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Effects of Farmyard Manure and Biochar Treatments on the Development and Water Use of Lettuce Under the Deficit Irrigation Regime

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A B S T R A C T

In this study, the effects of different organic matter additives [soil (control), 20 ton ha^{-1} farmyard manure, 20 ton ha^{-1} biochar, and 10 ton ha^{-1} farmyard manure+10 ton ha^{-1} biochar] to the soil of lettuce grown with different irrigation water levels [100% (full irrigation), 75% (25% deficit irrigation), 50% (50% deficit irrigation), and 25% (75% deficit irrigation)] on water and irrigation water productivity efficiencies and plant characteristics were investigated. Among the organic matter additives, the biochar reduced the amount of irrigation water and actual evapotranspiration of lettuce and increased its marketable yield, thus the highest water and irrigation water productivity efficiencies were obtained from biochar treatment. Despite the decreasing marketable yield in the 50% irrigation treatment, the proportionally decreasing amount of irrigation water and actual evapotranspiration caused the highest water and irrigation water productivity efficiencies to occur in the 50% irrigation treatment. While the root diameter, root fresh and dry weights, stem diameter and length, head fresh and dry weights, marketable leaf number and yield, chlorophyll, and leaf relative water content of lettuce decreased with decreasing irrigation water levels, root length and membrane damage increased. The effects of organic matter additives on all of these physical-physiological properties, except root diameter and membrane damage, were found to be significant, and the biochar provided the most effective development of these parameters under the deficit irrigation regime. Considering that the yield and yield characteristics in 75% irrigation treatment do not decrease at a very significant level compared to full irrigation (100%) and that these decreases can be compensated by biochar and that the farmyard manure+biochar as alternative treatment is also effective in improving the decrease in yield parameters, treatment of 10 ton ha^{-1} farmyard manure+10 ton ha^{-1} to the soil at 75% irrigation water level was found to be recommended in lettuce cultivation.

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Introduction

In today's conditions, drought and water scarcity due to climate change cause serious concerns in agricultural production. The 70% water use rate of the agricultural sector on a global scale consumes the majority of the world's available water (Ballesteros et al., 2016), resulting in a significant decrease in ground water and surface water resources (Falkenmark and Molden, 2008). Considering that water cannot be created from nothing, this situation has caused the deficit irrigation regime to come to the fore. Deficit irrigation can be defined as exposing the plant to drought stress on a certain scale during a certain growth period or the entire growth period. The main purpose of deficit irrigation is to increase production per area of water consumed instead of increasing production per area to cope with insufficient water resources (Zhang et al., 2017).

Decreases in the yield functions of plants that cannot provide sufficient water with deficit irrigation are certain. Drought, which is an important stress factor, is accepted as the most important ecological factor limiting the development of the plant (Le Houérou, 1996). With increasing drought, the physiological characteristics of the plant suffer significant damage (Cakmakci et al., 2022). Vegetables, in particular, are more sensitive to drought stress. Among the vegetables, lettuce, which is produced in abundance and consumed as a salad-vegetable (Sahin et al., 2016), is among the vegetables most sensitive to water stress with its shallow-rooted structure (Montenegro et al., 2011). Serious decreases in the yield and quality of lettuce grown under deficit irrigation conditions were reported in a study (Kuslu et al., 2008).

The yield-improving treatments are needed for effective management in the use of deficit irrigation against decreasing water resources. Although the trend toward drought-resistant plant populations comes to the fore, the pace of advances and studies improving tolerance to stress has remained quite limited (Sahin et al., 2015). Additionally, the methods used in this approach are time-consuming, laborious, and expensive (Athar and Ashraf, 2009). For this reason, studies should be carried out on more effective management of soil moisture and the use of soil moisture-retaining materials with economical and practical treatments.

Farmyard manure not only increases the water capacity of the soil and the water use availability of the plant (Blanco-Canqui et al., 2015) but also improves the nutrient content, cation exchange capacity, and biological aspects of the soil (Zhang et al., 2020). These developments increase the possibilities of using farmyard manure as farmyard manure provides a more efficient and high-quality plant product management on the soil surface. In addition, easy access to farmyard manure is among the reasons for preferring farmyard manure. However, the weak carbon bonds of farmyard manure reduce its retention in the soil, so fertilization should be repeated at the beginning of each production season. However, the stable carbon feature of biochar is such that it can remain in the soil for years. Biochar containing aromatic carbon has a stubborn form (Keith et al., 2011). Thus, biochar remains in the soil for longer periods, ensuring more effective preservation of soil moisture (Fang et al., 2014), and maintaining soil nutrient capacity and soil biological vitality (Ahmed et al., 2019). These effects can support a healthier and more efficient development of the plant production pattern.

Previous studies focused on the effects of farmyard manure and/or biochar on the development of different plants under varying irrigation practices but no study has been found in the literature examining the effects of farmyard manure and biochar treatments on the development of lettuce and water and irrigation water productivity efficiencies under deficit irrigation regime. In this context, the originality of this study was the comparison of the use of farmyard manure and biochar separately and together at different irrigation water levels, and the evaluation of the water and irrigation water productivity efficiencies of lettuce and plant characteristics. It was predicted that organic matter additives would increase water and irrigation water productivity efficiencies due to deficit irrigation treatments, and whether the treatment of farmyard manure+biochar in deficit irrigation would increase plant productivity was addressed as the research question of the study.

Materials and Methods

The experiment was conducted in 2023 in the experimental area of Van Yuzuncu Yil University, Faculty of Agriculture, Department of Biosystems Engineering. The climate data of the vegetation period (August 1 and September 27) of the lettuce plant (cv. Caipira) were measured by the climate station in the experimental area. Accordingly, the mean temperature, precipitation, wind speed, relative humidity, and evaporation values of August-September were 23.6-19.0 °C, 1.1-10.8 mm, 2.1-1.7 m s^{-1}, 30.4-40.9%, and 203.7-135.9 mm, respectively.

