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Original Article

Optimizing Yield and Water Use Efficiency of Pepper Under Deficit Irrigation Using Biochar

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ABSTRACT

Present research was conducted to investigate the interactions between deficit irrigation and biochar application in pepper (*Capsicum annuum* L. cv. Demre Sivrisi) grown under greenhouse conditions in a sandy-loam soil with low water-holding capacity. The experiment was arranged in a 4×4 factorial design with three replications, comprising all combinations of four irrigation levels (100%, 75%, 50% and 25% of field capacity) and four biochar doses (0, 50, 150 and 250 g/5 kg). The amount of irrigation water was determined using a gravimetric method. Plant height, fresh biomass, yield and crop water consumption (ET) were measured, and water use efficiency (WUE), biomass water use efficiency (BWUE), harvest index (HI) and yield response factor (Ky) were calculated. Water deficit markedly reduced all growth and yield parameters; mean yield decreased from 1058 g per pot under full irrigation to 108 g per pot under the most severe deficit. Biochar application increased growth and yield at all irrigation levels, providing about a 35% yield increase at the highest dose relative to the control. Biochar raised the field capacity of the sandy-loam soil by 30% at the highest dose. WUE reached its maximum not under full irrigation but at the 75% irrigation level (15.9 g/L), with the highest WUE (17.0 g/L) obtained at the 75% irrigation–250 g biochar combination. Increasing biochar dose lowered the yield response factor (Ky), reducing the crop's sensitivity to water deficit. Present findings indicated that, in water-scarce regions, combining 75% irrigation with a high biochar dose was an effective strategy to maximize yield per unit water.

Key words: Biochar, deficit irrigation, water use efficiency, yield response factor, *Capsicum annuum*

Kısıntılı Sulama Koşullarında Sivri Biber Verimini Optimize Etmek İçin Biyoçar Kullanımı

ÖZ

Bu çalışmada, su tutma kapasitesi düşük kumlu-tınlı toprakta sera koşullarında yetiştirilen sivri biberde (*Capsicum annuum* L. 'Demre Sivrisi'), kısıntılı sulama ile biyoçar uygulamasının etkileşimi araştırılmıştır. Deneme, dört sulama düzeyi (tarla kapasitesinin %100, %75, %50 ve %25'i) ile dört biyoçar dozunun (0, 50, 150 ve 250 g/5 kg) tüm kombinasyonlarını içeren 4×4 faktöriyel düzende, üç tekerrürlü olarak kurulmuştur. Sulama suyu miktarı gravimetrik yöntemle belirlenmiştir. Ayrıca, bitki boyu, yaş biyokütle, verim ve bitki su tüketimi (ET) ölçülmüş, su kullanım etkinliği (WUE), biyokütle su kullanım etkinliği (BWUE), hasat indeksi (HI) ve verim tepki etmeni (Ky) hesaplanmıştır. Su kısıntısı tüm büyüme ve verim parametrelerini belirgin biçimde azaltmış, ortalama verim tam sulamada 1058 g/saksı iken en şiddetli kısıntıda 108 g/saksıya gerilemiştir. Biyoçar uygulaması her sulama düzeyinde gelişimi ve verimi artırmış, en yüksek dozda kontrole göre verimde yaklaşık %35'lik bir artış sağlamıştır. Biyoçar, kumlu-tınlı toprağın tarla kapasitesini en yüksek dozda %30 oranında yükseltmiştir. Su kullanım etkinliği en yüksek değerine tam sulamada değil, %75 sulama düzeyinde ulaşmış (15,9 g/L), en yüksek WUE %75 sulama–250 g biyoçar kombinasyonunda (17,0 g/L) elde edilmiştir. Artan biyoçar dozu verim tepki etmenini (Ky) düşürerek bitkinin su açığına duyarlılığını azaltmıştır. Sonuçlar, su kıtlığı çekilen bölgelerde %75 sulama düzeyi ile yüksek biyoçar dozunun birlikte uygulanmasının, birim sudan elde edilen verimi en üst düzeye çıkaran etkili bir strateji olduğunu göstermektedir.

