



Evaluating Tomato and Kale Water use Efficiency Using Biochar-amended Substrate Under Three Irrigation Regimes

Lilin Chen¹ · Kuan Qin¹ · Yulong Chen¹ · Ping Yu¹

Received: 29 September 2025 / Accepted: 30 April 2026 / Published online: 8 May 2026
© The Author(s) 2026

Abstract

Container production faces water scarcity and limited peat moss resources, creating an urgency to improve water use efficiency and find alternatives to peat. Biochar shows promise, but its combined use with sensor-based irrigation on substrate water retention and efficiency is underexplored. This study investigated biochar's effects on plant performance under three substrate matric potentials. Nine treatments were created with three rates of biochar (0%, 15%, and 25%, by volume) and three substrate matric potentials (-5, -3.5, and -2 kPa), corresponding to low, medium, and high irrigation levels achieved by sensor-based irrigation. The substrate property changes and the morpho-physiological performance of tomato (*Solanum lycopersicum*, 'Micro-Tom') and kale (*Brassica oleracea*, 'Cane Pink') were measured biweekly. Results showed that biochar-amended substrates significantly improved substrate water retention and volumetric water content. The highest biomass of tomato plants was observed in 25% biochar treatments under medium irrigation, while fresh fruit yield did not differ significantly among treatment. Kale yielded the highest fresh biomass with 25% biochar under low irrigation. The results suggested that biochar-induced changes in substrate hydraulic properties that influence plant growth. Overall, biochar can potentially partially replace peat in soilless substrate without reducing crop productivity and may provide greater benefit for water-demanding crops under limited irrigation, supporting its potential as more sustainable substrate amendment in nursery production.

Keywords Greenhouse production · Micro-tom tomato · Moisture releasing curve · Sensor-based irrigation

1 Introduction

Agriculture accounts for 70% of freshwater consumption globally, and this demand is expected to be elevated by more than 50% by 2050 (Food and Agriculture Organization of the United Nations 2017). However, only about 0.003% of global water is accessible as fresh water. Growing concerns over climate change and population-driven water demand

highlight the urgent need for more efficient irrigation management practices in agriculture (Food and Agriculture Organization of the United Nations 2017).

Sensor-based irrigation poses the potential to address water scarcity issues for nursery and greenhouse production as it employs moisture sensors in substrates to schedule irrigation based on water potential and keep plant-available water within a range of -1 to -10 kPa, saving water while preventing plants from water stress (Munoth et al. 2016; Basiri Jahromi et al. 2020). However, sensor-based irrigation systems are not widely adopted due to high costs, low reliability, and/or technical difficulties (Jones 2004b; Belayneh et al. 2013). Currently, many growers irrigate plants based on their experience, weather conditions, and intuition without a scientific approach or evidence, resulting in low water use efficacy and unnecessarily large water usage (Belayneh et al. 2013). In contrast, sensor-based irrigation delivers water based on the substrate's volumetric water content (VWC), which could improve water use efficiency (WUE), thus largely reducing water usage (Cifre

✉ Ping Yu
pingyu@uga.edu
Lilin Chen
lilin.chen@uga.edu
Kuan Qin
kuanqin@uga.edu
Yulong Chen
yulong.chen@uga.edu

¹ Department of Horticulture, University of Georgia, Griffin, GA, USA

et al. 2005; Lichtenberg et al. 2013; Munoth et al. 2016; Ferreira et al. 2024). For instance, the total water usage of growing hydrangea (*Hydrangea paniculata*, ‘Silver Dollar’) over 8 weeks is 20% lower by irrigating based on substrate moisture sensors than by conventional irrigation, which delivered 1.8 cm of water in one event each day (Basiri Jahromi et al. 2020). Similarly, using a sensor-based irrigation system to cultivate lettuce (*Lactuca sativa* L. var. *capitata* cv. Mortarella d’inverno) in soilless substrate improved WUE from 25% to 70% compared with timer-based irrigation (Montesano et al. 2016).