According to the soil samples taken from 0-30 cm soil depth from different points to represent the area of the experimental plots, it was determined that the soil texture was sandy clay loam (sand: 45.9%, clay: 29.8%, loam: 24.3%), there was no salinity problem (0.42 dS m^{-1}), it was in the middle alkaline group (8.11), the amount of organic matter (1.25%) and Total Kjeldahl Nitrogen (0.09%) was low, and the lime content was in the middle class (10.79%). Farmyard manure and biochar materials were also analyzed with similar analysis methods. Accordingly, the electrical conductivity, pH, organic matter, and nitrogen contents of farmyard manure-biochar were determined as 4.65-1.78 dS m^{-1}, 7.78-8.29, 30.6-37.2%, and 1.06-1.21%, respectively.

The experiment was carried out in a total of 48 plots with 3 replications, according to the split-plot experimental design in a random blocks experimental plan, with 4 different organic matter additives to the soil [soil (control), 20 ton ha^{-1} farmyard manure, 20 ton ha^{-1} biochar, and 10 ton ha^{-1} farmyard manure+10 ton ha^{-1} biochar], at 4 different irrigation water levels [100% (full irrigation), 75% (25% deficit irrigation), 50% (50% deficit irrigation), and 25% (75% deficit irrigation)]. Experimental plots were created with dimensions of 4.5 m × 1.2 m with 4 rows, 30 cm × 30 cm row spacing, and plant spacing. To prevent interaction among treatments, a distance of 3 m was left between plots, blocks, and organic matter additives.

The experimental area was plowed with a mouldboard plow, and then organic matter additives (farmyard manure, biochar, and farmyard manure+biochar) were spread homogeneously on the soil, finally, all plots were processed with a disc harrow to ensure that the clods formed in the soil were broken down and the organic matter additives were mixed into the soil. After the organic matter additives were applied to the soil, lettuce seedlings were planted in the experimental plots.

In the experiment, irrigation was carried out using surface drip irrigation. Lateral pipes with in-line drippers with a flow rate of 2.3 l h^{-1} at 1 atm operating pressure, 33 cm dripper intervals, were used for irrigation. The operating pressure required for irrigation via lateral (Ø 16), manifold (Ø 32), and main (Ø 50) lines is provided by a centrifugal pump. Soil moisture measurements were carried out with a TDR (Trime-Pico, IPH/T3) calibrated to the study soil. For this purpose, soil moisture measurements were performed at the midpoint of the plots, at a soil depth of 30 cm between two laterals.

After the lettuce seedlings were planted, all parcels were irrigated equally to bring the field capacity according to the moisture amount determined by the soil (control) treatment at a 30 cm soil depth. With this approach, irrigation was continued as full irrigation (100%) until the adaptation process of the plants to the field conditions was completed. Afterward, the current moisture content at 30 cm soil depth was determined for the full irrigation of each organic matter additive treatment [soil (control), farmyard manure, biochar, and farmyard manure+biochar], and 100%, 75%, 50%, and 25% irrigation treatments were continued until the harvest process, to be completed to field capacity with a 65% wetting percentage. The reference plant water consumption approach was used to determine irrigation time.

The reference plant water consumption value was calculated daily in the CROPWAT program with the data received from the climate station in the experimental area. When the reference plant water consumption value was 25±5 mm, the current soil moisture was determined and irrigation was carried out according to the determined moisture with the help of Equation 1. Water meters were used to control the applied irrigation water volumes and irrigation volumes were confirmed with these water meters.

$$IW_v=[\{(FC–CM)\times BD\times D\times P\times IL\}/100]\times A \quad (1)$$

Where, IW_v is the volume of irrigation water (L), FC is the field capacity (29.7 P_w), CM is the current moisture determined before each irrigation (P_w), BD is the soil bulk density (1.32 g cm^{-3}), D is the irrigated soil depth (30 cm), P is the wetting percentage (65%), IL is the irrigation level (100%, 75%, 50%, and 25%), and A is the plot area (5.4 m^2).

Equations 2, 3, and 4 were used to determine actual evapotranspiration, water and irrigation water productivity efficiency values. A water budget equation was used to determine actual evapotranspiration but capillary rise, deep percolation, and runoff were not taken into account due to the absence of ground water in the experimental area, the lack of deep percolation and the selection of the dripper flow rate appropriate to the infiltration rate of the experimental area.

$$AET = IW_a + P_a + C_{sm} \quad (2)$$

$$WP = Y_M / AET \times 10 \quad (3)$$

$$WP_i = Y_M / IW_a \times 10 \quad (4)$$

Where, AET is the actual evapotranspiration (mm), IW_a is the amount of irrigation water (mm), P_a is the amount of precipitation (mm), C_{sm} is the change in soil moisture (mm), WP is the water productivity efficiency (kg m^{-3}), WP_i is the irrigation water productivity efficiency (kg m^{-3}), and Y_M is the marketable yield (kg ha^{-1}).

While head and root fresh weights were determined by weighing the plant samples harvested from the middle of the experimental plots, head and root dry weights were obtained by drying the same samples at 68°C until they reached a constant weight and then weighing them. Stem and root diameter values were measured with a digital caliper. A ruler was used to determine stem and root length values. The number of marketable leaves was determined by counting the leaves remaining after removing the yellowed, spoiled, rotten, and non-renewable leaves of the plant. Likewise, after removing the yellowed, spoiled, rotten, and non-renewable leaves of the plant, they were weighed and marketed yield was obtained by proportioning them to the unit area. A portable chlorophyll meter (SPAD-502) was used for chlorophyll measurements. Leaf relative water content and membrane damage were determined by Equations 5 and 6, according to Bowman (1989) and Jamei et al. (2009), respectively.

$$LRWC=(L_{fw} – L_{dw}) / (L_{tw} – L_{dw}) \times 100 \quad (5)$$

$$MD =(EC_a / EC_b) \times 100 \quad (6)$$

Where, LRWC is the leaf relative water content (%), L_{fw} is the fresh weight of the leaf (g), L_{dw} is the dry weight of the leaf kept in an oven at 65ºC for 48 hours (g), L_{tw} is the turgor weight of the leaf soaked in pure water for 4 hours (g), MD is the membrane damage (%), EC_a is the electrical conductivity of the leaf disc sample kept in 30 ml of pure water in 50 ml tubes for 24 hours (dS m^{-1}), and EC_b is the electrical conductivity of the same leaf disc sample after keeping it in a water bath at 95°C for 20 minutes and cooling it to room temperature(dS m^{-1}).