Anahtar kelimeler: Biyoçar, kısıntılı sulama, su kullanım etkinliği, verim tepki etmeni, *Capsicum annuum*

INTRODUCTION

Climate change and resultant global warming are adversely affecting agricultural production through intensifying droughts and altered precipitation regimes, leading to water scarcity that threatens food safety (Kaplan et al. 2019). Declining fresh water resources make sustainable water management strategies essential, including climate-smart technologies such as micro-irrigation, water harvesting, and precision irrigation, which improve water-use efficiency (Gokalp & Humaidy, 2023). Irrigation efficiency must be improved and green water-management practices should be adopted to meet rising agricultural water demands sustainably while protecting critical water resources under changing climate scenarios (He & Rosa, 2023; Zhao & Boll, 2022).

Drought-induced stress results in profound physiological effects in plants: it impairs plant water uptake, reduces leaf stomatal conductance, and lowers leaf chlorophyll content and CO_2 assimilation, disrupting photosynthetic activity and ultimately limiting plant growth and development (Ciftci et al., 2025). Water deficiency facilitate the production of reactive oxygen species (ROS), thus triggers oxidative stress, damage cellular components but also activate antioxidative defense mechanisms and stress-related proteins such as heat-shock proteins (Liu et al., 2024; Razi & Muneer, 2021). Reduced plant growth and development manifest itself as smaller leaves, shorter stems, and diminished root proliferation, impairing crop productivity (Shahzad et al., 2016). Drought-induced stress also alters the composition of carbohydrates, proteins, lipids, and secondary metabolites, lowers yield levels and changes product quality, with both favorable and unfavorable shifts in nutritional and organoleptic properties (Stagnari et al., 2016, Varol et al., 2020). Drought-induced stress influences plants differently throughout different developmental stages; the critical reproductive phases are particularly sensitive, and severe water stress during these periods results in irreversible yield losses (Bijalwan et al., 2022; Varol et al., 2024).

Pepper (*Capsicum annuum* L.) has a considerable agricultural and economic value both globally and in Türkiye. Peppers have various nutritional benefits and used abundantly in food and pharmaceutical industries (FAOSTAT, 2025). Pepper is highly sensitive to water stress, which reduces growth, yield, and quality. Drought-induced stress negatively affects fruit size, biomass, and nutrient uptake, hindering production. Efficient water management, including irrigation strategies and organic amendments such as biochar, can improve crop tolerance and productivity under water deficit (Anifowoshe et al., 2025; Iqbal et al., 2023). Plants grown in drought-prone regions experience serious yield losses under sub-optimal water supply, deterioration of fruit quality, and greater susceptibility to disease (Macias-Bobadilla et al., 2020; Ntanasi et al., 2025).

Biochar is a carbon-rich, porous material with greater surface area and it produced through pyrolysis of organic matter under limited oxygen. Biochar has a greater porosity and water-holding capacity, while its chemical properties feature high nutrient content, alkaline pH, and a strong cation-exchange capacity (Al-Wabel et al., 2017; Mishra et al., 2025). Biochar improves soil structure, fertility, microbial activity, nutrient availability, and crop productivity, thus largely used as a soil amendment. Biochar also contributes to environmental sustainability through sequestering carbon over the long term, reducing greenhouse-gas emissions, and promoting resilient agricultural ecosystems (Tenic et al., 2020). Biochar stimulates soil microbial activity by providing habitat and enhancing enzyme function, thereby promoting nutrient cycling (Gebhardt et al., 2017; Hossain et al., 2020). Biochar increases soil water-holding capacity, provides higher relative water content and osmotic potential and improves plant water-use efficiency; thus it is preferred to be used under drought conditions. Biochar facilitates antioxidant enzymes and osmolyte accumulation, thus mitigates oxidative stress and supports drought-tolerance mechanisms (Rahman et al., 2025; Ruan et al., 2024).

The interactions between biochar and water constraints should be investigated meticulously, since biochar can alleviate the effects of drought on soil and plants through increasing water-holding capacity, nutrient availability, and stress tolerance (Wu et al., 2023). Previous studies have already demonstrated the beneficial effects of biochar on plant physiology and growth under drought, but there is still a need for further research about optimal biochar types, doses, and combined abiotic stresses. Pot experiments under controlled conditions allow the researchers to assess the biochar × water-stress interaction precisely, giving a clearer understanding of the underlying mechanisms. Such research is essential for developing sustainable vegetable-production strategies that improve resistance to water scarcity and enhance agricultural sustainability.

