: top yield (t ha^{-1}); SY: sugar yield (t ha^{-1}); All values provided in the table represent means, and those accompanied by distinct letters indicate significant differences ($p \leq 0.05$) according to Duncan's multiple range test (DMRT); * indicate significant differences at $p \leq 0.05$

and grown in normal soil (S_1) under high level of biochar addition (B_{20}). Meanwhile, in saline soil and following limited water schedule (I_{60}), sugar beet plants produced their lowest yields RY, TY and SY respectively, for non-biochar amended plots (B_0).

3.7 Irrigation Water Applied and Water Productivity

According to the results inserted in (Table 8) the required amount of irrigation water in normal soil averaged 3696 ($\text{m}^3 \text{ha}^{-1}$). However, in saline soil due to added fraction of leaching requirements, the applied irrigation water was relatively increased and amounted 4375 ($\text{m}^3 \text{ha}^{-1}$). Furthermore, in each experimental site, the addition of irrigation water was varied according to the conducted irrigation regimes. The values of water productivity (WP) were significantly differed depending upon the soil type, used irrigation regime and application level of biochar amendment. The calculated WP values indicated significant increase as irrigation water applied decreased. Moreover, due to decreased amount of consumed irrigation water and higher yield in normal soil, the values WP were increased

Table 8 irrigation water applied and water productivity of sugar beet plants in response to salinity levels, deficit irrigation regimes and biochar amendment

Treatments	IWA	WP/ Roots	WP/ top	WP/ Sugar
Year		NS	NS	NS
2019/2020	4046	16.07a±0.18	9.05a±0.20	0.32a±0.11
2020/2021	4024	15.87a±0.17	8.76a±0.11	0.30a±0.12
Soil salinity (S)		*	*	*
S ₁	3696	18.27a±0.11	10.23a±0.08	0.38a±0.01
S ₂	4375	14.03b±0.22	7.78b±0.09	0.25b±0.03
Irrigation (I)				
I ₁₀₀	5044	15.45b±0.20	8.61b±0.10	0.29b±0.04
I ₈₀	4035	16.20ab±0.34	8.91b±0.12	0.32ab±0.02
I ₆₀	3026	16.53a±0.35	9.38a±0.11	0.33a±0.01
Biochar (B)		*	*	*
B ₀	4035	11.96c±0.21	7.77b±0.11	0.21c±0.01
B ₁₀	4035	17.43b±0.20	9.36a±0.12	0.33b±0.03
B ₂₀	4035	18.53a±0.32	9.58a±0.11	0.39a±0.05
S×I		*	*	*
S×B		*	*	*
I×B		*	*	*
S×I×B		*	*	*

S₁: non-saline soil (<4 dS m⁻¹); S₂: saline soil (10 dS m⁻¹); I₁₀₀, I₈₀, and I₆₀ represent 100%, 80%, and 60% of crop evapotranspiration (ET_c), respectively; B₀, B₁₀, and B₂₀ are biochar incorporation levels by 0, 10, and 20 t ha⁻¹, respectively; IWA: irrigation water applied (m³ ha⁻¹); WP/Roots: water productivity/ roots; WP/ top: water productivity/ top; W.P/sugar: water productivity/ sugar; All values provided in the table represent means, and those accompanied by distinct letters indicate significant differences ($p \leq 0.05$) according to Duncan's multiple range test (DMRT); * indicate significant differences at $p \leq 0.05$

by 23.24 and 23.94% for root and top yield respectively compared with saline soil. Regarding the effect of applied deficit irrigation levels, the maximum values of WP/Root and WP/ Top were detected for limited irrigation supply at (I₆₀). Interestingly, it is worth noting that, the differences in WP/Root and WP/ Top between (I₁₀₀) and (I₈₀) were in-significant. the addition of biochar amendment had a positive effect on recorded values of WP for roots and top yields. The use of biochar with level of (B₂₀) induced a significant increase by 55.02 and 23.35% for WP/Root and WP/ Top respectively higher than control (B₀). A similar trend was observed in expressed water productivity for sugar yield (WP/ sugar). In saline soil due restricted productivity of sugar and increased applied irrigation water the WP/ sugar was declined by 34.21% compared with non-saline soil. Under sever-drought condition (I₆₀), the (WP/ sugar) was improved and gave its greatest value. Also, applied biochar amendment statistically resulted significant deference in (WP/ sugar).