All data obtained as a result of the experiment were analyzed in the SPSS program (Ver. 23). Variance analysis was used to evaluate the data, and classification was made with the Duncan multiple comparison test for the means found to be significant.

Results and Discussion

The amount of irrigation water and actual evapotranspiration values of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime are given in Figure 1. During the vegetation period of lettuce (August 1 and September 27), the first 5 of a total of 18 irrigations were made as full irrigation (100%) to ensure the adaptation of the plants to the field conditions, and for this purpose, 37 mm of irrigation water was provided equally to all treatments. In addition, after the initial planting of lettuce seedlings, 28 mm of irrigation water was applied equally to all parcels to compensate for insufficient soil moisture to field capacity. Thus, a total of 65 mm of irrigation water was applied equally to all treatments. Afterward, irrigation treatments (100%, 75%, 50%, and 25%) were started and at this stage, a total of 13 irrigations were continued as planned irrigation until the harvest period. The mean irrigation interval during the experimental period was 3 days.

The mean irrigation water amount values in 100%, 75%, 50%, and 25% irrigation treatments were 154 mm, 131 mm, 107 mm, and 85 mm, respectively, while in soil (control), farmyard manure, biochar, and farmyard manure+biochar treatments were 124 mm, 120 mm, 116 mm, and 118 mm, respectively. On the mean, farmyard manure, biochar, and farmyard manure+biochar treatments saved 3.2%, 6.5%, and 4.8% of irrigation water, respectively, compared to soil (control) treatment.

While the effect of farmyard manure in reducing the amount of irrigation water can be explained by the organic matter contribution it provides to the soil, the effect of biochar in reducing the amount of irrigation water can be evaluated about the preservation of soil moisture thanks to the porous structure of biochar. It is thought that the decrease in the amount of irrigation water in the farmyard manure+biochar treatment compared to the soil (control) treatment is a result of a combination of these two effects. Amooh and Bonsu (2015) stated that organic matter in the soil provides higher levels of moisture to the soil by improving the number of pores, size, and distribution of the soil and increasing the specific surface area of the soil, thus reducing moisture loss. Charles Gould (2015) pointed out that by increasing soil organic matter from 1% to 2%, soil water storage can be increased by approximately 3 liters for every 0.0283 m^3 of soil. Cakmakci and Sahin (2022) defined biochar as a material that retains soil moisture not only within its pores but also between its micropores and particles, and they stated that thanks to this feature, it takes a longer time for biochar-applied soil to lose moisture in the soil and dry. Yerli et al. (2022) pointed out that under conditions where biochars with different raw material contents were applied to the soil, evaporation from the soil decreased by 2.2% to 6.1% compared to the control soil without biochar.

Due to the low amount of precipitation during the vegetation period of lettuce, irrigation water constituted the most important component of real evapotranspiration. The mean real evapotranspiration values in 100%, 75%, 50%, and 25% irrigation treatments were 189 mm, 160 mm, 134 mm, and 107 mm, respectively, while in soil (control), farmyard manure, biochar, and farmyard manure+biochar treatments were 154 mm, 149 mm, 141 mm, and 145 mm, respectively. On the mean, the actual evapotranspiration values of farmyard manure, biochar, and farmyard manure+biochar treatments decreased by 3.2%, 8.4%, and 5.8%, respectively, compared to the soil (control) treatment.

As a result of different studies conducted on lettuce plants, actual evapotranspiration values similar or different from the findings of this study have been reported (Kadayifci et al., 2004; Oliveira et al., 2005; Kuslu et al., 2008; Dediu et al., 2012; Sahin et al., 2016; Kurunc, 2021; Eaton et al., 2023). These differences or similarities can be explained depending on many factors such as climate, altitude, topography, soil characteristics and factors, irrigation amount, method and practices, harvest date and maturation period, main and second plant status, and plant genotype.

The water productivity efficiency and irrigation water productivity efficiency values of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime are given in Figure 2. The effects of irrigation water levels and organic matter additives on water productivity efficiency and irrigation water productivity efficiency were found to be statistically significant at the p<0.01 level. 50% irrigation treatment provided 4.9%-6.3%, 9.8%-6% and 35.1%-33.6% more water productivity efficiency-irrigation water productivity efficiency values than 100%, 75% and 25% irrigation treatments, respectively, while biochar treatment provided 15.7%-14.2%, 9.8%-8.1% and 5.4%-4.3% more water productivity efficiency-irrigation water productivity efficiency values than soil (control), farmyard manure, and farmyard manure+biochar treatments, respectively.

The increased water productivity efficiency and irrigation water productivity efficiency

values in the 50% irrigation treatment can be explained by the proportional decrease in the amount of irrigation water and real evapotranspiration (Figure 1) against the decreasing marketable yield (Table 1).