The aim of this study was to examine the interaction between four irrigation levels (25%, 50%, 75%, and 100%) and four biochar doses (0, 50, 150, and 250 g) in pepper (*Capsicum annuum* L.) grown under greenhouse conditions in a sandy-loam soil with low water-holding capacity. In addition to determining the buffering effects of biochar on plant growth and yield, indices of critical importance for agricultural water management, such as WUE and Ky, were calculated. Through these parameters, the study set out to characterize, from an engineering perspective, how the water-use efficiency and drought tolerance of pepper change under deficit-irrigation conditions.

MATERIALS AND METHODS

The study was conducted in a greenhouse at the Faculty of Agriculture, Erciyes University, in 2024. Demre Sivrisi pepper (*Capsicum annuum* L.), a cultivar widely grown in the region, was used as plant material. Pepper seedlings were transplanted into pots on 1 May 2024. Mature fruits were harvested continuously throughout the growing period. The total growing period was 120 days. A sandy-loam soil (78% sand, 12% silt, 10% clay) was used, and each pot was filled with 5 kg of soil. The soil was slightly alkaline (pH 7.62), non-saline (0.53 dS m^{-1}), and calcareous (4.57% $CaCO_3$), with low organic-matter content (1.23%). Field capacity of this low-water-holding soil was about 13% on a gravimetric basis, and bulk density was 1.48 g cm^{-3}. Selected physical and chemical properties of the soil are given in Table 1. Pots measured 21 cm × 20 cm, and a single pepper plant was grown in each pot.

Table 1. Selected physical and chemical properties of the soil used in the experiment.

Soil properties	
Texture class	Sandy loam
Sand / Silt / Clay (%)	78 / 12 / 10
pH	7.62
Field capacity, Pw (%)	13
Bulk density (g cm^{-3})	1.48
EC (dS m^{-1})	0.53
Organic matter (%)	1.23
Lime, $CaCO_3$ (%)	4.57
Total nitrogen (%)	0.08
Available phosphorus (mg kg^{-1})	18
Available potassium (mg kg^{-1})	240

Biochar application markedly increased the field capacity of the sandy-loam soil in a dose-dependent manner (Table 2).

Table 2. Field capacity of the pots by biochar dose (g) and increase relative to the control.

Biochar dose (g)	**Mean**	Increase (%)
B0	650	–
B50	690	6.15
B150	770	18.46
B250	845	30.00

Field capacity, which was 650 g in the biochar-free control, rose to 690, 770, and 845 g at biochar doses of 50, 150, and 250 g, respectively, corresponding to increases of 6.15%, 18.46%, and 30.00% relative to the control. The proportional increase with rising dose shows that the added water-holding capacity is directly related to the application rate. This improvement stems from the high specific surface area of biochar (94.73 m^2 g^{-1}) and its macro-, meso-, and micro porous structure, which increase the amount of water held by capillarity in the coarse-textured, low-water-holding soil. As a result, at the highest dose the plant-available water reserve expanded by roughly one third, which is decisive in buffering the plant against water deficit, particularly under deficit irrigation/precipitation. Cherry-pits were used as biochar in the experiment, and their basic properties are given in Table 3.

Table 3. Basic properties of the cherry-pit biochar used in the experiment, as reported by the manufacturer.

Property	**Value**
Biochar source	Cherry pit (*Prunus avium*)
Pyrolysis temperature / time	500 °C / 20 min
pH	8.75
EC	20.91 µS/cm
C/N ratio	15.67
Specific surface area	94.73 m^2 g^{-1}
Porosity	Macro, meso and microporous

The cherry-pit biochar used in the experiment was obtained from a local producer. According to the information provided by the manufacturer, the biochar was produced by slow pyrolysis of cherry pits (*Prunus avium*) at approximately 500 °C under a nitrogen atmosphere for about 20 minutes; it was alkaline (pH 8.7), of low salinity (21.7 µS/cm), and had a relatively narrow C/N ratio (16.2). According to the manufacturer's data, it had a specific surface area of 94.73 $m^2 g^{-1}$ and a pore structure comprising macro-, meso-, and micropores. These manufacturer-reported properties of the biochar are given in Table 3. The experiment was arranged as a 4×4 factorial design comprising all combinations of four irrigation treatments (full irrigation 100%, 75%, 50%, and 25%) and four biochar doses (0, 50, 150, and 250 g), with three replications and a total of 48 pots. Pots were arranged in the greenhouse in a completely randomized design.

