Pak. J. Bot., 58(5) May, 2026.

ARTICLE | DOI: http://dx.doi.org/10.30848/PJB2026-5(16)

DATE PALM EMPTY BUNCH AND PIT-DERIVED BIOCHAR: A SUSTAINABLE SOIL AMENDMENT FOR ALLEVIATING DROUGHT EFFECTS IN PROTECTED CUCUMBER CULTIVATION

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Abstract

Sustainable agricultural production strategies are essential for achieving food security in water limited regions. Among these, the use of biochar as a soil amendment conditioner is one of the strategies being practiced to conserve water and improve soil properties. Assessing the effect of biochar on cucumber yield using deficit irrigation is important to develop management strategies for the greenhouse production to conserve water and increase yield. Therefore, the present study aimed to assess the effects of biochar addition on the growth and quality of cucumbers under water stress conditions. Cucumber plants were grown under three irrigation regimes: 100% (no-water stress), 80% (moderate-water stress), and 60% (high-water stress) of the field capacity (FC). Two different feedstocks of date palm biomass were used to produce biochar, i.e., empty bunch (EB) and pit (PT), whereas sandy loam alone was used as a control. Findings of the experiment revealed that cucumber plants grown in EB and PT biochar-amended potting media and received water at 100% FC enhanced the crop growth, physiology, yield, and quality attributes. The study also found that cucumber plants grown in EB and PT biochar-amended media at 80% and 60% FC showed superior growth and development traits compared to the control at 100% FC. Cucumber plants grown in control at 80% and 60% FC showed significantly negative results. EB biochar at 100% FC produced superior results; however, at 80% and 60% FC, water conservation is possible at a slight compromise to cucumber growth, yield, and quality attributes.

Key words: Date palm; Cucumber; Drought; Field capacity; Empty bunch; Pits; Biochar; Growth; Development

Introduction

Global agricultural systems face unprecedented challenges from escalating water scarcity, driven by climate change-induced shifts in precipitation patterns, unsustainable irrigation practices, and increasing competition for freshwater resources across domestic, industrial, and environmental sectors (Rosa *et al.*, 2020). This increasing drought situation is a serious threat to food security, especially in arid and semi-arid areas where agriculture, by its very nature, is highly vulnerable. This demands urgent efforts on sustainable water management and resilient crops to maintain productivity under inevitable condition of increasing occurrence of severe and long droughts (Hameed *et al.*, 2020). This trend highlights a rising vulnerability in our global food systems that demands higher yields while using less water. The lack of spatial and temporal correspondence between water availability and agricultural demand intensifies this problem, threatening not only local livelihood but also regional commodity markets. The effects will not be limited to the immediate collapse of crops and can lead to the destabilization of the economies in the rural areas and increases socio-economic inequalities. Consequently, the agricultural sector is forced to move away from water-intensive paradigms to approaches that are characterised by substantially higher resource use efficiency (D'Odorico *et al.*, 2018; Pastor *et al.*, 2019; Morante-Carballo *et al.*, 2022).

Protected cultivation, including greenhouses and high tunnels, offers remarkable advantages for intensive vegetable production. It allows accurate environmental control, longer growing seasons, reduced pest and disease pressure, and water use efficiency relative to open fields. Yet, even these controlled environments, water stress is not necessarily removed in these systems during prolonged dry periods or under less-than-optimal irrigation system management. So, crops remain vulnerable to the harmful effects of drought (Calderón-Orellana *et al.*, 2021; Jain *et al.*, 2023; Rajiv & Kumari, 2023). Cucumber (*Cucumis sativus* L.), a high-value and water-demanding vegetable crop, widely cultivated in the greenhouses. Despite its economic importance and consumer preference, it prone to water stress. When stress sets in, it triggers physiological alarm reactions such as a decrease in photosynthetic rates, closure of stomata, impaired nutrient uptake, oxidative damage and, ultimately, leading to yield and quality losses, jeopardizing

Received: 08-07-2025 | Revised: 19-01-2026 | Accepted: 25-01-2026 | Online: 02-02-2026

the economic viability of the production systems of this crop (Taha *et al*., 2020; Razi & Muneer, 2021). The physiological implications of drought stress in cucumbers, as in many plants, is manifested in the form of disrupted water relations, leading to loss of turgor pressure, inhibition of cell expansion and division, reduction of chlorophyll synthesis and photosynthetic efficiency, accumulation of reactive oxygen species (ROS). Ultimately, this impairs fruit development via cellular damage, alteration in the signaling of phytohormones (specially increased concentration of abscisic acid), and compromised partitioning of assimilates. These cascading effects necessitates urgent interventions aimed at improving plant water status and tolerance mechanisms (Parkash *et al*., 2021; Wahab *et al*., 2022).

Amendments of soil to promote water retention, improve soil structure, and contribute to the growth of microorganisms provide a potentially effective source of reducing drought stress (Hussain & Shah, 2023). Among these, biochar stands out because of its unique physicochemical properties, which can significantly alter the soil hydrology and soil fertility (Munir *et al*., 2020; Mustafa *et al*., 2025; Rauf *et al*., 2025). The valorization date palm (*Phoenix dactylifera* L.) empty fruit bunches (EB) and pits (PT), an abundant biomass in the region, through the production of biochar is an economical approach that converts waste into a beneficial soil amendment for agriculture while helping resolve the waste management problems, increasing agricultural sustainability in the date palm growing regions (Burezq & Davidson, 2023). Biochar effectively reduces drought stress through several mechanisms. Its large surface area and porous structure increases soil porosity and water holding capacity, which improves water retention in the root zone. Biochar's highly charged surfaces enhance the soil's cation exchange capacity, leading to better nutrient availability and retention. It also promotes soil aggregation, which improves water infiltration and reduces evaporation. These conditions create ideal environment for the beneficial microbes that support soil structure and plant health. Additionally, it can also improve root architecture, encouraging deeper root growth that helps plants withstand water stress.

Biochar has significant potential, but research on regional feedstocks remained scarce. In particular, studies are needed to evaluate how biochar from date palm waste—like empty fruit bunches and pits—affects cucumber growth, physiology, and yield under drought stress in protected cultivation systems. Addressing this gap is critical for guiding effective field-level implementation. Therefore, this research investigates the potential of biochar from date palm waste as a sustainable soil amendment to mitigate drought stress in protected cucumber cultivation. It evaluates key growth parameters, physiological responses, yield, fruit quality, and water use efficiency under controlled water deficit conditions. We hypothesize that amending soil with date palm-derived biochar (EB and PT) will alleviate drought stress in cucumber plants by enhancing soil water retention and plant physiological efficiency, leading to improved growth, yield, and fruit quality under deficit irrigation. Furthermore, biochar will enable water conservation by maintaining productivity at 80% and 60% field capacity at levels comparable to or exceeding those of fully irrigated, non-amended controls.

Materials and Methods

The study was conducted in 2022-2023 in the research and training station at King Faisal University, Al-Ahsa, Saudi Arabia. Biochar was produced from two date palm byproducts, the empty fruit bunches (EB) and its pits (PT). Initially, the collected EB and PT were dried under sunlight for 24 hours, chopped into smaller pieces, followed by an over dry for another 24 hours at 60°C. The pyrolysis process was performed in a muffle furnace where the dried feedstock was heated up to 350°C for three hours. After pyrolysis, it was allowed to cool at room temperature (24 hours). Finally, it was grinded and sieved through 2 mm mesh size and packaged in plastic bags for storage (Munir *et al*., 2024). The chemical and physical properties of the EB and PT-biochar were characterized, as shown in Table 1.

Table 1. Physicochemical characteristics of date palm biochar feedstocks and sandy loam soil.

Physicochemical properties	Date Palm Biochar Feedstocks		Sandy loam soil
	Empty bunches (EB)	Pits (PT)	
Organic matter	74.8%	69.5%	0.33%
Total nitrogen (N)	5.54 kg t^{-1}	4.88 kg t^{-1}	0.31 kg t^{-1}
Available nitrogen (N)	245 mg kg^{-1}	222 mg kg^{-1}	16 mg kg^{-1}
Phosphorus (P)	1.65 kg t^{-1}	1.33 kg t^{-1}	0.26 kg t^{-1}
Potassium (K)	24.22 kg t^{-1}	19.35 kg t^{-1}	5.24 kg t^{-1}
Magnesium (Mg)	6.93 kg t^{-1}	6.43 kg t^{-1}	4.12 kg t^{-1}
Calcium (Ca)	20.77 kg t^{-1}	18.12 kg t^{-1}	23.67 kg t^{-1}
Sulphur (S)	5.97 kg t^{-1}	4.73 kg t^{-1}	0.46 kg t^{-1}
Zinc (Zn)	71.11 mg kg^{-1}	80.11 mg kg^{-1}	0.41 mg kg^{-1}
Copper (Cu)	5.51 mg kg^{-1}	3.14 mg kg^{-1}	0.48 mg kg^{-1}
Molybdenum (Mo)	1.21 mg kg^{-1}	0.98 mg kg^{-1}	0.08 mg kg^{-1}
Nickel (Ni)	3.22 mg kg^{-1}	3.43 mg kg^{-1}	0.89 mg kg^{-1}
Sodium (Na)	5.33 mg kg^{-1}	5.53 mg kg^{-1}	79.64 mg kg^{-1}
pH (1:1 water)	7.4	7.8	7.9
Electric conductivity	3.33 dS m^{-1}	3.45 dS m^{-1}	3.59 dS m^{-1}
Cation exchange capacity	37.88 cmol kg^{-1}	35.34 cmol kg^{-1}	6.26 cmol kg^{-1}
Water holding capacity	42.84%	40.13%	16.24%

Seeds of cucumber cultivar 'Marketmore' were purchased from Thompson and Morgan (Ipswich, UK). Prior to sowing, seeds were disinfected by soaking in a 2% sodium hypochlorite solution. They were then placed in modular trays filled with a peat-based compost and germinated in a growth chamber programmed for a 16-hour photoperiod, 25±2°C temperature, and 60±5% relative humidity. Transplantation into 10 L pots occurred once the seedlings had developed two true leaves. Each treatment was replicated five times, with three seedlings planted per pot initially; later, only the most vigorous seedling was kept per pot. The potting medium was a sandy loam soil uniformly supplemented with a 5% biochar treatment. Immediately after transplanting, the pots were watered. The complete recommended doses of phosphorus (130 kg ha^{-1}) and potassium (270 kg ha^{-1}) were incorporated into the soil mix at transplanting. Nitrogen fertilization (300 kg ha^{-1}) was split into two equal ap-plications: one at transplanting and a second dose one month thereafter (Munir *et al*., 2020). Standard crop management procedures were implemented for the duration of the study.