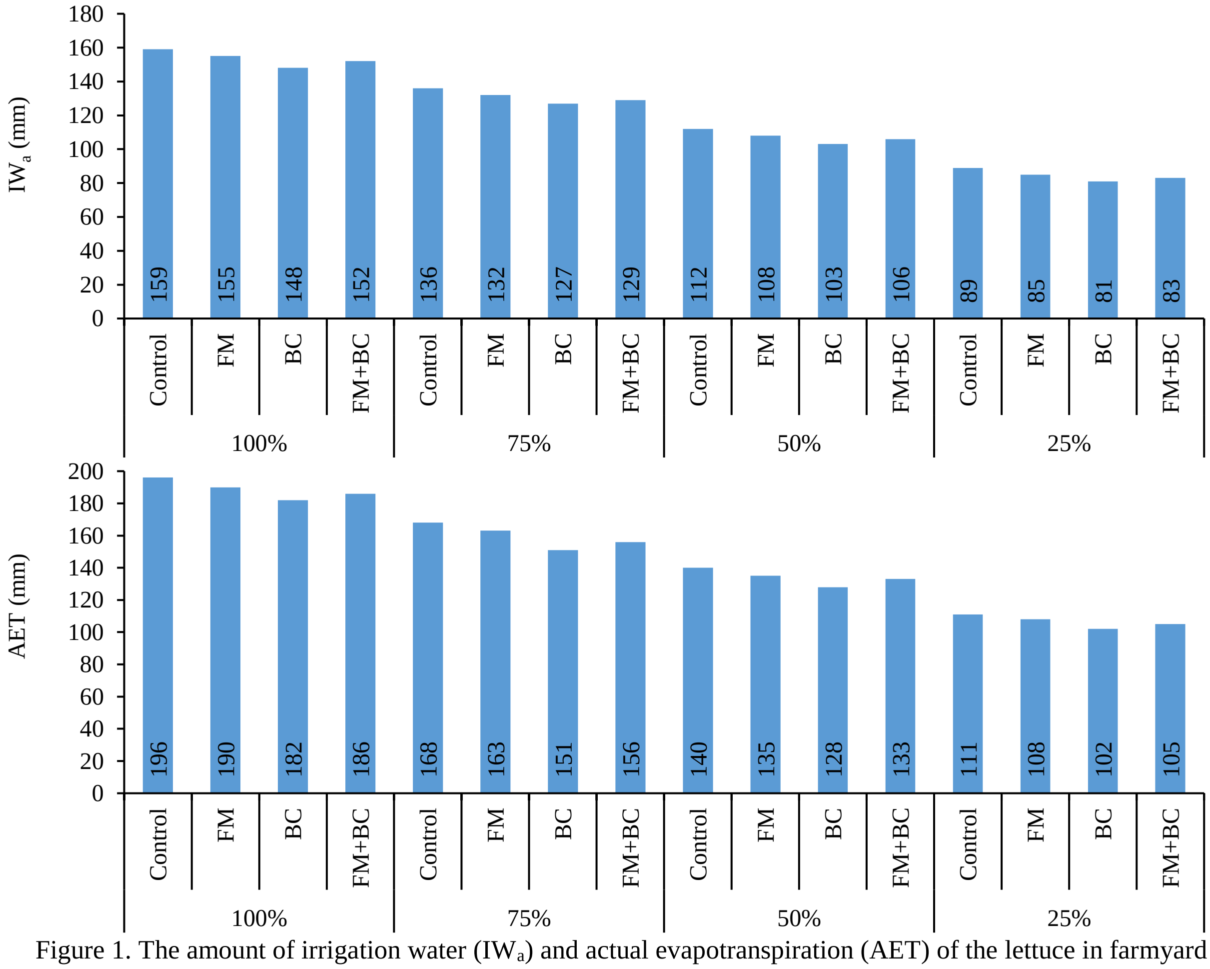

Figure 1. The amount of irrigation water (IW_a) and actual evapotranspiration (AET) of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime
(100%: full irrigation, 75%: 25% deficit irrigation, 50%: 50% deficit irrigation, 25%: 75% deficit irrigation, FM: farmyard manure, BC: biochar, FM+BC: farmyard manure+biochar)

Table 1. The properties of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime

Treatments		R_d (mm)	R_l (cm)	R_{fw} (g)	R_{dw} (g)	S_d (mm)
100%	Control	18.7±1.90	14.3±0.70	49.7±2.01	3.0±0.12	1.9±0.21
	FM	19.0±0.09	13.9±0.22	52.7±0.69	3.1±0.01	2.1±0.06
	BC	19.6±0.21	12.6±0.09	55.1±1.32	3.3±0.17	2.4±0.06
	FM+BC	19.2±0.09	13.2±0.21	53.8±0.23	3.2±0.03	2.2±0.06
75%	Control	17.5±0.29	14.9±0.09	43.8±0.99	2.7±0.09	1.7±0.06
	FM	17.8±0.06	14.7±0.03	45.5±0.62	2.8±0.03	1.8±0.06
	BC	18.3±0.28	14.4±0.07	48.1±1.16	3.0±0.13	2.0±0.03
	FM+BC	18.0±0.03	14.5±0.03	46.5±0.20	2.9±0.03	1.9±0.01
50%	Control	15.5±0.52	16.6±0.25	37.6±1.28	2.2±0.06	1.4±0.06
	FM	15.8±0.18	16.2±0.12	38.6±0.27	2.3±0.06	1.5±0.19
	BC	16.2±0.09	16.5±0.03	40.1±0.15	2.5±0.26	1.7±0.01
	FM+BC	16.0±0.06	16.4±0.01	39.3±0.12	2.4±0.03	1.6±0.01
25%	Control	12.0±0.58	18.2±0.35	31.6±0.88	1.9±0.03	1.0±0.18
	FM	12.4±0.15	18.1±0.26	33.5±0.47	2.0±0.12	1.1±0.12
	BC	12.8±0.09	17.4±0.06	35.6±1.32	2.3±0.07	1.3±0.01
	FM+BC	12.5±0.07	17.7±0.12	34.7±0.12	2.2±0.03	1.2±0.03
Mean	Control	15.9±0.88	16.0±0.49 ^{A}	40.7±2.13 ^{C}	2.4±0.14 ^{C}	1.5±0.12 ^{C}
	FM	16.3±0.75	15.7±0.48 ^{AB}	42.6±2.20 ^{B}	2.6±0.13 ^{BC}	1.6±0.12 ^{BC}
	BC	16.7±0.78	15.3±0.56 ^{C}	44.7±2.30 ^{A}	2.8±0.15 ^{A}	1.9±0.12 ^{A}
	FM+BC	16.4±0.76	15.5±0.53 ^{BC}	43.6±2.19 ^{AB}	2.7±0.13 ^{AB}	1.7±0.11 ^{AB}
Mean	100%	19.1±0.42 ^{A}	13.5±0.26 ^{D}	52.8±0.80 ^{A}	3.2±0.06 ^{A}	2.2±0.07 ^{A}
	75%	17.9±0.12 ^{B}	14.7±0.06 ^{C}	46.0±0.59 ^{B}	2.9±0.05 ^{B}	1.9±0.04 ^{B}
	50%	15.9±0.14 ^{C}	16.4±0.08 ^{B}	38.9±0.39 ^{C}	2.3±0.07 ^{C}	1.6±0.05 ^{C}
	25%	12.4±0.15 ^{D}	17.9±0.14 ^{A}	33.8±0.58 ^{D}	2.1±0.06 ^{D}	1.2±0.06 ^{D}