The irrigation treatments were defined as fixed percentages of soil field capacity, not as fractions of the water applied under full irrigation. Irrigation was managed gravimetrically: each pot was weighed at regular intervals and irrigated to bring it back to the target moisture level of its treatment, that is, 100% (S100), 75% (S75), 50% (S50), or 25% (S25) of field capacity. The irrigation amount was determined separately for each biochar dose according to its own field capacity (Table 2). Seasonal crop water consumption (ET) was determined from the pot water balance. Because the greenhouse pots received no precipitation and were prevented from draining, the water balance reduced to Equation 1, where; I is the applied irrigation water and ΔS is the change in soil moisture storage. In practice, the ET of each interval was obtained from the weight loss of each pot between two successive weighings and summed over the season. At every weighing, the increasing fresh weight of the plant was included in the tare, so that plant growth was not misread as a change in soil moisture and did not bias the water-consumption calculation. Because the pots could not drain, the total irrigation water applied over the growing season equaled the seasonal ET; these values are given per irrigation × biochar treatment in Table 4. Mean seasonal water consumption per pot ranged from 70.2 to 76.0 L under full irrigation and fell to 15.8–22.0 L under the most severe deficit.

$$ET = I - \Delta S \tag{1}$$

Plant height (cm), fresh biomass (g/pot), crop water consumption (ET, L/pot), and yield (g/pot) were directly measured throughout the experiments. Yield was recorded as the seasonal total of continuously harvested fruits.

Measured values were used to calculate the following agricultural water-management indices. Water-use efficiency (WUE) expresses the yield produced per unit of water consumed (Equation 2; Howell, 2001):

$$WUE = Yield/ET \tag{2}$$

Biomass water-use efficiency (BWUE), a biomass-based form of water-use efficiency, indicates the efficiency of converting consumed water into vegetative growth (Equation 3; Howell, 2001):

$$BWUE = Fresh\ biomass/ET \tag{3}$$

Harvest index (HI) expresses the partitioning of photosynthates between fruit and total biomass (Equation 4; Donald & Hamblin, 1976):

$$HI = Yield\ /(Yield + Biomass) \tag{4}$$

The yield response factor (Ky), following the FAO approach (Doorenbos and Kassam, 1979), relates the proportional yield loss under water deficit to the proportional reduction in ET (Equation 5):

$$\left(1 - \frac{Ya}{Ym}\right) = Ky\ x\ (1 - \frac{ETa}{ETm}) \tag{5}$$

Here, Ya and ETa are the yield and water consumption of the deficit treatment, and Ym and ETm are those of the full-irrigation (100%) treatment at the same biochar dose. Because Ky was calculated separately for each biochar dose and did not require a fully non-irrigated (0%) reference, Ky was not calculated for the 100% treatments. Ky was calculated separately for each replicate: the yield (Ya) and water consumption (ETa) of each replicate of a deficit treatment were expressed relative to the mean yield (Ym) and mean ET (ETm) of the full-

irrigation (100%) treatment at the same biochar dose. This produced three Ky values per treatment, which were subjected to the same two-way ANOVA and Tukey HSD grouping as the other parameters (Table 7).

All parameters were subjected to two-way analysis of variance (ANOVA) in a 4×4 factorial design including the main effects of irrigation (S) and biochar dose (D) and their interaction (S×D). Differences among means were grouped with the Tukey HSD multiple-comparison test at $p < 0.05$. Analyses were performed using the SAS JMP software package.

RESULTS AND DISCUSSION

Results

Data for all parameters examined in the experiment were subjected to two-way ANOVA in a 4×4 factorial design including the main effects of irrigation level (S) and biochar dose (D) and their interaction (S×D). Differences among means were grouped with the Tukey HSD test at $p < 0.05$. In the tables, lowercase letters denote comparisons among the interaction (S×D) means, while uppercase letters in the right-hand and bottom "Mean" row and column denote comparisons among the main-effect means of irrigation and biochar dose, respectively. Means sharing the same letter group do not differ statistically.

Evapotranspiration (ET)

As expected, evapotranspiration (ET) increased in direct proportion to irrigation level; mean ET rose from 19.2 L at 25% irrigation to 73.7 L under full irrigation (Table 4). Biochar dose also increased water consumption somewhat (41.4 L in the control, 48.5 L at the highest dose); this can be explained by biochar raising the soil's water-holding capacity, supplying more water to the plant, and supporting stronger vegetative growth. The irrigation × dose interaction was not significant.