Besides agricultural water scarcity, horticulture also faces the environmental concerns related to peat moss mining. Peat moss is one of the major substrate components in horticulture due to its ideal physical and chemical properties, including good water holding capacity combined with good drainage, lightweight, and high cation exchange capacity, etc. (Page et al. 2002; Sradnick et al. 2023). However, over-exploitation of peat resources has led to the degradation of wetlands, which serve as a critical habitat for red list species and act as a carbon sink for global carbon sequestration (Page et al. 2011; McCarter et al. 2021). Therefore, investigating alternative substrate components to replace peat moss has become essential for sustainable horticultural practices.

Biochar presents several benefits as a promising peat-moss alternative substrate. First, biochar is a carbon-rich byproduct that can be made of a variety of feedstock materials such as green wastes, coconut coir, rice hull, and wood bark that are pyrolyzed under inert or very low oxygen levels at a temperature range of 400 °C to 1200 °C (Demirbaş and Arin 2002; Weber and Quicker 2018). Additionally, the pyrolysis process generates pore spaces and surface area, leading to high total porosity for aeration and retaining water and nutrients, making it an excellent source as a substrate amendment to improve plants’ WUE (Weber and Quicker 2018; Leng et al. 2021). Moreover, biochar can be sourced from local agricultural and industrial waste streams, which can largely reduce transportation costs and alleviate environmental concerns (Yu et al. 2023).

Biochar-amended substrates had varied improvement effects on WUE depending on plant species. For instance, 15% eastern red cedar biochar-amended mixes (pyrolyzed between 500 and 550 °C) increase WUE by 14.3% and 15.8% for geranium (*Pelargonium graveolens* L.) and petunia (*Petunia* sp. J.), respectively, comparing to the control (Lamichhane et al. 2024). In addition, 60% conifer wood biochar-amended mixes (pyrolyzed at 450 °C) improve WUE from 0.29 to 1.1 g · L⁻¹ compared to the control for Crown-of-Thorns (*Euphorbia lomi*) plants. Biochar can improve plants’ WUE by enhancing substrate water retention and plant-available water. Pyrolysis generates pore spaces that allow it to retain more water as a substrate amendment,

thereby improving water holding capacity (Liu et al. 2017 a; Atkinson 2018). Biochar that contains mesopore spaces that can hold water between −1 kPa and −10 kPa, that is available for roots to uptake (Fukumori et al. 2018).

Both tomato and kale are water-sensitive plants that are commonly grown in the horticultural industry. The VWC significantly impact the biomass of both plants. For instance, as VWC increased from 0.16 to 0.6 m³ · m⁻³, tomato (*Solanum lycopersicum*) shoots dry weight increased from 1.78 to 2.01 g (*P* < 0.05) (Fidler and Gomez 2025). Similarly, kale (*Brassica oleracea* L. var. *acephala*) had a 22.5% increase in dry weight as VWC increased from 0.15 to 0.35 m³ · m⁻³ (Barickman et al. 2020).

Despite a few studies investigating the biochar effects on plants’ WUE, its combined use with a sensor-based irrigation system under different water regimes has been less reported. This study aimed to evaluate the effect of biochar application on WUE, plant growth, and development, as well as the physiological responses of tomato and kale under different irrigation regimes using a substrate moisture sensor-based irrigation system. The study hypothesized that biochar-amended substrates can improve WUE, plant growth, and development, as well as the physiological responses of tomato and kale under low irrigation conditions.

2 Materials and Methods

2.1 Plant Material and Substrate Treatments

Tomato (*Solanum lycopersicum*, ‘Micro-Tom’) seeds (Totally Tomatoes, Randolph, WI, USA) were sown on September 20th, 2024, and kale (*Brassica oleracea*, ‘Cane Pink’) seeds (Johnny’s Selected Seeds, Winslow, ME, USA) were sown on December 17, 2024. All the seeds were sown in 128-cell propagation trays (cell depth: 5.72 cm; cell top length & width: 53.98 cm & 28.58 cm; volume: 25.07 cm³) filled with propagation media (Pro-Mix FPX Bio-fungicide media, Quakertown, PA, USA). Uniform tomato and kale seedlings were selected and transplanted into 6-inch (15.24 cm) azalea pots (depth: 10.8 cm; top diameter: 15.5 cm; bottom diameter: 11.3 cm; volume: 1,330 mL) on October 24th, 2024, and January 13th, 2025, respectively. Slow-release fertilizer (Osmocote 15-9-12; Scotts Co., Marysville, USA) was applied on the surface of the substrate at a rate of 4 g · pot⁻¹ at 0 weeks after transplanting (WAT). The substrates were drenched with surfactant (Aquagro L, Aquatrols, Paulsboro, NJ) at 600 mg · L⁻¹ at the first time and 100 mg · L⁻¹ at the second time to prevent the surface from drying out in the first two weeks of transplanting.