Treatments		S_l (cm)	H_{fw} (g)	H_{dw} (g)	L_m	Y_m (kg ha^{-1})
100%	Control	8.7±0.29	598.4±9.1	35.4±0.56	32±1.7	56 350±107
	FM	9.1±0.12	621.9±2.1	37.0±0.97	34±0.3	57 470±220
	BC	10.1±0.22	649.6±4.3	38.4±0.37	38±1.2	59 350±994
	FM+BC	9.5±0.06	634.2±1.3	36.3±0.12	36±1.2	58 410±451
75%	Control	7.4±0.23	533.7±3.3	31.1±0.76	25±1.5	46 590±589
	FM	7.6±0.06	544.4±4.1	32.1±0.39	27±0.9	47 760±321
	BC	7.9±0.45	555.9±2.8	33.3±0.15	31±1.2	49 060±611
	FM+BC	7.7±0.06	549.7±1.3	31.6±0.22	29±0.6	48 170±50
50%	Control	6.2±0.19	482.4±5.9	25.4±0.61	20±1.2	41 720±741
	FM	6.5±0.15	488.9±1.7	26.2±0.31	22±1.9	42 810±480
	BC	7.0±0.55	496.7±4.1	27.6±0.25	24±0.6	44 300±491
	FM+BC	6.7±0.10	490.9±8.5	26.9±0.52	22±1.2	43 370±258
25%	Control	4.3±0.12	330.4±1.2	17.2±0.86	11±1.5	24 620±449
	FM	4.5±0.06	334.8±3.3	17.9±0.07	12±1.2	25 080±105
	BC	5.0±0.55	340.2±0.9	18.9±0.01	16±1.2	26 230±702
	FM+BC	4.8±0.17	336.1±3.1	18.0±0.24	13±0.9	25 510±153
Mean	Control	6.7±0.50 ^{C}	486.2±30.5 ^{B}	27.3±2.08 ^{C}	22±2.4 ^{C}	42 320±3481 ^{C}
	FM	6.9±0.51 ^{BC}	497.5±31.7 ^{AB}	28.3±2.16 ^{B}	24±2.5 ^{B}	43 280±3578 ^{BC}
	BC	7.5±0.59 ^{A}	510.6±34.1 ^{A}	29.5±2.18 ^{A}	27±2.5 ^{A}	44 740±3628 ^{A}
	FM+BC	7.2±0.51 ^{AB}	502.7±32.9 ^{A}	28.2±2.05 ^{B}	25±2.6 ^{B}	43 860±3592 ^{AB}
Mean	100%	9.3±0.18 ^{A}	626.0±8.5 ^{A}	36.8±0.41 ^{A}	35±0.8 ^{A}	57 890±663 ^{A}
	75%	7.7±0.12 ^{B}	545.9±2.8 ^{B}	32.0±0.31 ^{B}	28±0.8 ^{B}	47 900±325 ^{B}
	50%	6.6±0.15 ^{C}	489.7±4.1 ^{C}	26.5±0.31 ^{C}	22±0.7 ^{C}	43 050±359 ^{C}
	25%	4.6±0.15 ^{D}	335.4±1.5 ^{D}	18.0±0.27 ^{D}	13±0.7 ^{D}	25 360±255 ^{D}

R_d: Root diameter, R_l: Root length, R_{fw}: Root fresh weight, R_{dw}: Root dry weight, S_d: Stem diameter, S_l: Stem length, H_{fw}: Head fresh weight, H_{dw}: Head dry weight, L_m: Number of marketable leaves, Y_m: Marketable yield, 100%: full irrigation, 75%: 25% deficit irrigation, 50%: 50% deficit irrigation, 25%: 75% deficit irrigation, FM: farmyard manure, BC: biochar, FM+BC: farmyard manure+biochar, ±: Standard error, and the significance level of data is P<0.01

The basic hypothesis of water and irrigation water productivity efficiencies is based on increasing yield against the increasing water consumption and irrigation amount of the plant, and the plant must consume more water and be irrigated to increase water and irrigation water productivity efficiencies. Therefore, the increase in water and irrigation water productivity efficiencies with the irrigation water level shows that the increase in yield (Table 1) is supported by irrigation. In addition, similar to the findings of this study, Chala and Yohannes (2015) and Cakmakci and Sahin (2021) also stated that water and irrigation water productivity efficiency values increased due to decreasing yield, the amount of irrigation water and real evapotranspiration under deficit irrigation conditions.