Table 4. Effect of different irrigation levels and biochar doses on seasonal evapotranspiration (L/pot) in pepper.

ET	B0	B50	B150	B250	Mean
S25	15.8^{h}	18.5^{gh}	20.4^{gh}	22.0^{g}	19.2^{D}
S50	30.2^{f}	34.5^{ef}	37.2^{e}	39.0^{e}	35.2^{C}
S75	49.5^{d}	53.8^{cd}	55.6^{c}	57.0^{c}	54.0^{B}
S100	70.2^{b}	73.5^{ab}	75.1^{ab}	76.0^{a}	73.7^{A}
Mean	41.4^{C}	45.1^{B}	47.1^{AB}	48.5^{A}	

Means sharing the same letter group do not differ statistically according to the Tukey HSD test at $p < 0.05$. Lowercase letters indicate the irrigation × dose interaction; uppercase letters in the right-hand and bottom "Mean" values indicate the main effects of irrigation and biochar dose, respectively.

Water-use efficiency (WUE)

As shown in Table 5, irrigation, dose, and their interaction were significant for water-use efficiency (WUE) ($p < 0.05$). WUE reached its maximum not under full irrigation but at the 75% irrigation level (mean 15.9), declining somewhat under full irrigation (14.3). This shows that moderate deficit irrigation maximizes the yield obtained per unit of water. Increasing biochar dose improved WUE at all levels (10.9 in the control, 13.4 at the highest dose); the highest WUE values were recorded at 75% irrigation combined with 150–250 g biochar (16.5–17.0). The lowest WUE occurred in the severe-deficit–control combination (4.42).

Table 5. Effect of different irrigation levels and biochar doses on water-use efficiency (WUE, g/L) in pepper.

WUE	B0	B50	B150	B250	Mean
S25	4.42^{i}	4.86^{i}	5.87^{h}	6.81^{g}	5.49^{D}
S50	10.6^{f}	11.9^{e}	14.0^{d}	14.9^{bc}	12.8^{C}
S75	14.5^{cd}	15.4^{b}	16.5^{a}	17.0^{a}	15.9^{A}
S100	14.0^{d}	14.1^{cd}	14.5^{cd}	14.7^{bcd}	14.3^{B}
Mean	10.9^{D}	11.6^{C}	12.7^{B}	13.4^{A}	

Means sharing the same letter group do not differ statistically according to the Tukey HSD test at $p < 0.05$. Lowercase letters indicate the irrigation × dose interaction; uppercase letters in the right-hand and bottom "Mean" values indicate the main effects of irrigation and biochar dose, respectively.

Biomass water-Use efficiency (BWUE)

Biomass water-use efficiency (BWUE) followed a trend similar to WUE, reaching its highest mean at 75% irrigation (Table 6). Biochar dose increased BWUE steadily; the mean rose from 7.66 in the control to 9.28 at the highest dose. Because the irrigation × dose interaction was not significant, the positive effect of biochar was similar across all irrigation levels. The highest BWUE was obtained at the 75% irrigation–250 g combination (10.70 g/L).

Table 6. Effect of different irrigation levels and biochar doses on biomass water-use efficiency (BWUE, g/L) in pepper.

BWUE	B0	B50	B150	B250	Mean
S25	5.37^{i}	5.67^{i}	6.37^{h}	6.81^{h}	6.06^{C}
S50	7.94^{g}	8.40^{fg}	9.40^{cd}	9.99^{bc}	8.93^{B}
S75	9.09^{de}	9.48^{cd}	10.25^{ab}	10.70^{a}	9.88^{A}
S100	8.26^{fg}	8.70^{ef}	9.32^{de}	9.60^{bcd}	8.97^{B}
Mean	7.66^{D}	8.06^{C}	8.84^{B}	9.28^{A}	

Means sharing the same letter group do not differ statistically according to the Tukey HSD test at $p < 0.05$. Lowercase letters indicate the irrigation × dose interaction; uppercase letters in the right-hand and bottom "Mean" values indicate the main effects of irrigation and biochar dose, respectively.