Prior to seedlings transplanting, field capacity (FC) was determined gravimetrically for the potted soil. Pots were filled with water and covered with plastic sheets, and left for three days to drain. After drainage, the pot weights were recorded. Soil moisture content of FC was the weight after drainage minus the oven dry weight at 105°C for 24 hours (Ahuja *et al*., 2008). The water deficit levels were then estimated at 100, 80, and 60% FC. During the study, pots were weighed regularly on every alternative day using a digital balance, and the amount of water needed to restore the soil to the target weight for each irrigation level was added. This gravimetric method ensured precise and consistent maintenance of the intended soil moisture regimes across all treatments. The experiment was laid out in a two-factorial, completely randomized design with five replications in each treatment. The first factor was two types of date palm feedstocks biochar (EM and PT), and a sandy loam control (CT), whereas the second factor was three water deficit treatments (100, 80, and 60% FC).

Vine length, stem diameter, and plant spread were recorded at harvest. Vine length was measured from the base of the stem to the apical meristem of the primary vine using a standard measuring tape. Stem diameter was measured 50 cm above the soil surface using a digital caliper. Plant spread was determined by measuring the horizontal canopy diameter in two perpendicular directions and calculating the average. The number of days from sowing to the day the first flower opened, the number of days from sowing to the first observable fruit set (ovary to > 2 cm in length), and the number of days from sowing to when the first fruit on the plant reached horticultural maturity were counted. The total number of leaves per plant was counted at harvest. Subsequently, the total leaf area per plant was measured using a portable leaf area meter (LI-3100C, LI-COR Environmental, USA). Leaf area index (LAI) was determined non-destructively using a plant canopy analyzer (LAI-2200C, LI-COR Environmental, USA). Specific leaf area (SLA) is the ratio of leaf area to leaf dry mass and leaf dry matter content (LDMC), whereas LDMC is the ratio of leaf dry mass to fresh mass. The harvested leaves were immediately weighed to obtain their fresh mass (FM). They were then dried in a forced-air oven (Model 1184M74, Thomas Scientific, New Jersey, USA) at 75°C for 72 hours until a constant dry mass (DM) was achieved. SLA was calculated as [Leaf Area / DM] whereas LDMC was calculated as [DM / FM]. Leaf thickness was measured at three points along the mid-vein using a digital micrometer thickness gauge (0-12.7 mm, Desertcart, Dubai, UAE), and the average was recorded.

Estimation of chlorophyll content (*Chl*) was done using a handheld SPAD-502 chlorophyll meter. Net photosynthesis (*Pn*), stomatal conductance (*gs*), transpiration rate (*E*) and intercellular CO_2 concentration (*Ci*), were obtained using a LI-COR 6400XT photosynthesis system. The ratio between *Pn* and *E* was used to calculate the instantaneous water use efficiency (WUEinst) (Iqbal *et al*., 2022; Iqbal & Munir, 2024). The stem, leaf, and root parts of the cucumber plant were separately weighed immediately after harvest to record stem fresh weight (SFW), leaf fresh weight (LFW), and root fresh weight (RFW). Each part was then placed in a separate brown paper bag and dried at temperature of 70°C for 72 hours in a forced air oven, until a constant weight was reached. The dried samples were weighed to obtain stem dry weight (SDW), leaf dry weight (LDW) and root dry weight (RDW).

At harvest, all the marketable fruits from each plant were collected to determine fruit yield and average fruit weight using a digital balance. Fruit assessments consisted of the measurement of fruit length and diameter using a digital vernier caliper and firmness (FF) using a K95590 Koehler penetrometer. The water displacement technique was used to determine fruit volume (Concha-Meyer *et al*., 2018; Munir *et al*., 2020). The Hunter Lab color meter was used to record fruit colors (L*, a*, b*, C*, h°, and ΔE) (Munir *et al*., 2024). Fruit chemical analyses for pH and total soluble solids (TSS) were carried out using specific digital meters. Total sugars were quantified using the anthrone method. Fresh cucumber fruit sample (0.5 g) was boiled in 10 mL of 80% ethanol and subsequently filtered. The filtrate was brought to a final volume of 50 mL with distilled water. A reaction mixture consisting of 1 mL of filtrate and 5 mL of anthrone reagent was prepared, incubated in a water bath at 100°C for 15 min, and then allowed to cool at room temperature for 20 min. Absorbance was recorded at 620 nm against a similarly prepared blank. Total sugar concentration was determined from a standard calibration curve (Perveen & Bokahri, 2020). Proline content was determined from 0.5 g of fresh leaf tissue at harvest. Samples were homogenized in 3% sulfosalicylic acid, followed by centrifugation at 3000 rpm for 20 min. A 200 µL aliquot of the supernatant was mixed with 200 µL each of acetic acid and ninhydrin reagent, then boiled for 1 h. After cooling on ice, the absorbance of the solution was measured at 520 nm using a spectrophotometer (Bates *et al*., 1973). Relative water content (RWC) was determined using three 5 cm^2 leaf discs per sample. Immediately after collection, discs were sealed in pre-weighed airtight vials and stored at 10°C. Fresh weight (FW) was recorded, after which the discs were fully hydrated in deionized water for 24 h at room temperature, blotted dry, and the turgid weight (TW) measured. Discs were then oven-dried at 80°C for 48 h, cooled in a desiccator, and the dry weight (DW) recorded (Khakwani *et al*., 2012). RWC was calculated as:

$$\mathrm{RWC} = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \times 100$$

All collected data were statistically analyzed by applying two-way analysis of variance (ANOVA) using the SPSS software package (Version 28; IBM Corp., USA). When the results of the ANOVA revealed significant effects, significant differences between means in treatments were tested by the least significant difference (LSD) test at the 5% level of significance. Furthermore, a correlation analysis was carried out and the findings were visualised as heatmap, chord diagram, and dendrogram using R and RStudio software.

Results

Plant morphological characteristics: Fig. 1 showed significant ($p \leq 0.05$) trends in plant development parameters where date palm empty bunches biochar (EB) and date palm pit biochar (PT) treatments were consistently performing better than controls (CT) at all field capacity (FC) levels (100%, 80%, 60%). Vegetative growth metrics of plants grown in control showed the lowest performance at all FCs. Vine size was significantly shortened at all the control levels, with CT60 having the shortest average vine size (104.33 cm). This is a significant reduction of 37% from the best performing EB100 treatment (165.67 cm). Stem diameter was maximum at EB100 (13.30 cm) whereas the controls ranged between 6.90 to 9.03 cm. EB and PT performed better than controls in terms of plant spread parameter consistently, and the differences between EB and PT groups were minimal. Days to flowering showed little variation among treatments as it was between 25 and 30 days. However, days to fruit maturation showed a significant difference that control groups took significantly longer maturation periods (55.33-65.33 days) with CT60 showing the longest maturation period. In contrast, the fruit maturation time of all the EB and PT treatments was shorter (50-54.67 days).

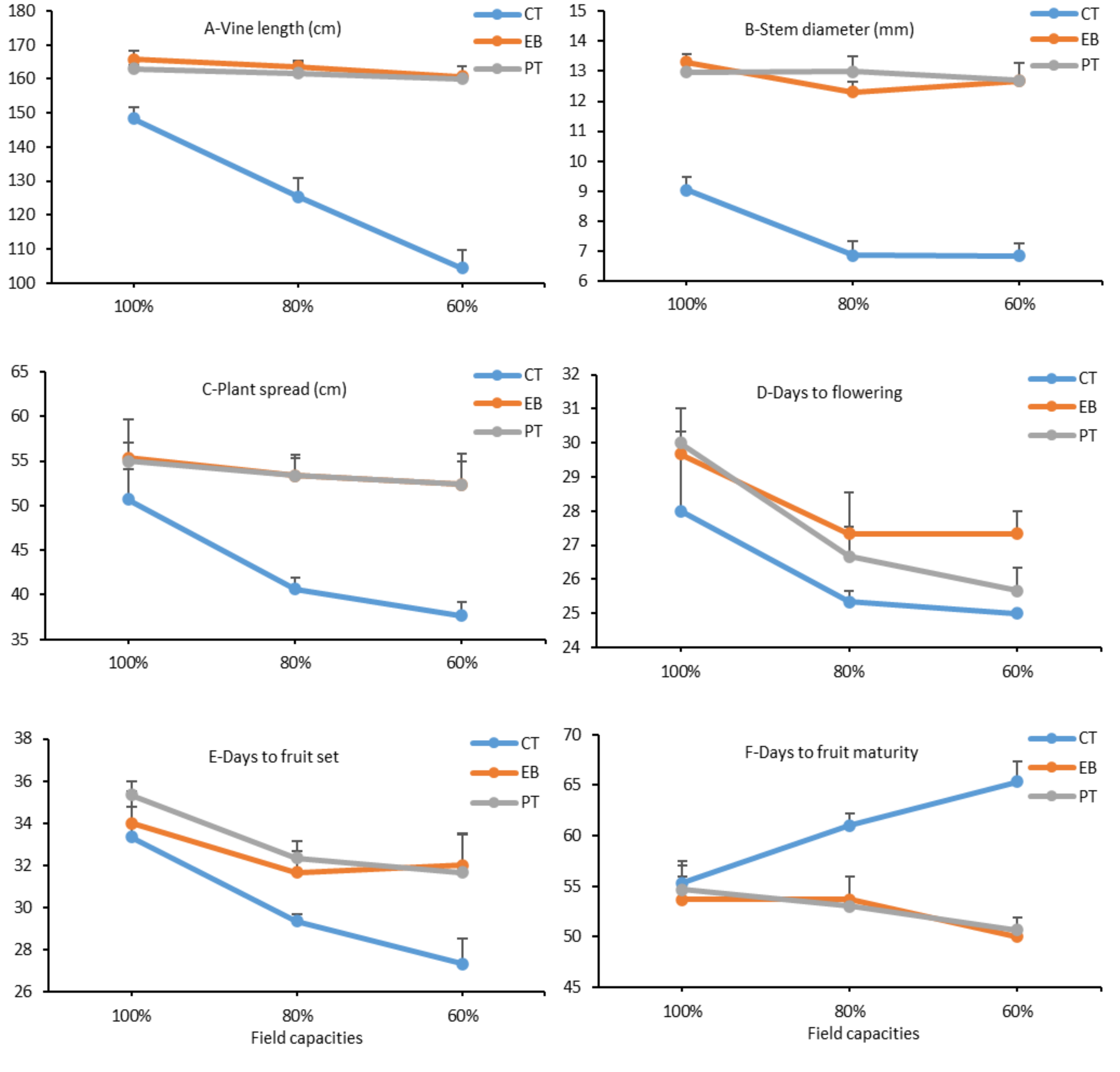

Fig. 1. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) vine length, (B) stem diameter, (C) plant spread, (D) day to flower, (E) day to fruit set, and (F) days to fruit maturity of cucumber. Y-bars on each data points represent the standard error within the replicates.