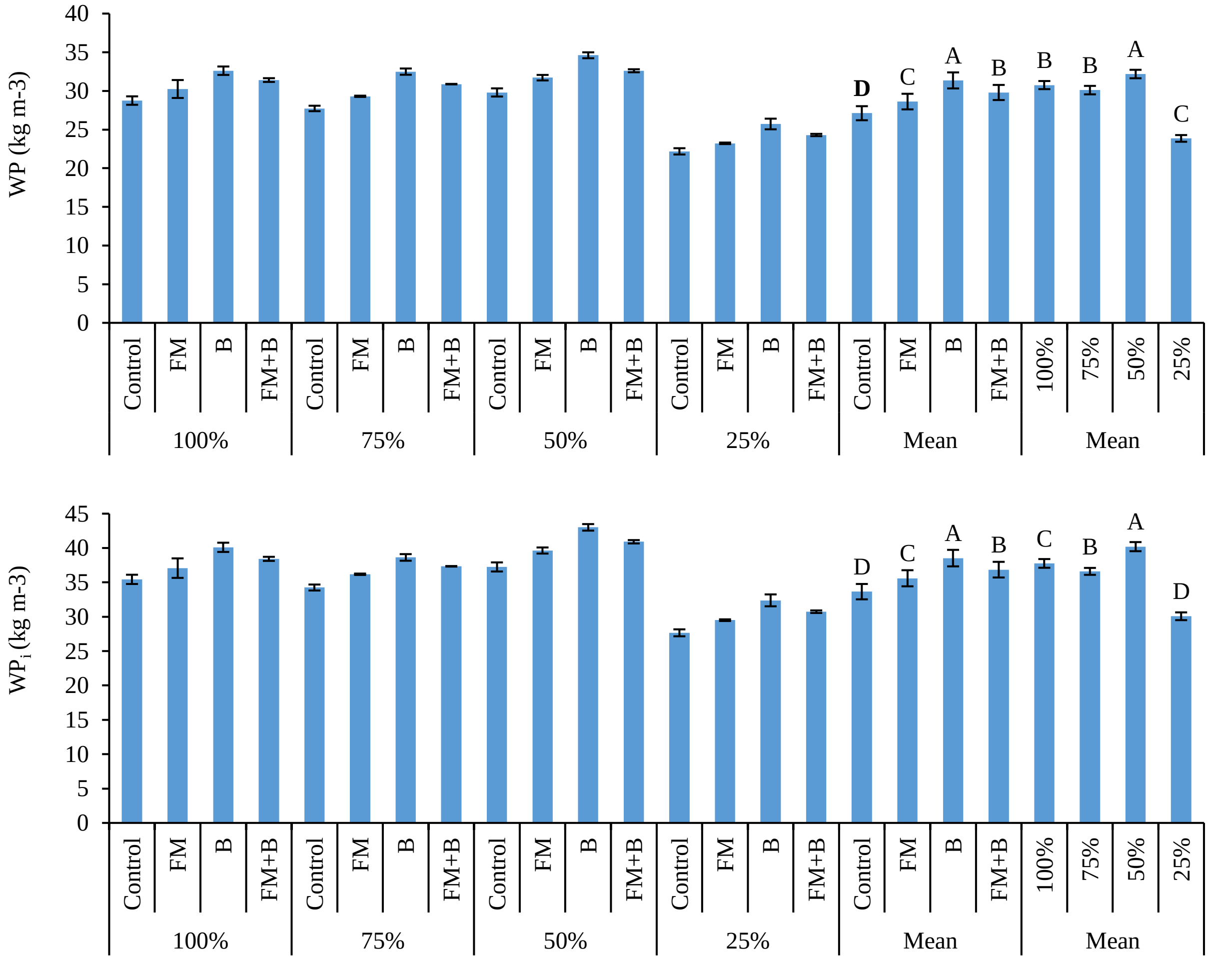

Figure 2. The water productivity efficiency (WP) and irrigation water productivity efficiency (WP$_i$) of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime
(100%: full irrigation, 75%: 25% deficit irrigation, 50%: 50% deficit irrigation, 25%: 75% deficit irrigation, FM: farmyard manure, BC: biochar, FM+BC: farmyard manure+biochar, and the significance level of data is P<0.01)

Increased water and irrigation water productivity efficiency values in biochar treatment can be explained by both increased marketable yield (Table 1) and decreased amount of irrigation water and real evapotranspiration (Figure 1). Because, based on the formulaic calculation component of water productivity efficiency and irrigation water productivity efficiency (Equations 3 and 4), the decreasing amount of irrigation water and real evapotranspiration values against the increasing yield potential results in an increase in water productivity efficiency and irrigation water productivity efficiency. Similar to the findings of this study, Alkhasha et al. (2019) and Baiamonte et al. (2020) also stated that water and irrigation water productivity efficiency values increased due to increased yield and decreasing amount of irrigation water and real evapotranspiration in biochar conditions.

The properties of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime are given in Table 1. While the effects of irrigation water levels and organic matter additives on root length, root fresh and dry weights, stem diameter and length, head fresh and dry weights, number of marketable leaves, and marketable yield were found to be statistically significant at the $p<0.01$ level, only the effect of irrigation water levels on the root diameter was significant at the $p<0.01$ level, and the effect of organic matter additives was found to be insignificant. While all properties of lettuce except root length increased with increasing irrigation water levels, the highest lettuce properties except root diameter and length among organic matter additives were achieved in the biochar treatment.

As an expected effect, the decrease in the yield and yield-related characteristics of lettuce in increasingly deficit irrigation practices can be explained by the limitation of plant growth due to insufficient soil moisture. Insufficient soil moisture negatively affects the metabolic and physiological processes of the plant, reducing physical development and limiting the growth of the plant. Plants exposed to water stress first reduce the development of their physical characteristics to maintain their vital functions (Gencoglan et al., 2006). The first affected organs of the plant growing in arid conditions are generally features such as height, diameter, weight, number of leaves, number of fruits, and area. Similar to the findings of this study, many previous studies have reported that the yield and yield-related characteristics of lettuce exposed to water stress decrease (Kadayifci et al., 2004, Kuslu et al., 2008, Sahin et al., 2015; Sahin et al., 2016; Al-Bayati and Sahin, 2018). In addition, unlike other physical characteristics, the root length of lettuce increased with increasing deficit irrigation practices. This can be interpreted as a relationship with the plant roots extending their roots further and developing their roots more to access water in case of water deficiency in the soil. Ekinci and Basbag (2019) reported that the cotton plants growing in drought conditions showed more root development to reach soil water. However, in the opposite direction, Ahmadi et al. (2018) found that root development of barley exposed to water stress decreased.