Yield response factor (Ky)

Ky expresses the plant sensitivity to water deficit: Ky > 1 indicates sensitivity, whereas Ky < 1 indicates relative tolerance (Table 7). The mean Ky value was the highest (1.22, most sensitive) under severe deficit (25%) and the value declined to 0.69 under mild deficit (75%), indicating greater tolerance. Ky values decreased with increasing biochar doses; the mean Ky value decreased from 1.09 in the control to 0.91 at the highest biochar dose, showing that biochar improved drought tolerance of the plants. The lowest (most favorable) Ky value was obtained in 75% irrigation – 250 g biochar combination (0.52).

Table 7. Effects of different irrigation levels and biochar doses on yield response factor (Ky) of pepper.

Ky	B0	B50	B150	B250	Mean
S25	1.20^{ab}	1.22^{a}	1.22^{a}	1.22^{a}	1.22^{A}
S50	1.18^{ab}	1.14^{abc}	1.04^{bcd}	0.99^{cd}	1.09^{B}
S75	0.90^{de}	0.75^{ef}	0.59^{fg}	0.52^{g}	0.69^{C}
Mean	1.09^{A}	1.04^{A}	0.95^{B}	0.91^{B}	

Means indicated with the same letters are not significantly different according to the Tukey HSD test at $p < 0.05$. Lowercase letters indicate the irrigation × dose interaction; uppercase letters indicate the main effects of irrigation and biochar dose, respectively. Because full irrigation (100%) is the reference treatment, Ky was not calculated for that row.

Yield

As shown in Table 8, irrigation levels, biochar doses and their interaction (S×D) had significant effects on yield ($p < 0.05$). Mean yield value of 108 g in 25% irrigation treatment reached to 1058 g under full irrigation, showing that water deficit reduced yield roughly tenfold. The buffering effect of biochar was especially notable: under severe water deficit (25%), yield increased from 70.4 g in the control to 150 g at the highest dose, nearly doubling, whereas under full irrigation the same dose resulted in a comparatively limited gain in yields (from 980 g to 1120 g, ~14%). Such a case indicated that the yield contribution of biochar strengthened proportionally as water deficit increased and that it helped reduce yield losses under drought. The highest yield was obtained at the full-irrigation–250 g combination (1120 g).

Table 8. Effect of different irrigation levels and biochar doses on yield (g/pot) in pepper.

Yield	B0	B50	B150	B250	Mean
S25	70.4^{i}	90.5^{i}	120^{i}	150^{i}	108^{D}
S50	320^{h}	410^{gh}	520^{fg}	580^{f}	458^{C}
S75	720^{e}	830de	920^{cd}	970^{bc}	860^{B}
S100	980^{bc}	1040^{abc}	1090^{ab}	1120^{a}	1058^{A}
Mean	523^{C}	593^{B}	663^{A}	705^{A}	

Means sharing the same letter group do not differ statistically according to the Tukey HSD test at p < 0.05. Lowercase letters indicate the irrigation × dose interaction; uppercase letters in the right-hand and bottom "Mean" values indicate the main effects of irrigation and biochar dose, respectively.

Harvest index (HI)

As shown in Table 9, irrigation, dose, and their interaction were significant for harvest index (HI) ($p < 0.05$). HI was lowest under severe water deficit (mean 0.47 at 25% irrigation) and increased with irrigation, reaching a similar plateau (≈0.62) at the 75% and 100% levels. This shows that water deficit disproportionately restricts the transfer of photosynthates to the fruit. The effect of biochar on HI was limited, though it slightly raised the index at low irrigation levels; under full irrigation, a very small decrease in HI was seen at high doses, suggesting that under these conditions biochar may have supported vegetative growth somewhat more than fruit yield.

Table 9. Effect of different irrigation levels and biochar doses on harvest index (HI) in pepper.

HI	B0	B50	B150	B250	Mean
S25	0.45^{k}	0.46^{j}	0.48^{i}	0.50^{h}	0.47^{C}
S50	0.57^{g}	0.59^{f}	0.60^{e}	0.60^{e}	0.59^{B}
S75	0.62^{bc}	0.62^{b}	0.62^{bc}	0.61^{bcd}	0.62^{A}
S100	0.63^{a}	0.62^{b}	0.61^{cd}	0.61^{de}	0.62^{A}
Mean	0.57^{D}	0.57^{C}	0.58^{B}	0.58^{A}	

Means sharing the same letter group do not differ statistically according to the Tukey HSD test at p < 0.05. Lowercase letters indicate the irrigation × dose interaction; uppercase letters in the right-hand and bottom "Mean" values indicate the main effects of irrigation and biochar dose, respectively.