4 Discussion

Soil salinity and drought are the two most common and frequently co-occurring environmental stresses restrict growth and sustainability of crop production. Drought and salinity have deleterious effects on plant development and yield throughout the crop life cycle. Accordingly, there is a pressing need to introduce more practical and efficient tools to maintain adequate moisture content and nutritional balance in grown crops exposed to drought and saline stress. Recently, deficit irrigation, as a water-saving irrigation approach, and biochar, as a soil amendment, have been used to cope with salinity and water stress. In this concern there are several studies which conducted to investigate the individual influences induced by salinity or drought on growth and yield of sugar beet plants (Abd El-Mageed et al. 2019; Ghaffari et al. 2021; Karagöz et al. 2018). However, the response of sugar beet plants to combined salinity- drought stress has not been sufficiently studied. Therefore, the objective of present study was to assessment the potential of biochar amendment in alleviating the combined effects triggered by drought and salinity factors on morph-physiological and biochemical responses of sugar beet plants.

The present study has revealed that the combined stress of salinity and drought induced significant changes in morphological, physiological, and biochemical responses of sugar beet plants, as well as yield and yield quality characteristics, resulting a considerable decrease in growth traits (Tables 5 and 6), relative water content (LRWC) (Fig. 1a), membrane stability index (MSI) (Fig. 1b), leaf chlorophyll content (SPAD) (Fig. 1c), and sugar yield (Table 7). Maintaining an appropriate soil–water regime is crucial for optimal crop growth under challenging conditions. To address this issue, biochar has been utilized as a soil amendment to enhance soil physicochemical properties and alleviate the negative effects of salinity-drought stress on sugar beet plants.

Soil physicochemical characteristics of the experimental site are sandy loam in texture (Table 2), which represents their lower capacity in terms of water and nutrient retention. The use of biochar amendment improved the soil–water relationships by increasing the water-holding pores and reducing the soil hydraulic conductivity (Table 4). Decreased bulk density of biochar amended soil might be due to a lower bulk density of used biochar material than soil; therefore, biochar probably decreased the soil bulk density due to its mixing or dilution effect (Verheijen et al. 2019). Biochar also had a beneficial effect on soil pore size, which significantly affected soil hydraulic properties. Indeed, clogging or filling of soil macropores with tiny biochar particles might contribute to