Higher yield and yield-related characteristics of lettuce in biochar treatment compared to soil (control), farmyard manure, and farmyard manure+biochar treatments can be explained as a result of the biochar's higher organic matter and nitrogen content, as well as its porous structure, which preserves soil moisture and manages soil moisture more effectively. In addition, the high salinity value of farmyard manure may have limited the yield and yield-related characteristics of lettuce. Biochar facilitates the plant's uptake of nutrients from the soil by improving the quality properties of soils with its specific surface area, porosity, nutrient element content, cation exchange capacity, and the ability to provide organic matter and nitrogen to the soil, thus supporting the increase in productivity and quality of the plant (Puhringer, 2016). Cakmakci et al. (2022) explained the yield contribution of biochar to the plant by improving porosity in favor of beneficial water retention by improving the gaps between biochar aggregates. Liu et al. (2013) stated that biochar mixed into the soil enriches the soil with organic matter and macronutrients, increasing the water and nutrient uptake of the plant, and thus, the plant grown in the biochar-applied soil offers higher yield and yield characteristics. In addition, plants growing in biochar soil reflect this situation in their productivity by using the root profile more effectively to absorb soil water and nutrients instead of accumulating root biomass (Xiang et al., 2013). Similar to the findings of this study, Cakmakci et al. (2022) also stated that the yield and yield-related characteristics of lettuce grown in biochar-applied soil increased and that this increase further improved with increasing biochar rates. In addition, similar to the findings of this study, many previous studies have reported that the yield and yield-related characteristics of lettuce grown in biochar-applied soil increased (Carter et al., 2013; Caroline et al., 2016; Galadima et al., 2020). In addition, contrary to other characteristics, the root length of lettuce was lower in the biochar treatment compared to the soil (control), farmyard manure, and farmyard manure+biochar treatments. This can be evaluated as being related to the decrease in root length as a result of the roots being able to access water more easily in soil with biochar.

The chlorophyll, leaf relative water content, and membrane damage of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime are given in Figure 3. While the effects of irrigation water levels on the chlorophyll, leaf relative water content, and membrane damage were found to be statistically significant at the $P<0.01$ level, the effects of organic matter additives on the chlorophyll and leaf relative water content were significant at the $P<0.01$ level but the effect of organic matter additives on the membrane damage was found to be insignificant. While chlorophyll and leaf relative water content increased with increasing irrigation water levels, membrane damage decreased and the highest chlorophyll and leaf relative water content among organic matter additives were achieved in the biochar treatment.

The decrease in the chlorophyll content of lettuce in increasingly deficit irrigation practices can be explained by the plant being exposed to stress due to insufficient soil moisture. Chlorophyll content, which is a clear indicator of water stress, causes damage to chlorophyll functions under deficit irrigation conditions. Many studies have also reported that chlorophyll content decreases due to decreasing irrigation water levels (Soureshjani et al., 2019; Cakmakci and Sahin, 2021; Cakmakci et al., 2022). The decrease in leaf relative water content of lettuce in increasingly deficit irrigation practices can be evaluated by the decrease in water storage in the leaves as a result of the plant not receiving sufficient water in decreasing soil moisture. In arid conditions, plants lose more water from their leaves, causing lower leaf relative water content (Cakmakci et al., 2022). Many studies have also reported that leaf relative water content decreases due to decreasing irrigation water levels (Camoglu et al., 2019; Cakmakci and Sahin, 2021; Cakmakci et al., 2022; Yildirim et al., 2021). The increase in membrane damage of lettuce in increasingly deficit irrigation practices can be considered as related to the increase in leaf temperature due to insufficient leaf water content and the resulting damage to the cell membrane systems. In drought conditions, as the stomata close, the temperature of the leaves increases and the leaf relative water content decreases, subsequently, the functionality of the cell membrane system is disrupted and membrane damage occurs. In addition, the severity of damage to cell membrane systems may increase as a result of damage to mesophyll cells due to the decrease in chlorophyll content with increasing water stress (Marcinska et al., 2013). Many studies have also reported that membrane damage increases due to decreasing irrigation water levels (Cakmakci and Sahin, 2021; Cakmakci et al., 2022; Yildirim et al., 2021).

The higher chlorophyll content in biochar treatment compared to soil (control), farmyard manure, and farmyard manure+biochar treatments can be explained by the fact that it contributes more organic matter and total nitrogen to the soil depending on the content of biochar, as well as the fact that biochar preserves soil moisture and manages soil moisture more effectively thanks to its porous structure. Soil organic matter supports moisture conservation in the soil and encourages the development of the plant's chlorophyll content. The sufficient level of nitrogen, a building block of chlorophyll, in the soil improves the chlorophyll content of the plant (Bojovic and Markovic, 2009). The effects of biochar in managing soil moisture and protecting the plant from water stress enable the development of physical and physiological properties of plants growing in biochar conditions. In addition, many studies have also reported that biochar-applied to the soil supports the development of the plant's chlorophyll content (Cakmakci et al., 2022; Yildirim et al., 2021; Qianqian et al., 2022). The higher leaf relative water content in biochar treatment compared to soil (control), farmyard manure, and farmyard manure+biochar treatments can be evaluated as being related to more organic matter contribution to the soil, depending on both the porous structure and organic matter content of the biochar.