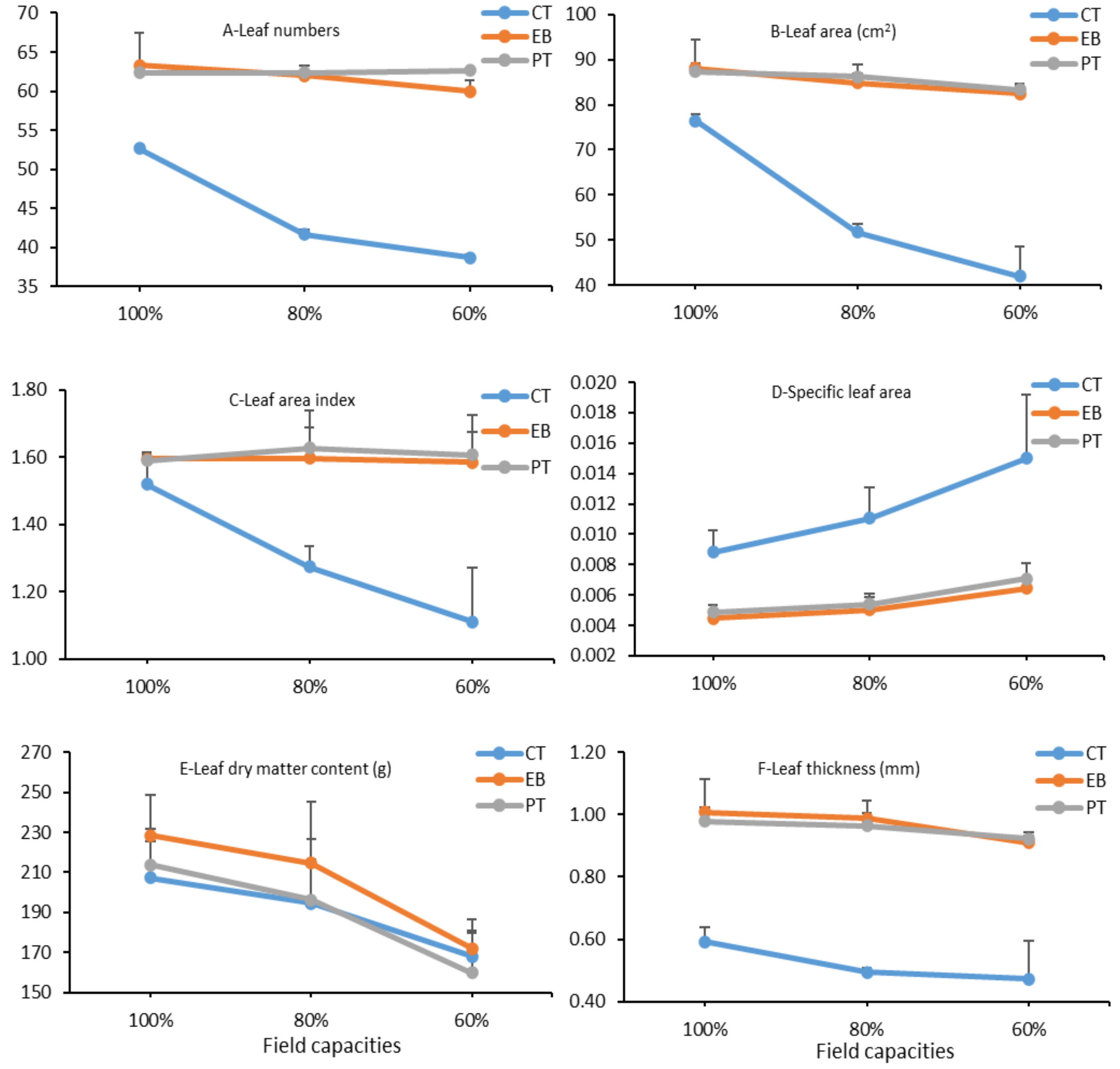

Fig. 2. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) leaf No, (B) leaf area, (C) leaf area index, (D) specific leaf area, (E) leaf dry matter content, and (F) leaf thickness of cucumber. Y-bars on each data points represent the standard error within the replicates.

Data presented in Fig. 2 indicated treatment-induced significant ($p \leq 0.05$) variation in morphologic traits of leaves. As result EB and PT amendments consistently improved the leaf development with minimal water stress effects as compared with the controls. EB100 showed the maximum LA (88.14 cm^2) and LN (63.33) which was much higher than all control treatments, but CT60 showed severe suppression in these parameters. Treatments also had a profound effect on leaf structure: EB100 had the maximum LT (1.01 mm); maximized LDMC (228.45), which was correlated with increased photosynthetic efficiency. Controls on the other hand had significantly higher SLA (up to 0.015, in CT60), indicated thinner leaves, with lower structure. The LDMC of EB60 and PT60 also decreased significantly, compared to EB100 and PT100, which may indicate concentration thresholds for dry matter accumulation.

Physiological characteristics: The results in Fig. 3 showed that EB and PT amended soils significantly ($p \leq 0.05$) improved photosynthetic performance compared with controls with EB100 and PT100 having the highest improvement. Chlorophyll content was significantly increased in the presence of EB100 (36.5 SPAD) and PT100 (35.63 SPAD) about 16-18% (31.5 SPAD) higher than in the highest control treatment (CT100). This was highly correlated with the net photosynthetic rates, where EB100 had a photosynthetic rate 15.41 µmol m^{-2} s^{-1}, which was 9% higher than CT100. Stomatal conductance (0.182 mol m^{-2} s^{-1}) and transpiration rates (3.51 mmol m^{-2} s^{-1}) were significantly enhanced in EB/PT treatments. Despite an increase in gas exchange parameters there was a significant decrease in intercellular CO_2 concentration in both EB and PT treatment combinations (157-171 µmol mol^{-1}) compared to controls (211-295 µmol mol^{-1})

suggesting that EB and PT treatment combinations exhibit a higher CO_2 assimilation efficiency. While instantaneous water use efficiency was higher in CT60 (7.76), revealing their low transpiration and photosynthetic proficiency. Controls plants under water stressed conditions (CT60% and CT80%); chlorophyll content and net photosynthesis were decreased with increasing intercellular CO_2 level—indicating impaired carbon fixation.

Plant biomass characteristics: The results showed that the amendment of soil with date palm waste-derived biochar (EB and PT) significantly ($p \leq 0.05$) increased the biomass of cucumber plants at all levels of FC than CT (Fig. 4). The SFW was increased by 10% (EB100) and 9% (PT100), and SDW was increased by 30% (EB100) and 25% (PT100). This trend was pronounced in leaves, with LFW increasing by ~61% for both treatments (EB100 and PT100) and LDW increasing by ~82% (EB100) and ~69% (PT100). Similarly, RFW and RDW increased 18-28 and 29-41% in both biochar (EB100 and PT100), respectively. When irrigation was reduced from 100% to 60% FC, the CT showed severe reductions of all measured biomass parameters. For example, at 60% FC, CT plants had reductions in 23% (SFW), 53% (SDW), 44% (LFW), 53% (LDW), 39% (RFW) and 47% (RDW) when compared to a fully irrigated control (CT100). Both EB and PT biochar behaved remarkably similarly in all parameters and stress levels and did not show any consistent significant difference.

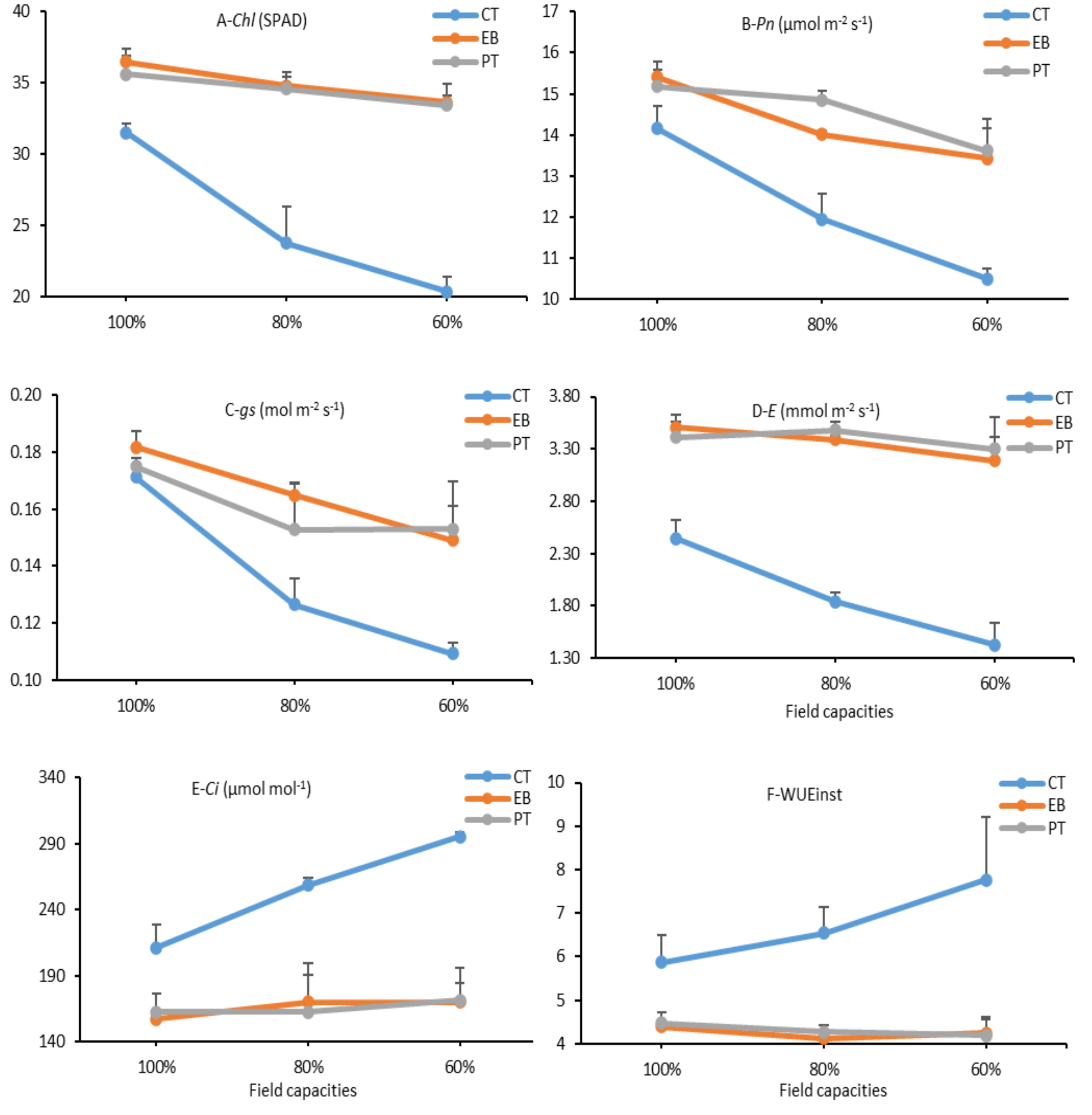

Fig. 3. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) chlorophyll content-*Chl*, (B) net photosynthesis-*Pn*, (C) stomatal conductance-*gs*, (D) transpiration rate-*E*, (E) intercellular CO_2 concentration-*Ci*, and (F) instantaneous water use efficiency-WUEinst of cucumber. Y-bars on each data points represent the standard error within the replicates.