a considerable reduction in quickly drainable pores, and at the same time, enhance the proportion of slowly drainable pores, which in turn results in decreased soil hydraulic conductivity. In addition, the high surface area of biochar (Batista et al. 2018) increases the capacity of soil to hold water. A similar pattern was noticed by (Razzaghi et al. 2020) who pointed out the addition of biochar improved soil aeration and soil water holding capacity. In addition, (Seyedsadr et al. 2022) stated that biochar application to soil resulted in a notable enhancement in the soil's water retention capacity. Moreover, the enhancement of soil moisture retention due to biochar amendment could be attributed to the high surface area of biochar particles that inherently contain OH and COOH functional groups (Jačka et al. 2018; Tan et al. 2020; Tomczyk et al. 2020), which directly attract water molecules through polar interactions and indirectly through the positive effects of biochar on soil structure and aggregation stability (Seyedsadr et al. 2022). In addition, biochar exhibits a substantial ability in terms of water retention (Jačka et al. 2018). Biochar has a negative charged surface and high surface area, therefore incorporating biochar in the soil significantly affect the soil's porosity, water holding capacity, surface area and pore-size distribution (Sharma et al. 2021). In addition to enhancing the soil's physical properties, the incorporation of biochar also positively influenced its chemical characteristics. Biochar amendment reduced the salinity of saline soil (Table 4). This reduction may be associated with improved salt leaching. Enrichment of the soil with biochar can accelerate the salt leaching process, causing a decrease in soil salinity (de Vasconcelos 2020; Lee et al. 2022). In contrast, the observed slight increase in soil electrical conductivity (ECe) values in non-saline soil following biochar application might be a result of the higher ECe of the biochar amendment (Table 4) than that of the soil (Hafeez et al. 2022; Singh et al. 2019). Moreover, the improved ion release during the decomposition of organic matter may be attributed to increased soil salinity. Interestingly, soil pH was increased in correspondence of applied biochar amendment (Table 4). (Wei et al. 2023) stated that, over time, biochar experiences oxidation, resulting in the release of alkaline ions (such as Ca^{+2} and K^{+}) into the soil. These ions replace the originally adsorbed Al^{+3} and H^{+} on the negative sites of soil particles, thereby causing a rise in soil pH. Also, (Chen et al. 2020; Singh et al. 2022) noted that, the process of pyrolysis in biochar preparation has the potential to generate alkaline substances, including oxides, hydrides, and carbonates. These functional groups play a role in elevating the soil pH. These findings were similar to those documented by (ALVES et al. 2021; EL-Samnoudi et al. 2021; Seyedsadr et al. 2022; Zhang et al. 2020). Interestingly, it is worth noting that biochar is a rich organic carbon material (Saravanan and Kumar

2022); consequently, the organic matter content and cation exchangeable capacity in the two experimental sites was significantly increased with biochar application compared with the control (Table 4). These findings are consistent with those reported by (EL-Samnoudi et al. 2021; Saifulah et al. 2018).

Regarding the influence of salinity and drought on plant performance, it is worth noting that both drought and salinity stress inhibited morphological, physiological, and biochemical responses in addition to yield and yield quality of sugar beet plants.

Growth traits (i.e., root length, root fresh weight, root dry weight, top fresh weight, top dry weight, leaf area, and root/top ratio) of sugar beet plants were significantly reduced in response to salinity and drought stress (Tables 5 and 6). Growth retardation of sugar beet plants is closely associated with physiological and biochemical alterations generated under stressful conditions. Limited water intake due to salinity and drought stress (Yolcu et al. 2021) causes cellular dehydration (Ahluwalia et al. 2021), which negatively affects the division and expansion of plant cells (Lv et al. 2019), resulting in growth retardation. Drought stress causes reduction in plant growth by disrupting photosynthesis, decreasing nutrient uptake, and stimulating of ROS production (Gharred et al. 2022). Likewise, drought, salinity stress impairs plant growth due to increased osmotic potential and ionic toxicity (Ludwiczak et al. 2021). According to (Abd El-Mageed et al. 2022; Ma et al. 2020), an increased soil osmotic potential decreases the uptake of water by plant roots. However, the application of biochar as a soil amendment had a positive effect on growth traits of sugar beet plants (Tables 5 and 6). Biochar amendment inherently contained considerable amounts of N, P and K (Table 3), which eventually enhanced the growth parameters of beet plants. Moreover, the slight increase of soil pH following the biochar addition (Table 4), which enhances the availability and uptake of nutrients (Barrow and Hartemink 2023). In addition, the increase in plant growth in response to biochar amendment could mainly due to the ameliorative effect of biochar on soil physical properties (Table 4) by enhancing the capacity of soil to hold more water, which in turn improved the water uptake. Likewise, improved soil chemical characteristics including organic matter content and cation exchange capacity (Table 4) are reasonable for better plant growth. Hence, this distinctive performance of sugar beet growth features reflects the beneficial role of biochar in reducing the harmful impacts of environmental stress on cultivated beet plants. Multiple studies have validated these findings (Durukan et al. 2020; Zhang et al. 2020).