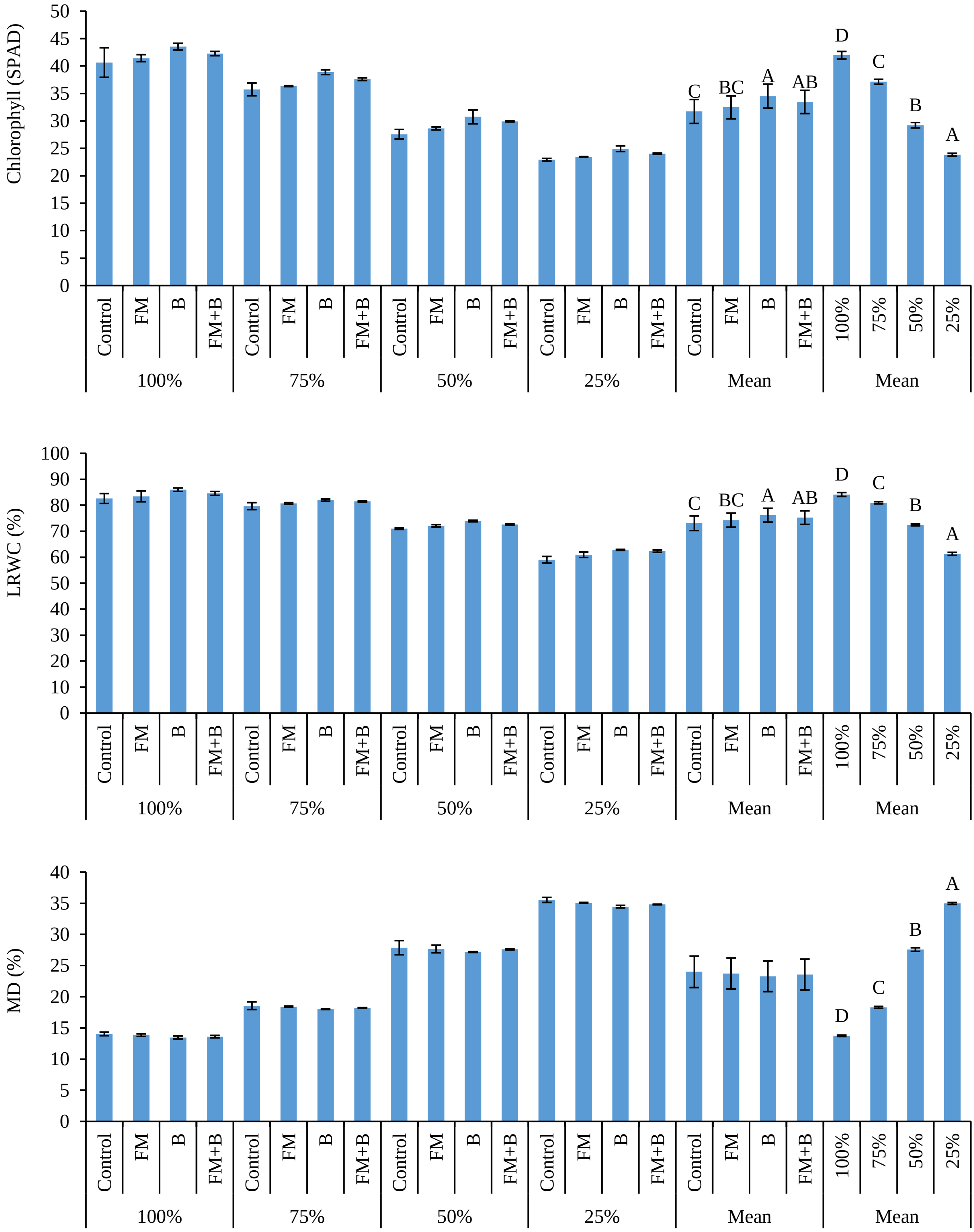

Figure 3. The chlorophyll, leaf relative water content (LRWC), and membrane damage (MD) of the lettuce in farmyard manure and biochar treatments under the deficit irrigation regime
(100%: full irrigation, 75%: 25% deficit irrigation, 50%: 50% deficit irrigation, 25%: 75% deficit irrigation, FM: farmyard manure, BC: biochar, FM+BC: farmyard manure+biochar, and the significance level of data is P<0.01)

Organic matter ensures the preservation of soil moisture by increasing soil porosity, surface area, and water retention capacity and by regulating the physical properties of the soil to reduce evaporation (Ors et al., 2021). Thus, the leaf relative water content of the plants growing by making adequate use of soil moisture increases. Kul et al. (2021) stated that the increase in water storage of the plant as a result of the increased organic matter in the soil with biochar supports the maintenance of soil moisture balance, increasing the leaf relative water content. In addition, many studies have also reported that biochar-applied to the soil supports the development of the leaf relative water content of the plant (Cakmakci et al., 2022; Kul et al., 2021; Yildirim et al., 2021).

Conclusion

The organic matter additives in the deficit irrigation regime made a significant contribution to reducing the amount of irrigation water and real evapotranspiration of lettuce and improving its physical and physiological properties and marketable yield, thus increasing the water and irrigation water productivity efficiencies. In addition, the contribution of the organic matter remaining after production in soils loaded with organic matter to the sustainability of soil fertility is also very important. It has been determined that deficit irrigation practices can be used in lettuce cultivation to protect decreasing water resources, and that 75% irrigation water level (25% deficit irrigation) in lettuce cultivation reduces the yield and yield-related characteristics of lettuce but this decrease is not at very significant level compared to full irrigation (100%), and that this decrease in the yield and yield-related characteristics can be compensated by the biochar, and despite the high cost of biochar, the farmyard manure+biochar treatment as an alternative is also effective in improving the decrease in the physical and physiological properties and yield parameters of lettuce. Thus, as an alternative, economical, and practical action to protect water resources, the treatment of 10 tons ha^{-1} farmyard manure+10 tons ha^{-1} biochar to the soil at 75% irrigation water level in lettuce cultivation can be recommended among the findings of this study.

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Declaration of Conflict of Interest

The authors declare that no competing interests.

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