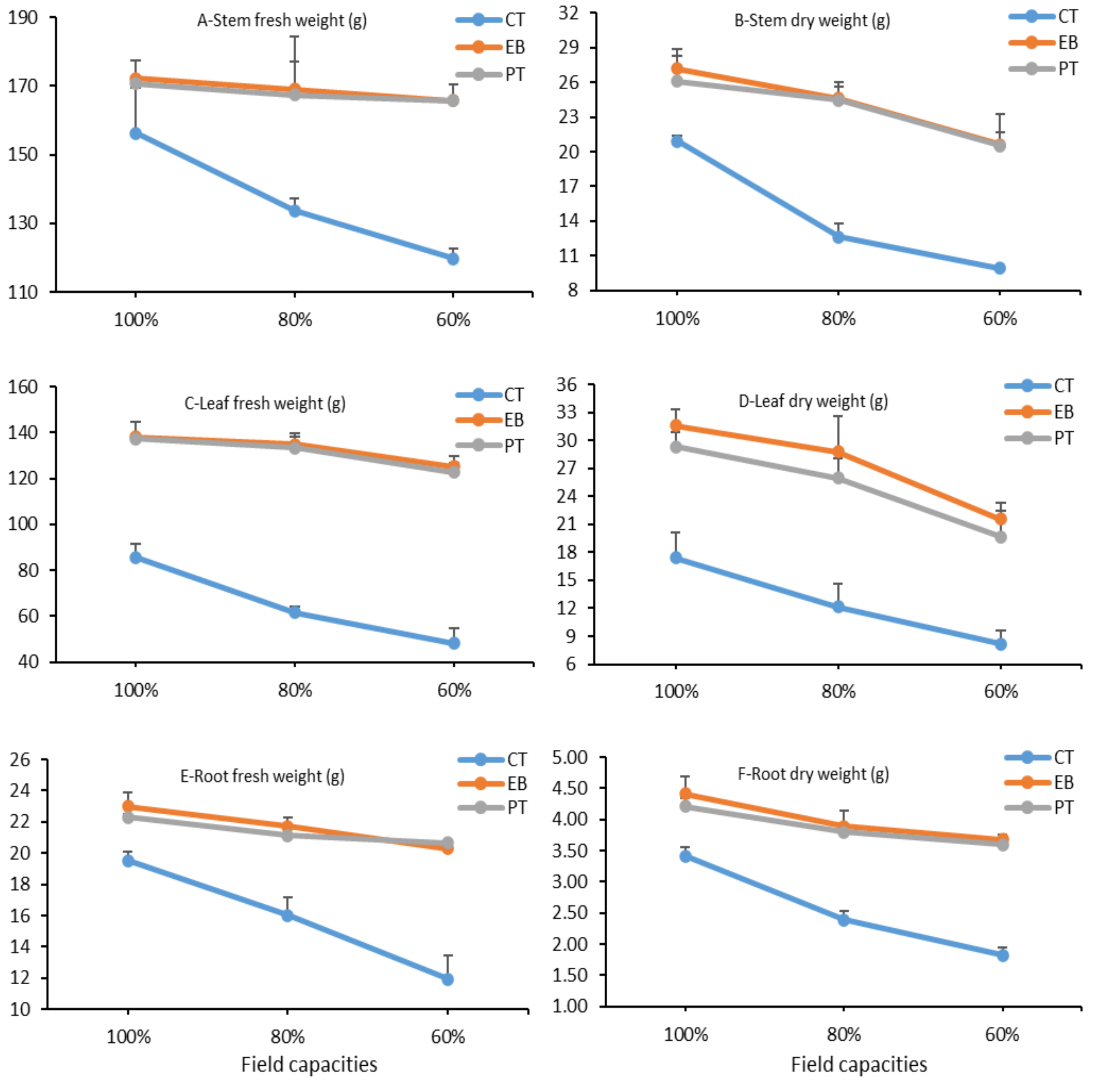

Fig. 4. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) stem fresh weight, (B) stem dry weight, (C) leaf fresh weight, (D) leaf dry weight, (E) root fresh weight, and (F) root dry weight of cucumber. Y-bars on each data points represent the standard error within the replicates.

Fruit yield, quality, color, and biochemical characteristics: Plants grown in EB100-amended soil produced significantly ($p \leq 0.05$) higher fruit yield per plant (1951.93 g) and was closely followed by the PT100 (1897.18 g) (Fig. 5). These amendments further showed the highest fruit length (16.73 and 16.40 cm for EB100 and PT100, respectively), fruit diameter (36.45 and 35.88 mm), and fresh fruit weight (154.03 and 153.77 g) resulted in an increase in both fruit size and quality. On the other hand, the CT60 treatment showed the lowest performance in all the parameters measured, i.e., fruit yield per plant (367.17 g), fruit length (9.07 cm), and fruit diameter (18.96 mm). Plants grown in EB60 and PT60 amendments had relatively high yields (1563.13 and 1584.95 g, respectively) compared to CT100 (1050.94 g) showing the potential of these organic amendments in mitigating the impact of water limitation.

The results regarding the fruit color parameters as presented in Fig. 6 showed that there were significant ($p \leq 0.05$) variations which were affected by both the irrigation levels and the biochar amendments. Among the treatments, the control under severe water stress (CT60) showed the highest total color difference (56.68) representing a large deviation in fruit color than that of the higher FCs and biochar feedstocks. This was coupled with distinct changes in chromaticity values exhibiting a higher chroma (11.45) and a hue angle (128.13), which might indicate unwanted color changes in response to limited water availability. On the other hand, treatments amended with EB100 and PT100 under full irrigation (100% FC) showed the smallest color deviation with color difference values of 45.22 and 45.39, respectively.

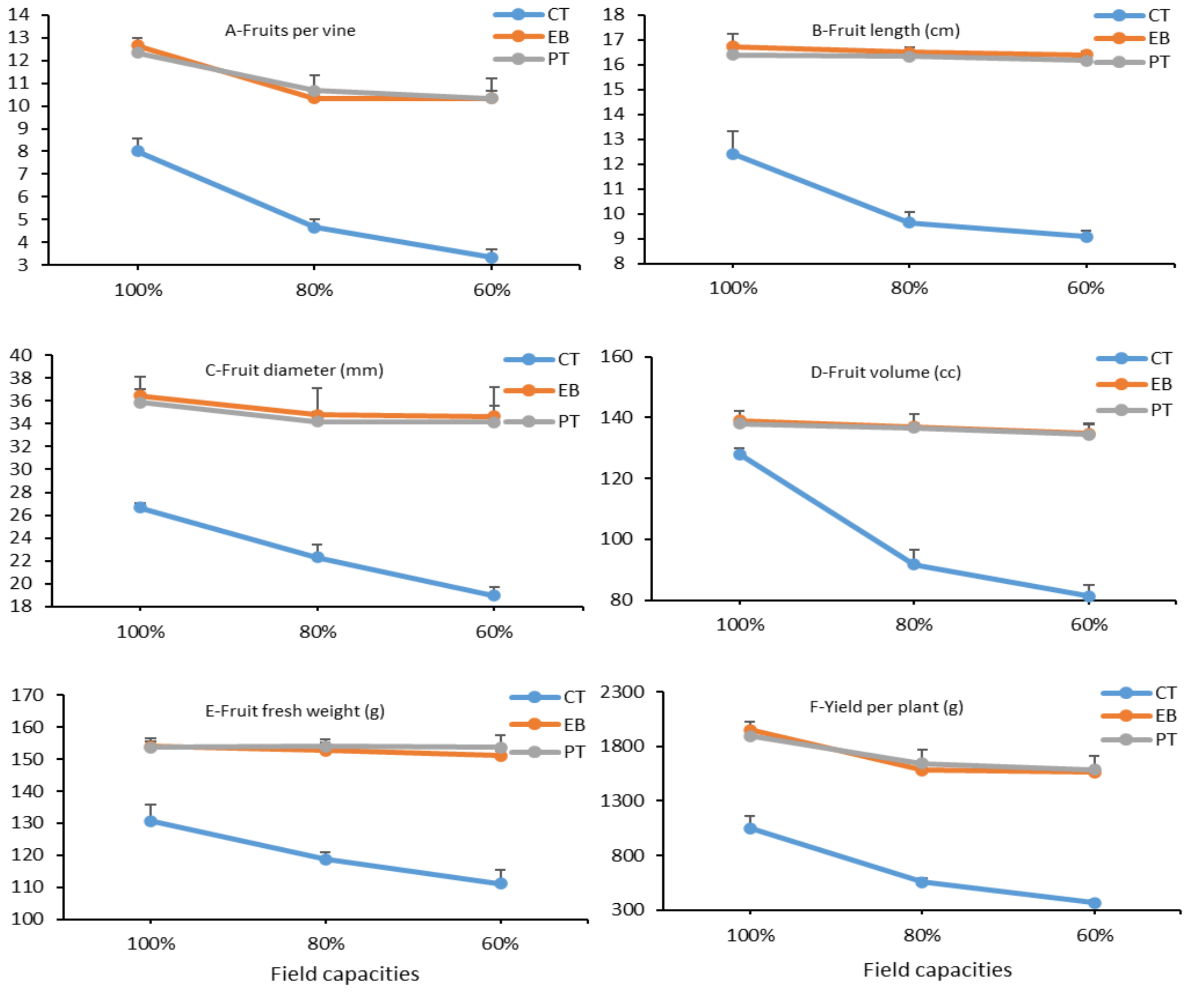

Fig. 5. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) fruits per vine, (B) fruit length, (C) fruit diameter, (D) fruit volume, (E) fruit fresh weight, and (F) yield per plant of cucumber. Y-bars on each data points represent the standard error within the replicates.