Salinity and drought stress had an inhibitory effect on plant physiological responses, including reductions in leaf relative water content LRWC% (Fig. 1a), membrane stability index MSI% (Fig. 1b) and chlorophyll content SPAD

(Fig. 1c). The LRWC is an essential indicator of plant water status. The lack of water absorption by roots under insufficient water supply and/or the existence of excess salt ions contributes to protoplasm dehydration of plant cells (Xiao and Zhou 2023), resulting in a decrease in leaf RWC. The decrease in membrane stability may be attributed to the accumulation of reactive oxygen species under adverse conditions, which causes lipid oxidation (Andrés Juan et al. 2021; Juan et al. 2021) and increases the penetrability of ion leakage (Ozturk et al. 2021). Chlorophyll is the main plant photosynthesis pigment, that is responsible for the absorption and transformation of light energy (Shin et al. 2021). Consequently, the chlorophyll content serves as a prominent physiological indicator of plant damage caused by salinity and drought stress (Farhat et al. 2022; Shin et al. 2021). The unfavorable impact of drought and salinity on leaf chlorophyll content SPAD of sugar beet plants could be a result of reduced leaf area (Table 6), a destruction of chloroplast and photosynthetic system and photo-oxidation (Pallavolu et al. 2023). This finding was observed by (Hameed et al. 2021) who demonstrated that, stress conditions inhibit the chloroplasts and negatively impact the activity of PSII and the assimilation rate of CO₂. The decline in chlorophyll content in stressed- sugar beet, might be attributed to the production ROS, which in turn causes pigment degradation, reduction in CO₂ influx and photosynthesis (Ahluwalia et al. 2021). Conversely, biochar addition at two doses (10 and 20ton ha⁻¹) enhanced the physiological attributes of saline-drought stressed sugar beet plants compared to the control (B0) (Fig. 1a, 1b and 1c). Improved photosynthesis in water-stressed plants following biochar addition has been reported in several previous studies (Liu et al. 2022; Zhang et al. 2023). This positive impact of biochar on plant-water relations and chlorophyll content might be linked to the ameliorative impact of biochar on soil physic-chemical properties (Table 4), leading to increased water availability in the root media. Furthermore, the accumulation of osmoprotectants in plant cells due to biochar amendment (Fig. 2a, 2b and 2c) could be responsible of improved nutrients and water uptake (Sharma et al. 2019), leading to better physiological responses than non-amended beets. Interestingly, the detected improvement in MSI in response to biochar application might be referred to the positive impact of biochar in reducing the uptake of Na⁺ ions (Jin et al. 2018), which eventually resulting in lower electrolyte leakage. (Parkash and Singh 2020) observed decrease in levels of electrolyte leakage in eggplant plant amended with biochar in saline soils. In fact, the production of these osmolytes (i.e., total soluble sugar (Fig. 2a), sucrose (Fig. 2b) and proline (Fig. 2c)) motivates the root water uptake and facilitates the transfer of water among plant tissues, which maintain cell turgor. For instance, (Tanure et al. 2019) reported that plants under optimum nutritional and water conditions open

their stomata, which motivates the assimilation of CO₂ molecules and increases the transpiration rate. According to (Lebrun et al. 2022) increasing the content of osmoprotectants with biochar is closely-related with improved LRWC content in biochar-amended sugar beet plants.