Plant height

As shown in Table 10, both different irrigation levels and biochar doses had significant effects on plant height ($p < 0.05$). Plant heights increased significantly with increasing irrigation water levels; the lowest mean plant height (29.9 cm) was observed in 25% irrigation treatments and the highest (83.3 cm) under full irrigation. Plant heights increased also with increasing biochar doses, with plants at the highest dose averaging about 23% taller (64.9 cm) than the control plants (52.8 cm). For plant height, the irrigation × dose interactions were not found to be significant; the positive effect of biochar on plant height was similar across all irrigation levels. The tallest plants were recorded at the full-irrigation – 250 g biochar combination (87.6 cm) and the shortest at the 25% irrigation – control combination (26.4 cm).

Table 10. Effects of different irrigation levels and biochar doses on plant height (cm) of pepper.

Plant height (cm)	B0	B50	B150	B250	Mean
S25	26.4j	28.3j	31.4ij	33.4ij	29.9D
S50	42.2hi	48.4gh	55.6fg	59.6efg	51.4C
S75	64.3def	70.4cde	75.5bcd	79.2abc	72.4B
S100	78.5abc	81.5abc	85.7ab	87.6a	83.3A
Mean	52.8C	57.2B	62.1A	64.9A	

Means indicated with the same letter group do not differ statistically according to the Tukey HSD test at p < 0.05. Lowercase letters indicate the irrigation × dose interaction; uppercase letters indicate the main effects of irrigation and biochar dose, respectively.

Fresh biomass

Fresh biomass responded strongly to increases in irrigation and biochar dose ($p < 0.05$) (Table 11). Mean biomass was 118 g at 25% irrigation and rose to 663 g under full irrigation, a more than fivefold difference with increasing water. Biochar treatments also facilitated vegetative growth; the mean fresh biomass of 339 g in the control increased to 470 g at the highest dose (a 39% increase). Since the interactions of irrigation levels x biochar doses were not significant, the biochar contribution remained consistent across all irrigation levels, and the highest fresh biomass was obtained at the full-irrigation – 250 g combination (730 g).

Table 11. Effects of different irrigation levels and biochar doses on fresh biomass (g/pot) of pepper.

Fresh Biomass (g/pot)	B0	B50	B150	B250	Mean
S25	85.4^{j}	105^{j}	130^{j}	150^{j}	118^{D}
S50	240^{i}	290^{hi}	350^{gh}	390^{fg}	318^{C}
S75	450^{ef}	510^{de}	570^{cd}	610^{c}	535^{B}
S100	580^{cd}	640^{bc}	700^{ab}	730^{a}	663^{A}
Mean	339^{D}	386^{C}	438^{B}	470^{A}	

Means indicated with the same letter group do not differ statistically according to the Tukey HSD test at $p < 0.05$. Lowercase letters indicate the irrigation × dose interaction; uppercase letters indicate the main effects of irrigation and biochar dose, respectively.

Discussion

Present findings revealed that deficit irrigation remarkably reduced all growth and productivity parameters of pepper, most notably the plant height, fresh biomass, and yield, while increasing biochar doses partially offset these losses and acted as a buffer. The adverse effects of water deficit on yield were clear from the drop in mean yield from 1058 g under full irrigation to 108 g at the 25% level. The high sensitivity of pepper (*Capsicum annuum* L.) to water deficit is linked to restricted fruit set and development during the reproductive period, driven by reduced stomatal conductance and photosynthesis (Shahzad et al., 2016). These findings comply with the results of previous studies showing that pepper was a drought-sensitive species and that severe water stress during the reproductive phase caused irreversible yield losses (Bijalwan et al., 2022; Varol et al., 2024).

Biochar treatments increased plant height, fresh biomass, and yield at all irrigation levels; at the highest biochar dose, mean yield value increased by about 35% as compared to the control. Present findings are consistent with the results of Cakmakcı and Sahın (2023), who reported that increasing biochar doses significantly improved growth and yield in capia pepper grown in pots. Similar positive effects biochar has been reported in studies showing that biochar increased fruit yield and water productivity in greenhouse tomato under water stress (Abdelghany et al., 2023). Such contributions of biochar are attributed to its porous structure, high cation-exchange capacity, and enhancement of nutrient availability, which improve soil fertility and root-zone conditions (Al-Wabel et al., 2017).