Figure 7 showed the significant ($p \leq 0.05$) impacts of biochar amendments and irrigation levels on fruit firmness, pH, TSS, total sugars, leaf proline, and RWC. The use of EB and PT at full irrigation (100% FC) contributed to better physiological and biochemical fruit quality attributes. EB100 showed the highest total sugars (121.99 mg g^{-1} DW) and RWC (80.94) and the lowest accumulation of proline (18.98 µmol g^{-1} FW) in the leaf, which reveals the low physiological stress, resulting in an increase in water status in the plants. Similarly, PT100 had high RWC (80.16) and total sugars (117.67 mg g^{-1} DW). In contrast, the high values of leaf proline (28.63 µmol g^{-1} FW) and fruit firmness (0.23 N mm^{-1}), and low values of total sugars (42.44 mg g^{-1} DW) and RWC (47.44) were recorded in the control under severe water-deficit conditions (CT60), indicating a stress response to limited irrigation in the absence of biochar amendments. Similarly, pH of the fruit juice was highest (8.03) in EB100, which was decreased in water-stressed fruits indicating better fruit biochemical stability.

Interactions of soil amendments and drought on cucumber traits: a heatmap analysis: The heatmap illustrates the interactive effects of biochar amendments derived from date palm feedstocks—empty bunch (EB), pit (PT), and a control (CT)—combined with varying field capacities (100%, 80%, and 60%, representing full irrigation, mild drought, and severe drought, respectively) on morpho-physiological, biochemical, yield, and fruit quality parameters in cucumber plants (Fig. 8). The heatmap analysis revealed that the EB100% and PT100% treatments consistently resulted in the highest values for the majority of growth (VL, SD, PS, LN, LA, LT, LDMC, SFW, SDW, LFW, LDW, RFW, and RDW), physiological (*Chl*, *Pn*, *gs*, *E*, and RWC), fruit color (a* and h°), yield (NFV, FL, FD, FV, FFW, and YPP), and quality (FF, pH, TSS, and TS) parameters, indicating optimal plant performance under full irrigation with biochar. The performance under EB80% and PT80% was comparable to, and often exceeded, that of the CT100% treatment, demonstrating that biochar application at 80% FC can mitigate water deficit effects to maintain productivity levels equivalent to a well-watered control. Similarly, the EB60% and PT60% treatments frequently outperformed the drought-stressed CT60% and CT80% control, which consistently showed the lowest values across almost all measured traits, highlighting the severe impact of drought and the protective role of biochar even under severe water stress conditions.

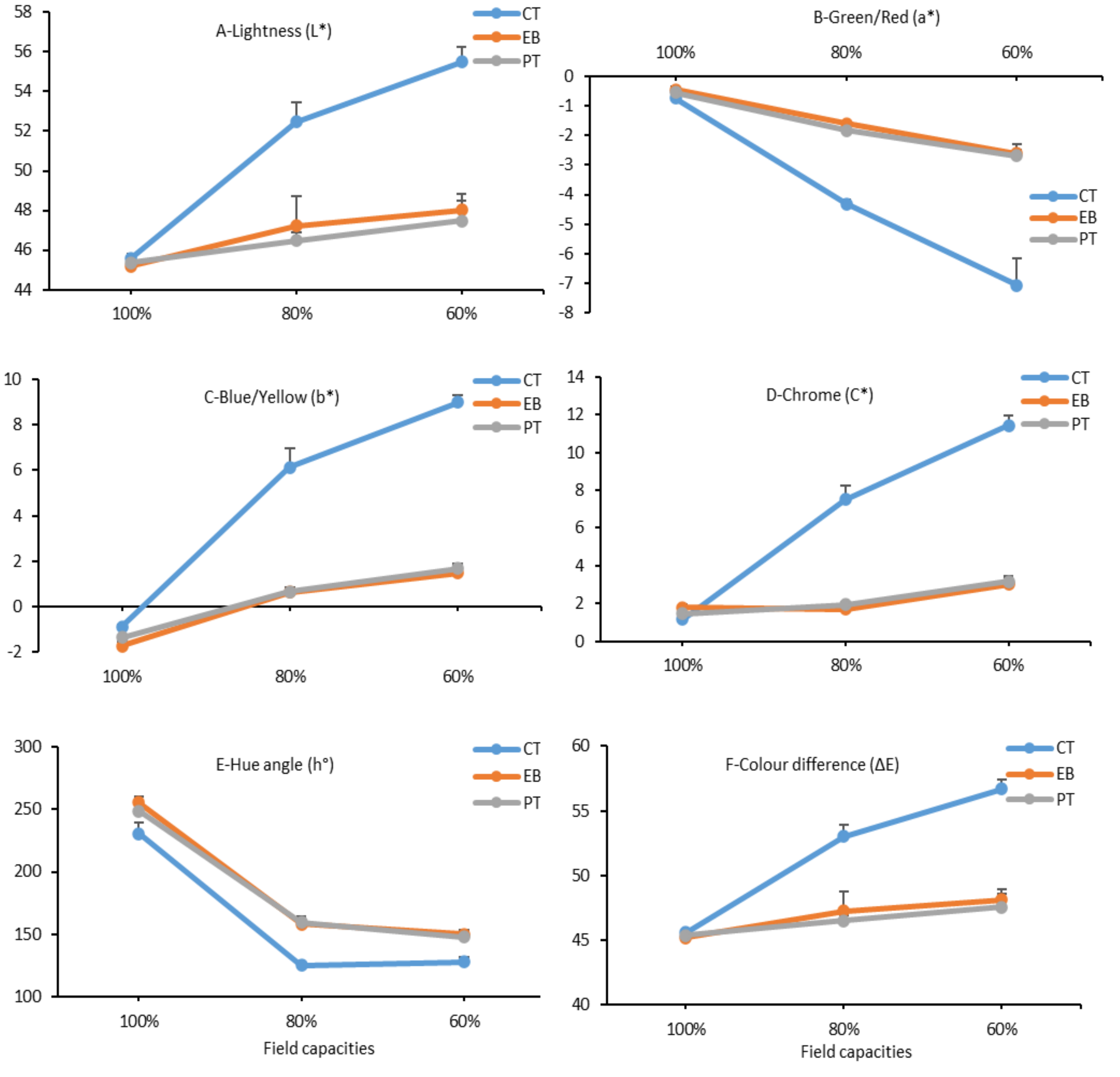

Fig. 6. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) lightness-L*, (B) green/red-a*, (C) blue/yellow-b*, (D) chrome-C*, (E) hue angle-h°, and (F) color difference-ΔE of cucumber. Y-bars on each data points represent the standard error within the replicates.

Correlation matrix of cucumber traits: The correlation matrix (Fig. 9) reveals a complex and highly interconnected network of relationships among the measured growth, physiological, yield, and quality parameters in cucumber. Parameters such as VL, SD, PS, LN, LA, and LAI show highly significant ($p<0.001$) positive correlations with each other, indicating that improvements in one parameter of vegetative growth are closely linked to improvements in all others. This correlated group associates strongly with physiological performance, with chlorophyll *Chl*, *Pn*, and *gs* also showing positive correlations with growth traits, suggesting that enhanced canopy architecture directly facilitates greater photosynthetic capacity. This synergistic relationship continues into biomass accumulation and yield components. All fresh and dry weight metrics for stems, leaves, and roots (SFW, SDW, LFW, LDW, RFW, RDW) are positively correlated with the growth and physiological parameters, highlighting a direct influence of vegetative vigor and photosynthetic efficiency into overall plant biomass. This investment in growth leads to a higher fruit yield, as evidenced by strong positive correlations with yield-related traits such as NFV, FL, FD, FV, FFW, and YPP. The fruit quality parameters (pH, TSS, and TS) are also positively integrated into this group, indicating that higher-yielding plants also produced fruit with superior quality.

Conversely, these positively correlated traits exhibit significant negative correlations with *Ci* and WUEinst, suggesting that the plants with the most vigorous growth had lower internal CO_2 levels and different water use dynamics. A major negative correlation pattern is also evident with fruit color metrics. The fruit skin color coordinates, L*, a*, b*, C*, and ΔE, all show significant negative correlations with the growth-yield attributes, implying that higher productivity was associated with a darker, potentially more mature or deep-green fruit coloration. The phenological traits show such as DF and DFS are positively correlated with each other and with several other traits, suggesting a slight delay in flowering was not detrimental to final outcomes. In contrast, DFM is strongly negatively correlated with nearly all growth and yield parameters, clearly indicating that earlier maturing plants were more productive and vigorous. However, LDMC and h° demonstrate relatively different behavior, with weaker correlations, marking them as more independent variables. The strong positive correlation of RWC with yield and biomass highlights the critical association between plant water status and overall performance.

Association between the field capacities and the cucumber traits: The chord diagram (Fig. 10) shows that at 100% FC, the plant exhibits optimal growth and productivity. Strong positive association was found between water availability and key parameters: vigorous growth (high VL, SD, LA, LFW, LDW, RDW), efficient physiological function (maximized *Pn*, *gs*, *E*, RWC), and ultimately, superior yield and fruit quality (high FPV, FV, YPP, TSS). This condition represents minimal stress, with resources allocated towards development and reproduction. At 80% FC (mild stress), the plant initiates adaptive responses. To conserve water, physiological parameters such as *gs* and *E* decline, potentially reducing *Pn* and slowing growth metrics (LA, LFW). The plant may begin to prioritize root investment (RDW) to explore deeper soil moisture. This stage represents a trade-off, where mild stress slightly compromises above-ground growth and yield potential to enhance resilience, possibly indicated by a slight rise in osmolytes such as LP. Under severe stress (60% FC), survival mechanisms dominate, leading to declines across most parameters. Physiological function is significantly impaired (*Pn*, *gs*, *E*, RWC all drop sharply), triggering accelerated phenological development (DFS, DFM) to complete the life cycle prematurely. Growth is severely stunted (VL, SD, LA, all biomass weights), and yield traits (FPV, YPP). Fruit quality also affected (FF, TSS). Concurrently, stress markers such as LP accumulate for osmotic adjustment. The chord diagram would show these dramatic shifts, with strong association now centered on stress-induced parameters and survival traits, while the links to growth and yield weaken or become negative.