Osmotic adjustment is crucial for maintaining cell turgor and alleviating the osmotic imbalances induced by salt and drought stress (Abou-Sreya et al. 2022; Ghosh et al. 2021; Selem et al. 2022). It involves the accumulation of organic and inorganic osmolytes under increased the osmotic potential of the environment. The accumulation of compatible solutes (i.e. total soluble sugar (Fig. 2a), sucrose (Fig. 2b) and proline (Fig. 2c)) in plant cells was significantly increased by salinity and drought stress. Indeed, plants under adverse conditions such salinity and drought promote the accumulation of these osmoprotectants to sustain their physiological activities. This increase in sucrose, total soluble sugar and proline owing to salinity and drought stress has been detected in several previous studies. (Wang et al. 2019) observed an increase in the leaves content of free amino acids, proline and glycinepine of saline-stressed sugar beet plants. The accumulation of sucrose, fructose and glucose plays an effective role in regulating osmotic adaptation (Yang et al. 2019), reducing leaf temperature (Wang et al. 2018; Wiśniewska et al. 2019) and preventing protein denaturation (Naguib et al. 2021) in drought-salt stressed beet plants. Proline is an important amino acid, that play a fundamental role for osmotic adjustment under various stressful conditions, besides its significant function in maintaining membranes integrity and preventing proteins denaturation (Alkahtani et al. 2021; Ghosh et al. 2022; Ibrahim et al. 2022). Generally, proline is concentrated in the cytosol, for maintaining osmotic adjustment in the cytoplasm (Ghaffari et al. 2021; Hinai et al. 2022; Semida et al. 2020). Significant increases in accumulated proline molecules have been observed in different organs of sugar beet plants under drought and salt stress (Alkahtani et al. 2021; Ghaffari et al. 2021) however, not all plant species are able to produce an adequate amount of these osmo-regulators to reduce the negative effects of harsh conditions. Interestingly, it is worth to mention that, the addition of biochar substantially increased the levels of these compatible solutes (Fig. 2a, 2b and 2c), which in turn improved the tolerance of beet plants to a biotic stress. This increase in sucrose and total soluble sugar after biochar addition might be a result of improved soil water retention capacity, transportation and assimilation of nutrient, that led to increased rates of photosynthesis and carbohydrate synthesis. Previous studies have documented an elevation in sucrose content in beet plants following the application of manure and biochar amendments (Abd El-Mageed et al. 2021; McKay et al. 2021; Zhang et al. 2020). The observed increase in proline levels in biochar amended sugar beet plants might be attributed to improved soil

nutrient status and nutrient uptake by plants, which in turn enhanced the synthesis of nitrogen compounds like proline in tissues of beet plant grown under harsh conditions. Hence, it's important to indicate that, although the levels of these osmotic regulators (soluble sugars, proline, and sucrose) were increased in correspondence of increased salinity and drought stress, they were not sufficient for sugar beet plants to defend themselves against stress to perform acceptable growth and yield. However, amending the soil with biochar could be stimulated plants to concentrate more contents of these osmoprotectants to survive well under these adverse conditions. This finding was in line with several studies that have shown an increase in proline levels in response of used organic fertilizers (Haider et al. 2022; Mahmoud et al. 2022; Obadi et al. 2023). In contrast (Ghassemi-Golezani and Rahimzadeh 2023; Nehela et al. 2021) observed a reduction in proline concentration in plants following the addition of organic amendments. Therefore, this different behavior of plants might be associated with the plant's tolerance threshold and stress severity of salinity and drought.

The contents of potassium, α -amino nitrogen and sodium are considered major impurity components that influence sugar yield (EL-Samnoudi et al. 2021; Hassan and Mostafa 2018; Nassar et al. 2018). Increased levels of these substances lead to a notable decrease in sugar extractability as a result of increased sugar loss in molasses (Rahimi et al. 2019). The concentration of sodium (Fig. 3a), potassium (Fig. 3b) and α -amino nitrogen (Fig. 3c) in roots of beet plants were increased, particularly under salinity and severe water stress, compared with the sufficiently watered beet plants. Increasing the accumulation of these elements (Na, K and α -amino nitrogen) disrupt the crystallization process, leading to a higher amount of sugars being retained as molasses while reducing the yield of refined sugar. (Hassan and Mostafa 2018) revealed that, the industrial purification of sucrose was adversely affected with increased concentration of α -amino nitrogen, that influencing the overall sugar quality. Elevated α -amino nitrogen concentration reduces juice alkalinity, that causing a decrease in its thermostability, that increase the molasse lose sugar. Therefore, the low sugar purity under adverse conditions is a result of increased impurity factors. On the other hand, this increase in Na^+ and K^+ ions in sugar beet plants could be considered a protective mechanism against drought and salinity stress (dos Santos et al. 2022). Similar findings were observed by (Yolcu et al. 2021), who documented that water stress significantly influenced Na^+ , α -N, and K^+ concentrations in water-stressed sugar beet plants. This increase in α -N under limited water supply might be due to the synthesis of N-substances that regulate imbalanced osmotic pressure in the leaves of drought-stressed beet plants (Ghaffari et al. 2021). In contrast, the application of biochar reduced the accumulation of these components. Accordingly, the high purity values of sugar were observed under well-irrigated sugar beet plants and