Substrates were mixed with woodchip biochar (ARTi Des Moines, IA, USA) at rates of 0%, 15%, and 25% (by

Table 1 Particle size distribution (percent by weight at <0.25 mm, 0.25–<0.5 mm, 0.5–2 mm, and >2 mm) of substrate mixes containing three biochar (BC) amendment rates (0%, 15%, and 25%, 100% by vol.) in a commercial substrate

Substrates	Size Fraction (%)			
	<0.25 mm	0.25–0.5 mm	0.5–2 mm	>2 mm
0%BC	1.2±0.4c ^z	23.0±0.4c	39.4±1.3	51.2±1.3a
15%BC	8.8±0.6b	25.4±0.8b	35.9±1.2	45.0±0.6b
25%BC	11.5±0.8a	38.2±0.6a	35.3±0.6	41.9±0.6c

^z Means±standard error ($n=3$) within a column followed by the same letter were not significantly different according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P\leq 0.05$

volume, by vol.), with the remaining being commercial substrate mixes (Jolly Gardener Pro-line HFC/25 Growing Mix, Oviedo, FL, USA). The biochar used in this study was made from fast pyrolysis at 550 °C, consisting of fine to medium-sized particles rather than intact woodchip fragments (Table 1), with a pH of 8.41 and electrical conductivity (EC) of $0.42 \text{ mS} \cdot \text{cm}^{-1}$, measured by pour-through methods (Wright 1986). The commercial substrate mix consisted of 55% aged pine bark, and the remaining 45% was composed of Canadian sphagnum peat moss, hydrafiber, and perlite, and was used as the control.

The experiment was conducted in a greenhouse located at the University of Georgia, Griffin, Georgia. During the tomato growing period, the average humidity and temperature were 71.44% and 20.78 °C, respectively. During the kale growing period, the average humidity and temperature were 62.35% and 20.26 °C, respectively.

2.2 Physical and Chemical Properties of Substrate

Physical properties of substrate mixes, including container capacity, air space, total porosity, and bulk density, were

measured by using the North Carolina State University Horticultural Substrates Laboratory porometers (Fonteno et al. 1995). Chemical properties, including the pH and electrical conductivity (EC) of each substrate, were determined by the pour-through method using a pH/EC meter before transplanting and at harvest (HI 98129, Hanna Instruments, Woonsocket, RI, USA) (Wright 1986).

2.3 Determine Irrigation Threshold and Deployment of Automated Irrigation System

For three rates of biochar-amended substrates, the moisture retention curve (Fig. 1) was measured using a Hyprop (Meter Group, Pullman, WA, USA) to determine the proper VWC levels for irrigation threshold between –10 kPa and –1 kPa (O'Meara et al. 2014). Three irrigation levels (low, medium, and high) were determined based on the substrates' VWC at –5 kPa, –3.5 kPa, and –2 kPa between easily available water and water buffer capacity range. Therefore, nine treatments were created with three rates of biochar and three levels of irrigation. Low irrigation threshold at –5 kPa corresponded to 0.27, 0.32, and $0.34 \text{ m}^3 \cdot \text{m}^{-3}$ for 0, 15, and 25% biochar, respectively. Medium irrigation threshold at –3.5 kPa corresponded to 0.29, 0.35, and $0.37 \text{ m}^3 \cdot \text{m}^{-3}$ for 0, 15, and 25% biochar, respectively. High irrigation threshold at –2 kPa corresponded to 0.32, 0.4, and $0.41 \text{ m}^3 \cdot \text{m}^{-3}$ for 0, 15, and 25% biochar, respectively, as shown in Fig. 1.