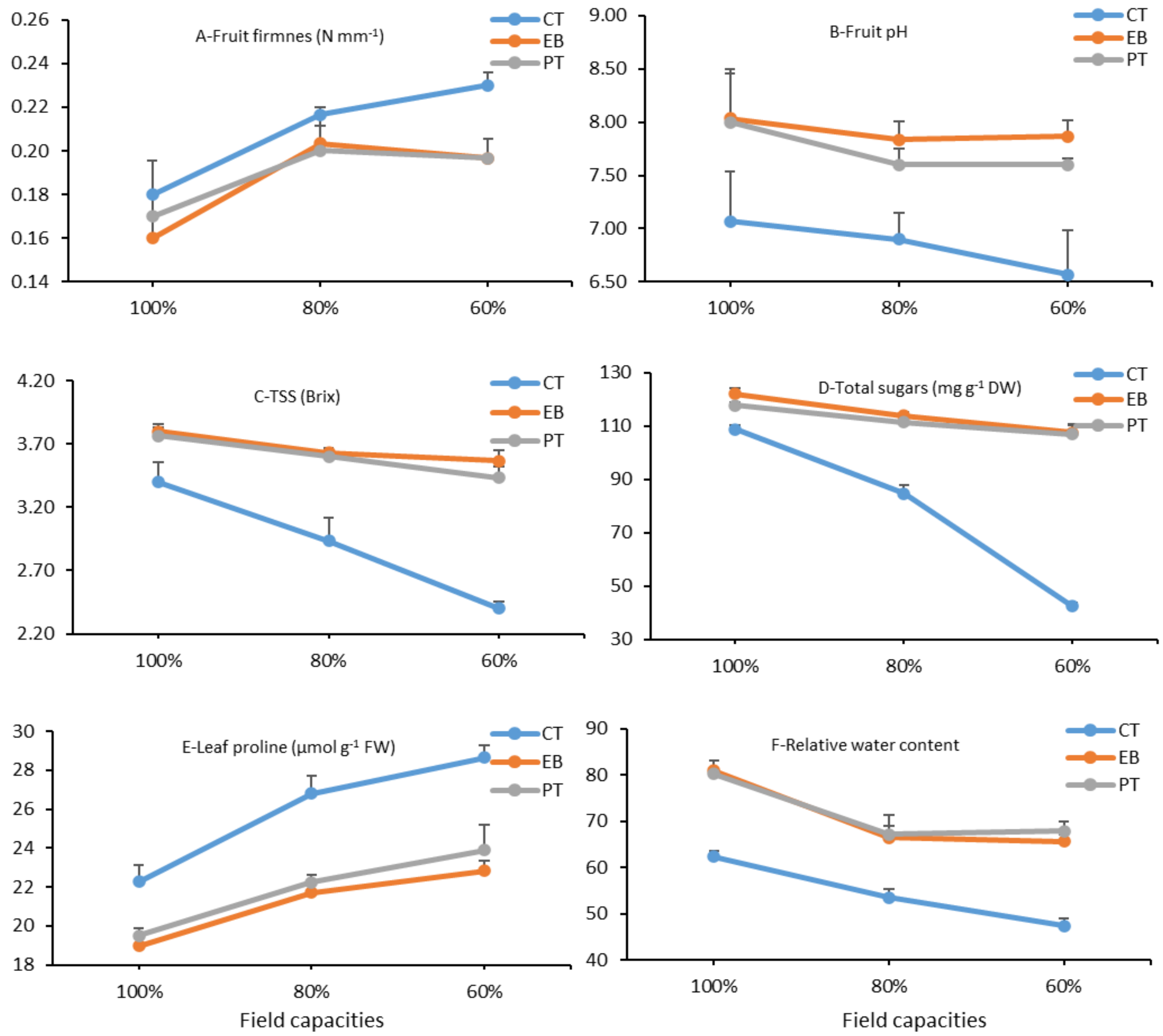

Fig. 7. Effect of drought stress (100, 80, and 60% FC) and date palm biochar feedstocks (empty bunch-EB, pit-PT, and control-CT) on (A) fruit firmness, (B) fruit pH, (C) total soluble solids, (D) total sugars, (E) leaf proline, and (F) relative water content of cucumber. Y-bars on each data points represent the standard error within the replicates.

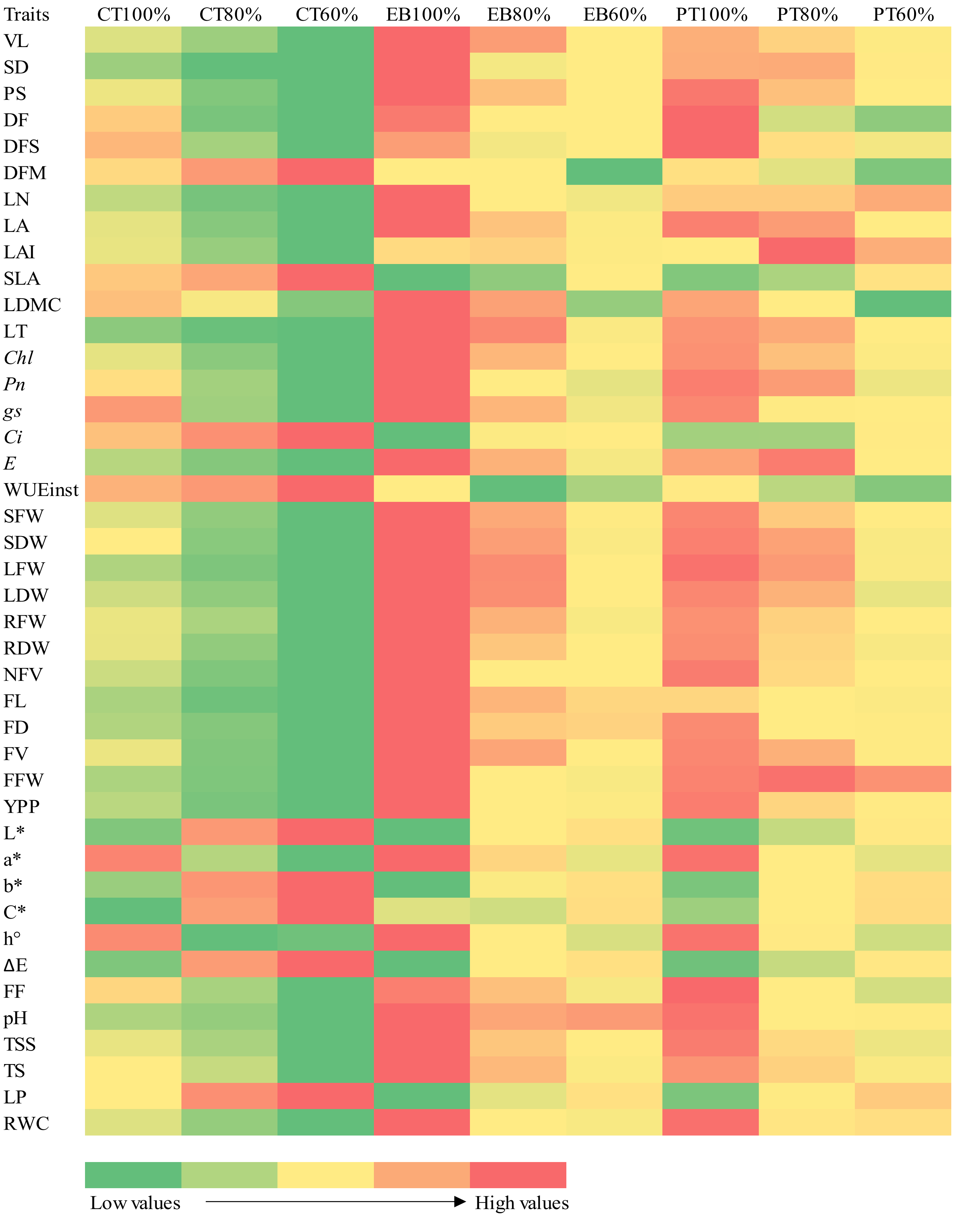

Fig. 8. Heatmap displaying the effects of drought stress (100%, 80%, 60% FC) and biochar feedstock (CT: control, EB: empty bunch, PT: pit) on growth, phenological, physiological, and biochemical characteristics of cucumber. Abbreviations: VL, vine length; SD, stem diameter; PS, plant spread; LN, leaf number; LA, leaf area; LAI, leaf area index; SLA, specific leaf area; LDMC, leaf dry matter content; LT, leaf thickness; SFW, stem fresh weight; SDW, stem dry weight; LFW, leaf fresh weight; LDW, leaf dry weight; RFW, root fresh weight; RDW, root dry weight. DF, day to flower; DFS, day to fruit set; DFM, day to fruit maturity. *Chl*, chlorophyll content; *Pn*, net photosynthesis; *gs*, stomatal conductance; *E*, transpiration rate; *Ci*, intercellular CO_2 concentration; WUEinst, instantaneous water use efficiency; RWC, relative water content. FPV, fruits per vine; FL, fruit length; FD, fruit diameter; FV, fruit volume; FFW, fruit fresh weight; YPP, yield per plant; FF, fruit firmness; pH, fruit pH; TSS, total soluble solids; and TS, total sugars. L*, lightness; a*, green/red; b*, blue/yellow; C*, chroma; h°, hue angle; ΔE, color difference, and LP, leaf proline.

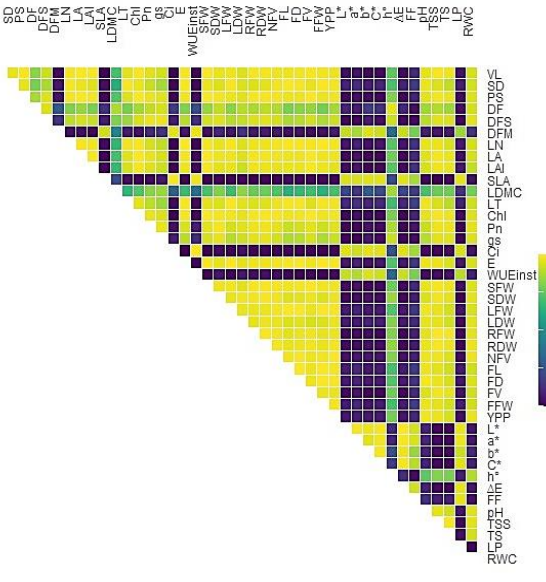

Fig. 9. Correlation analysis showing the effects of field capacities (100%, 80%, 60% FC) and biochar feedstock (CT: control, EB: empty bunch, PT: pit) on growth, phenological, physiological, and biochemical characteristics of cucumber. Abbreviations: VL, vine length; SD, stem diameter; PS, plant spread; LN, leaf number; LA, leaf area; LAI, leaf area index; SLA, specific leaf area; LDMC, leaf dry matter content; LT, leaf thickness; SFW, stem fresh weight; SDW, stem dry weight; LFW, leaf fresh weight; LDW, leaf dry weight; RFW, root fresh weight; RDW, root dry weight. DF, day to flower; DFS, day to fruit set; DFM, day to fruit maturity. *Chl*, chlorophyll content; *Pn*, net photosynthesis; *gs*, stomatal conductance; *E*, transpiration rate; *Ci*, intercellular CO_2 concentration; WUEinst, instantaneous water use efficiency; RWC, relative water content. FPV, fruits per vine; FL, fruit length; FD, fruit diameter; FV, fruit volume; FFW, fruit fresh weight; YPP, yield per plant; FF, fruit firmness; pH, fruit pH; TSS, total soluble solids; and TS, total sugars. L*, lightness; a*, green/red; b*, blue/yellow; C*, chroma; h°, hue angle; ΔE, color difference, and LP, leaf proline.