received biochar amendment. Hence, the biochar amendment improved the qualitative traits of sugar yield by improving the (sucrose%, purity%, extractable sugar%, and coefficient of extractable sugar) and reducing the (impurity% and sugar lost in molasses%).

Regarding the effect of applied treatments on yield and yield contributing characters of saline and water stressed sugar beet plants it was observed that, the low values of top yield, root yield and sugar yield as outlined in table (Table 7), possibly due to limited leaf area (Table 6) and alterations in RWC (Fig. 1a) and membrane stability (Fig. 1b) resulting in photosynthetic disruption and yield loss. Additionally, the decline in yield may be related to restricted growth traits under these harmful conditions (Tables 5 and 6). In contrast, the observed increase in beet yield (i.e., root yield, top yield, and sugar yield) after biochar application might have occurred because of improved soil moisture content and plant nutritional status. The improvement in yield and quality of sugar beet plants could be a result of enhanced availability of macro and micro nutrients as well as improved soil physical environment (Table 4). Likewise, improved yield traits of sugar beet plant are a result of increased growth traits as aforementioned above in this research work (Tables 5 and 6). These results have provided a good evidence that the application of biochar, particularly at a rate of 20 tons per hectare had beneficial effects on soil moisture and nutrient status. Furthermore, it positively impacted the growth, root yield, sugar yield, and quality characteristics of both non-stressed and stressed sugar beet plants. This finding is in agreement with those of previous studies (Hossain et al. 2020; Tanure et al. 2019; Zhang et al. 2020).

The improved water productivity values (Table 8) for grown sugar beet plants in non-saline soils and exposed to limited irrigation scheme, is a result of reduced irrigation water and enhanced root and sugar yields under biochar application. Compared with sufficient irrigation supply, saving the applied irrigation water by 40% under the irrigation regime (I60) resulted in the highest WP values. Biochar addition significantly increased WP in the saline- and drought-inhibited sugar beet plants. Biochar improved the soil physicochemical properties (Table 4), thereby enhanced the growth and yield of sugar beet plants, leading to higher WP than in un-amended plants (ALVES et al. 2021; Durukan et al. 2020; Ndede et al. 2022; Tanure et al. 2019; Yang et al. 2020).

5 Conclusion

Salinity and drought stress adversely affected the growth attributes, yield and quality traits, meanwhile, it increased the accumulation of compatible solutes in sugar beet plants.

The incorporation of biochar as an amendment effectively ameliorated soil moisture retention and nutrient capacity. Biochar at level (B_{20}) produced the highest growth characters, root yield (95.02 t ha^{-1}) and sugar yield (20.24 t ha^{-1}) for full irrigated sugar beet plants in non-saline soil. Additionally, biochar enhanced water productivity by 55.02% over control (B_0) as average for drought and saline stressed sugar beet plants. Hence, the addition of biochar amendment by 20 t ha^{-1} could be effectively used as a helpful agro-management strategy in mitigating the inhibitory impacts of salinity and water stress on sugar beet plants, improving soil quality and enhancing water productivity to ensure water sustainability and food security, especially in areas of limited water supply.

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Data Availability The datasets used and /or analyzed during the current study are available from the corresponding author on reasonable request

Declarations

Competing Interests The authors declare no competing interests.

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