Nine soil moisture sensors (CS655; Campbell Scientific, Logan, UT, USA) were connected to a datalogger (CR1000X; Campbell Scientific, Logan, UT, USA) to measure and control the VWC of 9 different irrigation treatments (Fig. 2) using a relay (SDM16AC/DC controller; Campbell Scientific, Logan, UT, USA) and 9 solenoid valves (3-valve Inline Manifold Assembly; Orbit; Salt Lake

Fig. 1 Moisture release curve for biochar (0%, 15%, and 25%, by vol.) mixes with commercial substrate. Three water matric potential –5 kPa, –3.5 kPa, and –2 kPa were indicated with red vertical lines. The low setpoint was the volumetric water content (VWC) at –5 kPa (0.27, 0.33, $0.34 \text{ cm}^3 \text{ cm}^{-3}$ for 0%, 15%, and 25% biochar amendment rate, respectively). The medium setpoint was the VWC at –3.5 kPa (0.29, 0.36, $0.37 \text{ cm}^3 \text{ cm}^{-3}$ for 0%, 15%, and 25% biochar amendment rate, respectively). The high irrigation setpoint was the VWC at –2 kPa (0.32, 0.41, $0.44 \text{ cm}^3 \text{ cm}^{-3}$ for 0%, 15%, and 25% biochar amendment rate, respectively)

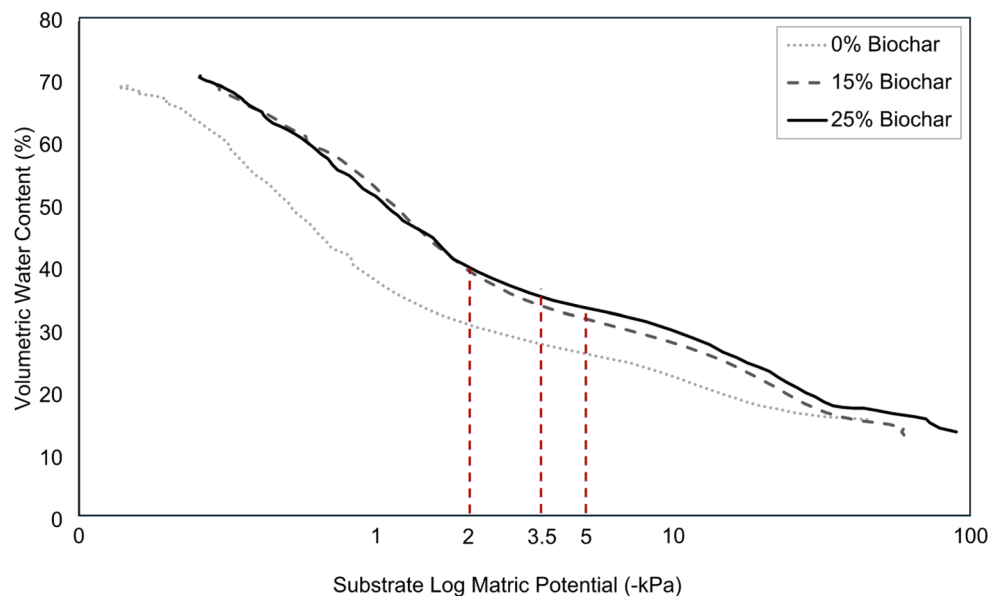
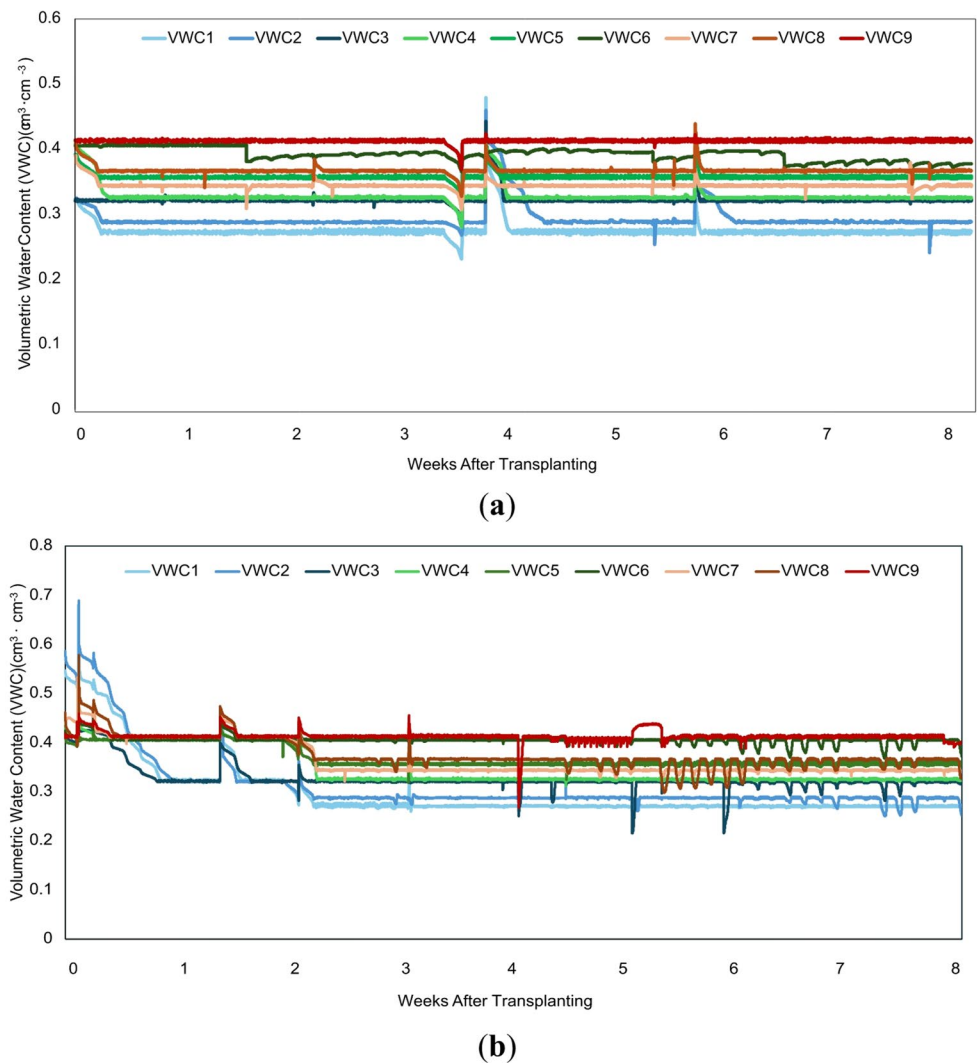