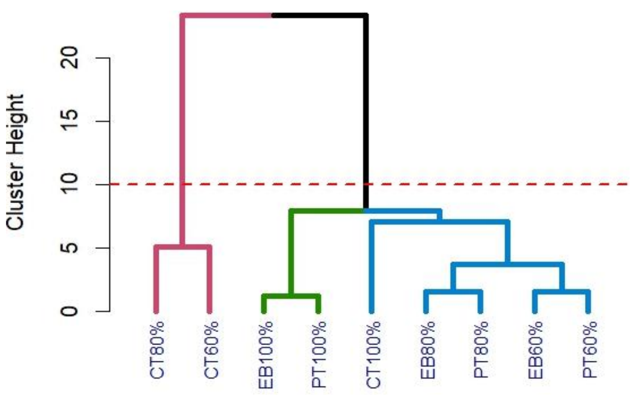

Fig. 11. Dendrogram from hierarchical cluster analysis of cucumber morpho-physio, and biochemical responses to biochar amendments (EB, PT) and control (CT) under varying water regimes (100%, 80%, 60% FC).

The analysis of the chord data reveals a significant positive association between different field capacities with VL (R^2 = 1.00; p = 0.0000), SD (R^2 = 0.99; p = 0.0466), PS (R^2 = 1.00; p = 0.0001), DF (R^2 = 0.99; p = 0.0229), DFS (R^2 = 1.00; p = 0.0002), LN (R^2 = 1.00; p = 0.0003), LA (R^2 = 1.00; p = 0.0000), LAI (R^2 = 1.00; p = 0.0000), LDMC (R^2 = 1.00; p = 0.0186), LT (R^2 = 1.00; p = 0.0155), *Chl* (R^2 = 1.00; p = 0.0096), *Pn* (R^2 = 1.00; p = 0.0082), *gs* (R^2 = 1.00; p = 0.0071), *E* (R^2 = 1.00; p = 0.0055), SFW (R^2 = 1.00; p = 0.0045), SDW (R^2 = 1.00; p = 0.0041), LFW (R^2 = 1.00; p = 0.0038), LDW (R^2 = 1.00; p = 0.0035), RFW (R^2 = 1.00; p = 0.0032), RDW (R^2 = 1.00; p = 0.0029), NFV (R^2 = 1.00; p = 0.0027), FL (R^2 = 1.00; p = 0.0025), FD (R^2 = 1.00; p = 0.0023), FV (R^2 = 1.00; p = 0.0021), FFW (R^2 = 1.00; p = 0.0020), YPP (R^2 = 1.00; p = 0.0018), pH (R^2 = 1.00; p = 0.0186), TSS (R^2 = 1.00; p = 0.0186), TS (R^2 = 1.00; p = 0.0186), LP (R^2 = 1.00; p = 0.0010), and RWC (R^2 = 0.98; p = 0.1183), indicating that increases in water availability are strongly associated with improved plant performance. On the other hand, a significant negative association was observed between different field capacities with DFM (R^2 = –0.96; p = 0.1712), SLA (R^2 = –1.00; p = 0.0186), *Ci* (R^2 = –0.86; p = 0.3333), WUEinst (R^2 = –0.94; p = 0.2114), L* (R^2 = –1.00; p = 0.0186), a* (R^2 = –1.00; p = 0.0186), b* (R^2 = –1.00; p = 0.0186), C* (R^2 = –1.00; p = 0.0186), h° (R^2 = –1.00; p = 0.0186), ΔE (R^2 = –1.00; p = 0.0186), and FF (R^2 = –0.94; p = 0.2114), indicating an inverse association, where parameter values decrease as field capacity increases. Several color-related parameters (L*, a*, b*, C*, h°, ΔE) show a negative association suggesting fruit color changes significantly as water levels decrease.

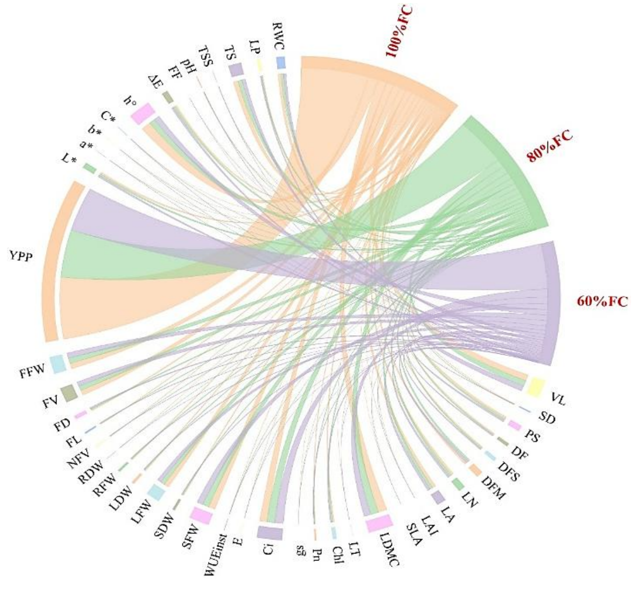

Fig. 10. Chord diagram showing the association between the different growth, phenological, physiological, and biochemical characteristics of cucumber with water stress levels (100%, 80%, and 60% FC). The chords are unidirectional whereas the chord thickness corresponds to the observed values of different attributes that is related to respective water stress levels. Abbreviations: VL, vine length; SD, stem diameter; PS, plant spread; LN, leaf number; LA, leaf area; LAI, leaf area index; SLA, specific leaf area; LDMC, leaf dry matter content; LT, leaf thickness; SFW, stem fresh weight; SDW, stem dry weight; LFW, leaf fresh weight; LDW, leaf dry weight; RFW, root fresh weight; RDW, root dry weight. DF, day to flower; DFS, day to fruit set; DFM, day to fruit maturity. *Chl*, chlorophyll content; *Pn*, net photosynthesis; *gs*, stomatal conductance; *E*, transpiration rate; *Ci*, intercellular CO_2 concentration; WUEinst, instantaneous water use efficiency; RWC, relative water content. FPV, fruits per vine; FL, fruit length; FD, fruit diameter; FV, fruit volume; FFW, fruit fresh weight; YPP, yield per plant; FF, fruit firmness; pH, fruit pH; TSS, total soluble solids; and TS, total sugars. L*, lightness; a*, green/red; b*, blue/yellow; C*, chroma; h°, hue angle; ΔE, color difference, and LP, leaf proline.

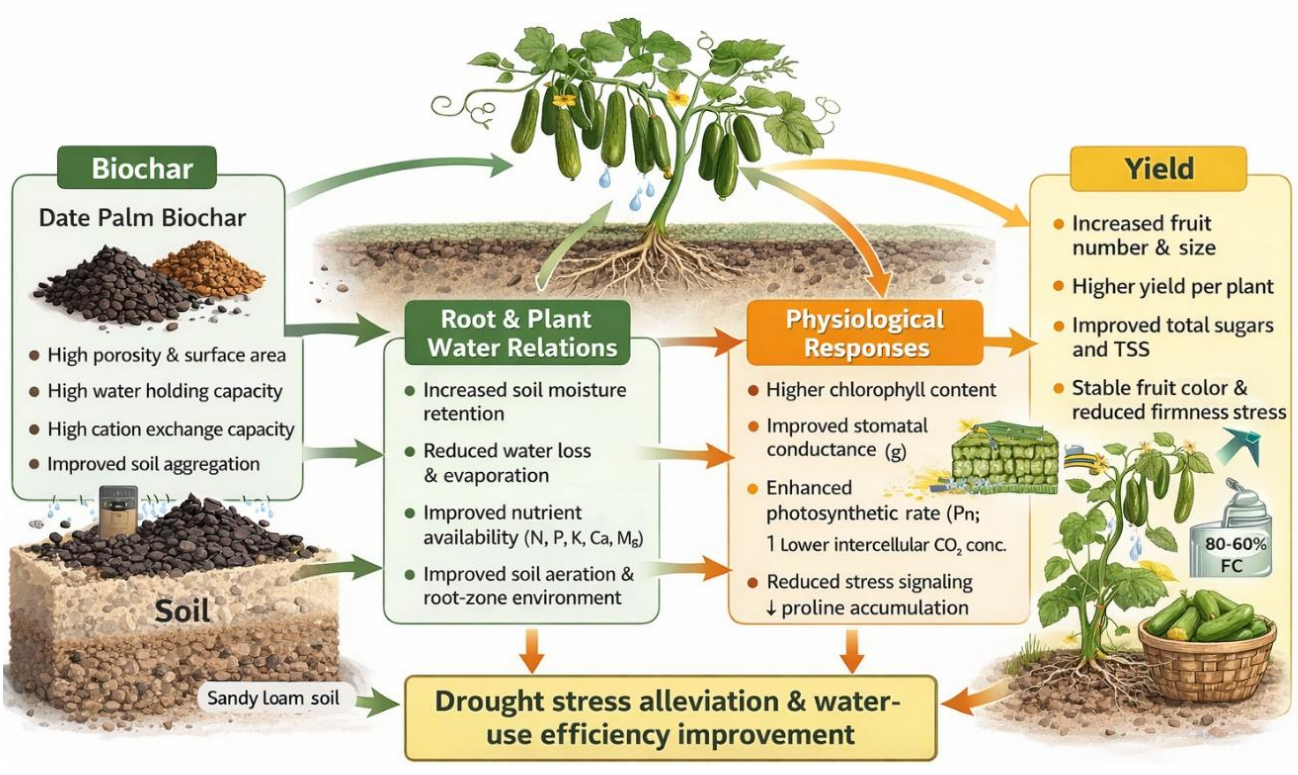

Fig. 12. Mechanistic diagram illustrating how date palm empty bunch (EB) and pit (PT) biochar mitigate drought stress in cucumber under reduced field capacity. Biochar improves soil water retention and nutrient availability, enhances root water uptake and plant water status, maintains photosynthetic efficiency, reduces stress indicators, and ultimately sustains yield and fruit quality under water-deficit conditions.

Hierarchical clustering of biochar amendments and field capacities combinations: Cluster analysis based on a comprehensive data set of various parameters led to a quantitative evaluation of the differential effects of biochar amendments and irrigation regimes on cucumber plants. The resulting dendrogram (Fig. 11) showed a clear separation between the experimental treatments, so that they were effectively grouped according to their ability to counteract drought stress. The clusters were segregated dominated not by the type of biochar but by the presence of biochar and severity of the water deficit. All the biochar amended treatments (EB and PT) formed a major cluster distinct from the non-amended control (CT) treatments. This main division highlights the major role of biochar soil amendment in changing the plant response to both stressed and non-stressed conditions. Within the biochar cluster sub-clusters were further defined by levels of irrigation. The 100% FC treatments (EB100% and PT100%) were grouped most closely indicating the two biochar feedstocks had high similarity under ideal irrigation. As water stress increased, the 80% and 60% FC treatments remained distinct within their own sub-groups, but they were still part of the larger cluster of biochar. Showing the consistent nature of biochar in its drought stress benefit. The result of the cluster analysis shows that the drought-stressed biochar treatments (EB80%, PT80%, EB60% and PT60%) form a separate, solid group. This close clustering suggests that the type of biochar feedstock (EM or PT) is not as important in determining the plant's response to water deficit conditions as the simple presence of biochar under water deficit conditions. The high similarity between these treatments shows that both types of biochar consistently induce a similar, robust physiologic state in the cucumber plants under drought stress, which can be considered as having separated them from both the stressed control and well-watered treatments.