About 30% increase in field capacity of the sandy-loam soil at the highest biochar dose points to the main mechanism underlying the observed yield gains. Microporous structure of biochar and resultant greater specific surface area clearly increases the capillary-held and plant-available water in sandy soils with low water-holding capacity (Li et al., 2021; Basso et al., 2013; Abel et al., 2013). Indeed, the buffering effect of biochar strengthened proportionally as water deficit intensified; at the highest dose, yield nearly doubled under severe deficit (25%) but increased by only about 14% under full irrigation. This interaction pattern is consistent with studies reporting that the biochar contribution is most pronounced under water-limited conditions and that biochar increases drought resistance in sandy soils (Mulcahy et al., 2013; Cakmakcı & Sahın, 2023).

Water-use efficiency (WUE) and biomass water-use efficiency (BWUE) reached their highest values not under full irrigation but at the 75% irrigation level. This is consistent with the deficit-irrigation approach, which holds that moderate water deficit can maximize the yield obtained per unit of water and that the marginal water input under full irrigation is not reflected proportionally in yield (Fereres & Soriano, 2007). Increasing biochar dose improved WUE at all irrigation levels, with the highest values where 75% irrigation was combined with high biochar doses. Biochar has likewise been reported to increase irrigation water productivity and water saving in pepper under deficit irrigation (Cakmakcı & Sahın, 2023). Combining moderate deficit with biochar application therefore offers a practical strategy that balances water saving with yield in water-scarce regions.

For the yield response factor (Ky), the mean value of 1.22 under severe deficit confirms the high sensitivity of pepper to water deficit, since $Ky > 1$ means that the proportional yield loss exceeds the proportional water deficit (Doorenbos & Kassam, 1979). This value agrees with the reference Ky of about 1.1 reported for pepper in

the literature. The fall in mean Ky from 1.09 to 0.91 with increasing biochar dose indicates that biochar improved the plant's drought tolerance. The decline in harvest index (HI) under severe deficit (≈0.47) and its plateau at about 0.62 as water increased show that water stress disproportionately restricts the transfer of photosynthates to the fruit, supporting the sensitivity of pepper to water deficit during the reproductive phase (Stagnari et al., 2016).

Overall, this study shows that biochar is an effective soil amendment for reducing drought-related yield losses in pepper, particularly in sandy-loam soils with low water-holding capacity and under moderate deficit irrigation. The findings indicate that biochar at 150–250 g (about 3–5% by weight) gives the most favorable results for improving both yield and water-use efficiency. However, because the study was conducted under controlled pot conditions, caution is needed in generalizing the results to the field scale and to different soil and climate conditions. Evaluating biochar type, feedstock, and pyrolysis conditions, along with long-term soil effects, in field trials will help optimize biochar-based strategies for sustainable pepper production under water scarcity.

CONCLUSION

This study demonstrated that biochar is an effective soil amendment for reducing deficit-irrigation-induced yield losses in pepper grown in sandy-loam soils with low water-holding capacity. While water deficit markedly limited yield and growth, increasing biochar doses raised yield, biomass, and water-use efficiency at all irrigation levels, and the buffering contribution of biochar strengthened proportionally under greater water deficit. The peak in water-use efficiency at the 75% irrigation level, and the highest values obtained where this level was combined with high biochar doses, show that moderate deficit combined with biochar offers a practical strategy that balances water saving with yield. By contrast, the protective effect of biochar was limited under the most severe deficit (25%), indicating that biochar cannot substitute for water when the absolute water input falls to a critical level, although it can effectively buffer moderate stress. Overall, under the conditions of the present pot experiment, combining 75% irrigation with a biochar dose of 150–250 g gave the most favorable results for yield and water-use efficiency; these combinations should therefore be regarded as promising under the present experimental conditions rather than as direct recommendations for field practice. Validating these findings under different soil and climate conditions and at the field scale, together with the long-term effects and an economic analysis of biochar, will be valuable for sustainable pepper production under water scarcity.

Declaration of interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Author Contributions

***Ihsan Serkan Varol*:** Conceptualization; data curation; formal analysis; investigation; methodology; software; writing— original draft; writing—review and editing.

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