Fig. 2 Substrate volumetric water content (VWC) throughout the experiments for tomato **(a)** and kale **(b)** plants amended with three biochar rates (0%, 15%, and 25%, by vol.) and maintained at nine irrigation thresholds. This nine-substrate volumetric water content threshold was maintained from 2 weeks after transplanting (WAT) to 8 WAT. From 0 WAT to 2 WAT, each treatment was irrigated to a matric potential of -2 kPa based on their respective substrate water retention curve to ensure full plant establishment in the container



City, UT, USA). The sensors used in this study were individually calibrated for each substrate prior to the start of the experiment. Calibration curves were developed by plotting sensor output against gravimetrically determined VWC. Then VWC was calculated using substrate bulk density and gravimetric water content, which was determined as the difference between wet and dry weights divided by dry weight. This calibration procedure was repeated for nine sensors, and each sensor was calibrated specifically to the substrate used in this study. The sensors were inserted 10 cm into the substrate at the center of each pot. The VWC was read every 5 min for tomato plants and 10 min for kale plants. Once the VWC was below the set threshold, the solenoid valves opened to irrigate about 5 s (a total of 5 mL per irrigated event) of water for tomato plants and 10 s for 10 mL per irrigated event of water for kale plants. The datalogger recorded each irrigation event (Fig. S1).

2.4 Plant Growth and Water Use Efficiency

Height and two perpendicular widths were recorded biweekly. The growth index (GI) is calculated from the height and widths as $GI = \text{height}/2 + (\text{width}_1 + \text{width}_2)/4$ (Chen et al. 2024). The greenness of leaves (SPAD) was recorded with a chlorophyll meter (SPAD-502 Minolta Camera Co., Osaka, Japan) biweekly by averaging the measurements of three mature leaves per plant.