In contrast, the control treatments (CT100%, CT80%, CT60%) formed a separate and tight cluster, characterizing the fact that the plants in unamended soil had a fundamentally different and less favorable plant profile. The hierarchical structure in this control cluster exhibited a gradient directly along the level of water deficit with CT60% most distant from the biochar groups. This pattern underlies the extreme effect of drought in the absence of soil amendment. The clear bifurcation in the dendrogram validates the application of both EM and PT-derived biochar modulated the response of the cucumber plants to drought and shifted their performance to a different and, presumably, more resilient state in comparison to the control.

Discussion

The outcome of the study demonstrated that the use of date palm empty bunch (EB) and pit (PT) biochar offered a promising solution for boosting cucumber plants to thrive under drought conditions. Soil amendments on cucumber plant cultivated under different field capacities (100%, 80%, 60% FC) showed a deep and multi-faced improvement of the drought stress impacts on the plant at morphological, physiological and biochemical levels. The advantage of biochar amended plants, especially under water deficient conditions is basically due to the ability of this material to alter the soil-plant-water continuum (Das *et al*., 2022; Jabborova *et al*., 2023). Biochar's highly porous structure adds immense value to the soil's water holding capacity providing a reserve to buffer the water deficit from irrigation issues and also keeps the water supply more uniform (Munir *et al*., 2024; Xu *et al*., 2025). This direct hydrological benefit is translated into significantly improved plant water status as shown by the constantly higher RWC for EB and PT treatments compared to the CT. Consequently, cucumber plants in amended soils maintain turgor pressure, which is the major force behind cell expansion and growth. This is well exhibited in the morphological data where parameters such as VL, SD, PS, and LN were significantly greater in the biochar treatments regardless of the FC levels. Thickening of the leaves, showing greater leaf architecture in biochar amended plants, was given highest importance among the morphological adaptations; plants grown with biochar developed thicker leaves (LT) with high LDMC and low SLA. This change suggests the transition to increased strength of the mesophyllic structure and greater density, one of the identified stress resistance adaptive mechanisms to save water and sustain photosynthesis (Zahedi *et al*., 2025). This improved leaf development and thus, the largest LA under EB100, brings a larger photosynthetic factory, which is directly linked to the large ameliorations in biomass accumulation. The better partitioning of biomass to both photosynthetic (leaves) and resource-foraging (roots) organs is very important, with EB100 showing the highest LDW and RDW (Guo *et al*., 2021). The improved root system is especially important, as it is promoted by the improved soil aeration and physicochemical conditions driven by the biochar addition, which enable to collect water and nutrients more efficiently (Wan *et al*., 2023).

Physiologically, the benefits of biochar go beyond improved water availability and influence other core plant processes (Joseph *et al*., 2021). Photosynthetic apparatus is directly supported by the high levels of *Chl* in EB and PT treatments, which was attributed by the high oligomerization factors of biochar in terms of cation exchange capacity (Dey *et al*., 2023). Additionally, these improvements were reflected precisely in gas exchange responses. Biochar amended plants exhibited higher *Pn*, *gs*, and *E* with a significantly lower *Ci*. This combination is critical because it shows that the increased CO_2 diffusing into the leaf through the open stomata are being fixed by the Calvin cycle at a rapid and efficient rate (Gonçalves *et al*., 2024). It is an indication of the plants increased their internal capacity for photosynthesis, at the biochemical level, for example, by increasing the activity of Rubisco. This is a more fundamental type of adaptation than by just opening their stomata in order to relieve the typical CO_2 limitation they can have during drought (Murtaza *et al*., 2024). This antagonistic and efficient assimilation is indicative of actual improvement in physiological proficiency, that facilitates the plant to keep its productivity high (Khan *et al*., 2025). The high WUEinst in the severely stressed CT60 plants is highly reflective of severely suppressed transpiration as a result of stomatal closure, and a simultaneous reduction in photosynthesis, indicating a plant in survival mode (Sinha *et al*., 2025). Phenologically, this physiological efficiency is responsible for the development under faster time intervals of the critical day to fruit maturity growing season in plants that were given biochar soil amend media as soil nutrient source. This acceleration is an important drought avoidance strategy and thus is a way for the plant to finish its own reproductive cycle before stress increases (Adekiya *et al*., 2025).

Overall, the observed improvements in plant morphology and physiology led to better yield and superior fruit quality. The increased 'source' capacity (larger canopy, higher *Pn*) is an efficient source of photoassimilates to 'sink' (fruits) leading to dramatically increased yield per plant, fruit size and fruit weight (Falchi *et al*., 2020; Liu *et al*., 2024). The fact that yields under reduced irrigation with biochar (EB60, PT60) surpassed the yield of the control under full irrigation (CT100) provides us with the great potential of these amendments to water conservation in agriculture (Munir *et al*., 2024). Fruit quality is also improved to a great extent by biochar amendments. The higher concentration of TS is a direct result of higher photosynthetic output and efficient translocation (Ren *et al*., 2022). Reduced fruit firmness of the biochar-treated plants, compared with the harder fruits observed in water-stressed controls, indicated improved fruit development and is frequently a sign of a desirable quality of cucumbers (Li *et al*., 2024; Agrawal *et al*., 2025). The stability of fruit color parameters with the lowest total color difference measured for EB100 and PT100 is another important quality attribute. Drought stress significantly impairs the synthesis of pigments resulting in uneven and undesirable colouration which impacts on marketability (Espley & Jaakola, 2023; Munir *et al*., 2024). Water stress caused by biochar makes sure the physiological levels are at par with the pigment growth being uniform. This two-fold action of increasing yield and leaf quality is further supported by the biochemical marker, leaf proline. Accumulation of proline is a well-established stress response and functions as an osmoprotectant (Ali-Dinar *et al*., 2023). The slightest proline accumulation in biochar-treated plants even at 60% FC gives biochemical insight into a fundamental reduction of plant experience from water deficit stress, preventing the necessity to initiate a strong osmotic adjustment response (Gharred *et al*., 2022). The efficacy of application of date palm-based biochar, and specifically EB biochar applied at full irrigation (EB100), is based on an integrated mechanism: physical (improving soil hydrology), chemical (increasing nutrient bioavailability) and physiological (increasing photosynthetic efficiency and plant water status). This synergy helps in reducing drought stress at its root cause, resulting in better growth, faster development, and enhanced fruit yield and quality in a very short time. It makes these amendments a powerful tool to promote cultivation in a water-limited environment.

The findings of this study strongly align with the principles of sustainable nutrient management and circular economy–based agriculture. Converting date palm wastes, empty bunches and pits, which are produced in large amounts in arid regions, into biochar is a valuable way to recycle these materials, helping to return nutrients and carbon back into the agricultural system. By enhancing soil CEC, nutrient retention, and water holding capacity, date palm biochar improved the efficiency of applied nutrients and reduced potential losses through leaching and volatilization, particularly under water-limited conditions. This improved nutrient-use efficiency enabled cucumber plants to maintain physiological activity, biomass production, and fruit quality at reduced irrigation levels, thereby lowering dependence on excessive fertilizer and water inputs. From an agronomic sustainability perspective, the optimal performance of biochar-amended soils at 80% and 60% FC compared with fully irrigated controls (100% FC) indicates a move toward more resource-efficient production systems in which crop yield is less dependent on high external inputs. Environmentally, the stabilization of carbon in biochar contributes to long-term soil carbon sequestration, while the productive reuse of date palm waste mitigates disposal-related environmental problems. Overall, these findings identify date palm biochar as a multifunctional soil amendment that integrates waste valorization, improved nutrient management under climate stress, and water conservation, supporting the transition toward circular, low-input, and climate-smart horticultural production systems in arid and semi-arid regions.

Conclusion

Conclusively, the application of biochar produced from date palms empty bunches (EB) and pits (PT) proved to be highly effective soil amendments for mitigating drought stress in protected cultivation of cucumbers. The biochar amendments showed significant improvement in soil water retention, which subsequently led to improved plant water status, as reflected by higher relative water content, and maintained important physiological processes such as photosynthetic rate and stomatal conductance even in water deficit conditions. This improvement translated into excellent vegetative growth, biomass buildup, and a dramatic increase in fruit maturation. Crucially, the use of EB and PT biochar at 60% and 80% FC led to cucumber growth and yields which exceeded those of the non-amended control at 100% FC showing a significant capacity for conserving water without a corresponding loss in productivity. Furthermore, biochar application improved critical fruit quality parameters, including higher total sugars and more stable color, while decreasing biochemical stress indicators (proline in leaves). Therefore, the valorization of date palm waste into biochar offers a sustainable circular economy approach to improve water use efficiency, yield and fruit quality, and build resilience for cucumber production systems under water scarcity.

Acknowledgement

The authors acknowledge the use of Grammarly and QuillBot for assistance with language editing. The final content remains the sole responsibility of the authors. The authors also extend their gratitude to the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Kingdom of Saudi Arabia, for funding the publication of this work under the Ambitious Researcher program (KFU253084).

Conflict of Interest: The authors declare no conflicts of interest.

Authors Contribution: Conceptualization, Muhammad Munir; methodology, Muhammad Munir, Maged Mohammed, Hassan M. Ali-Dinar; validation, Muhammad Munir, Nashi K. Alqahtani, Abdul Ghafoor, Zafar Iqbal; formal analysis, Muhammad Munir, Salim A. Ali, Abdul Ghafoor, Zafar Iqbal; investigation, Muhammad Munir, Maged Mohammed, Babiker M.A. Abdel-Banat, Hesham S. Ghazzawy; data curation, Muhammad Munir, Abdul Ghafoor, Zafar Iqbal; writing—original draft preparation, Muhammad Munir; writing—review and editing, Muhammad Munir, Babiker M.A. Abdel-Banat, Hesham S. Ghazzawy, Hassan M. Ali-Dinar, Zafar Iqbal, Abdul Ghafoor; visualization, Muhammad Munir; funding acquisition, Muhammad Munir and Nashi K. Alqahtani. All authors have read and agreed to the published version of the manuscript.

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