At the end of the experiment, tomato fruit numbers, fruit dry weight, and fresh weight were measured. Plant shoot and root fresh weights were measured. Shoots and root dry weights were measured after drying in the forced air oven at 80°C for 48 h (Grieve 343, Fisher Scientific, Hampton, NH, USA).

For tomato plants, the water use efficiency (WUE) of the plants was calculated using the following formula (Blum 2009). The total dry weight was calculated by adding dry

fruit, shoot and root weight together. The total volume of irrigation was recorded throughout the experiment.

$$WUE = \frac{\text{Total dry weight of plants (g)}}{\text{Total water applied (L)}}$$

For kale plants, fresh weight-based WUE was calculated using the following formula (Blum 2009). The total fresh weight was calculated by adding fresh shoot and root weight together.

$$\text{fresh weight based WUE} = \frac{\text{Total fresh weight of plants (g)}}{\text{Total water applied (L)}}$$

2.5 Physiological Measurements

Photosynthetic parameters were measured using a photosynthesis measuring system (LI-6800; Li-Cor Co., Inc., Lincoln, NE, USA). Three plants of each treatment were randomly picked to measure net photosynthesis rate ($A = \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), stomatal conductance ($g_s = \text{mol m}^{-2} \text{ s}^{-1}$), and transpiration rate ($E = \text{mmol m}^{-2} \text{ s}^{-1}$) at 6, 8, 10 WAT between 10:00 am to 2:00 pm.

At the end of the experiment, the chlorophyll fluorescence (F_v/F_m) was measured on three fully expanded leaves per plant, and three plants per treatment. Leaves were dark-acclimated for 30 min using leaf clips, after which F_v/F_m was determined using a fluorometer (OS5p+, OPTI-SCIENCES, Hudson, NH, USA).

2.6 Experimental Design and Statistical Analysis

The experiment was a randomized complete block design (RCBD) with 3 blocks. Each block contained 9 treatments with 3 replications. The treatments were randomly assigned to pots within each block. Two-way analysis of variance (ANOVA) was used to test the effects of biochar application rates and irrigation levels on substrate properties, plant growth, and development. To further evaluate the relationship between WUE for tomato, FreshWUE for kale and total volume of water applied, additional regression analysis was performed.

Data were analyzed using R (R.3.5.2, The R Foundation, Vienna, Austria), and RStudio (R 1.1.463, Boston, MA, USA). When the main effect was significant, Tukey's honestly significant difference (HSD) test was used to determine the mean comparisons among treatments ($P \leq 0.05$).

3 Results

3.1 Physical and Chemical Properties of the Substrates

Among all the different biochar-amended mixes, 0% biochar mixes (the control) had the highest percentage of coarse particles ($> 2 \text{ mm}$) at 51.17% (Table 1). Increasing the biochar rate has decreased the coarse particles that were larger than 2 mm but increased medium particle sizes that were between 0.25 and 0.5 mm, and fine particle sizes that were less than 0.25 mm. There were no significant differences in total porosity, container capacity, air space, or bulk density among all the mixes (Table 2). Water-holding capacity was numerically increased in biochar-amended substrate, with 15% being the greatest, though not significantly different from other treatments. Biochar-containing substrates had higher pH.

For tomato plants, there was a significant interaction effect between biochar rate and irrigation level on pH and EC at the end of the experiment ($P < 0.01$) (Table 3). At the medium irrigation level, the biochar effect on increasing pH was the most pronounced. The lowest pH was observed at 0% biochar rate with low/medium irrigation levels (6.90 and 6.92, respectively). The highest pH was observed at 25% biochar with a medium irrigation level (7.48). For the EC, the lowest value was observed at 15% biochar with a high irrigation level of $0.22 \text{ mS} \cdot \text{cm}^{-1}$. The highest EC was observed at 0% biochar rate with low/medium irrigation levels (0.75 and $0.76 \text{ mS} \cdot \text{cm}^{-1}$, respectively).

For kale plants, only the biochar rate had a significant effect on pH and EC ($P < 0.01$) (Table 3). The pH was significantly increased with the biochar rate, where 25% biochar resulted in the highest pH at 7.19. However, 15% and 25% of biochar reduced the EC from 0.55 to 0.29 and 0.32 $\text{mS} \cdot \text{cm}^{-1}$, respectively.

Table 2 Physical properties (total porosity, water holding capacity, air space, and bulk density) and chemical properties (pH and electrical conductivity (EC)) of 3 rates of biochar (BC, 0, 15, and 25%, by vol.) in a commercial substrate mix

Substrates	pH	EC ($\text{mS} \cdot \text{cm}^{-1}$)	Total Porosity (%)	Water-holding Capacity (%)	Air Space (%)	Bulk Density ($\text{g} \cdot \text{cm}^{-3}$)
0%BC	$6.63 \pm 0.04\text{b}^z$	1.17 ± 0.08	65.3 ± 3.2	45.5 ± 0.8	19.7 ± 3.0	0.14 ± 0.00
15%BC	$6.81 \pm 0.03\text{a}$	1.35 ± 0.08	69.0 ± 2.6	52.3 ± 5.1	16.8 ± 2.5	0.14 ± 0.01
25%BC	$6.86 \pm 0.03\text{a}$	1.20 ± 0.01	68.3 ± 1.3	49.8 ± 3.4	18.6 ± 2.7	0.13 ± 0.01

^z Means $\pm$ standard error ($n=3$) within a column followed by the same letter were not significantly different according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$

Table 3 Effect of biochar (0, 15, and 25%, by vol.) and irrigation levels (low, medium, and high) on pH and EC of tomato and kale plants at 8 weeks after transplanting

	Tomato		Kale	
	EC (mS · cm ⁻¹)		pH EC (mS · cm ⁻¹)	
Biochar (%)				
0	6.98 c ^z	0.63 a	6.84 b	0.55 a
15	7.16 b	0.39 b	6.91 b	0.29 b
25	7.34 a	0.37 b	7.19 a	0.32 b
Irrigation				
Low	7.21 a	0.54 a	7.01 a	0.42 a
Medium	7.15 a	0.47 ab	6.97 a	0.42 a
High	7.13 a	0.37 b	6.96 a	0.32 a
<i>P</i> value				
Biochar	<0.01	<0.01	<0.01	<0.01
Irrigation	0.14	0.02	0.39	0.29
Biochar × Irrigation	<0.01	<0.01	0.68	0.07

^z Means within a column, followed by the different alphabet letters, indicate significant differences according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$

3.2 Plant Growth and Development

At the end of the experiment, neither biochar nor irrigation levels significantly affected the GI or SPAD of tomato and kale (Table S1). In addition, the number of tomato fruits and the fresh and dry weight were not affected by biochar or irrigation levels either (Table 4 and S1).

In contrast, biochar rates significantly influenced the shoot fresh and dry weight, root fresh weight, and total dry weight across all three irrigation levels for tomato plants

(Table 4). At low and medium irrigation levels, an increase in biochar rates improved shoot fresh and dry weight, as well as root fresh weight (Fig. 3a–c). Specifically, tomato plants grown in 25% biochar treatments under medium irrigation treatments had the highest shoot fresh weight (71.26 g), shoot dry weight (15.10 g), and root fresh weight (17.56 g). Similarly, tomato plants grown at a 25% biochar mix under low irrigation resulted in a moderate increase in fresh weight (61.33 g), shoot dry weight (13.4 g), and root fresh weight (17.51 g). In contrast, 25% biochar mixes with high irrigation led to a reduction in shoot fresh weight (49.18 g), shoot dry weight (8.78 g), and root fresh weight (11.24 g). Under high irrigation, 0% and 15% biochar treatments produced similar shoot and root weights. Tomato plants grown with 25% biochar treatments had the highest total dry weight under low (18.45 g) and medium (20.68 g) irrigation levels (Fig. 3d). However, their total dry weight significantly decreased under high irrigation, dropping to 14.36 g (Fig. 3d).

For the kale plants, biochar and irrigation had interaction effects on shoot fresh weight (Table 5; Fig. 4a). Under low irrigation, kale plants grown in the 25% biochar rate had the highest shoot fresh weight (217 g) (Fig. 4a). Under medium irrigation, shoot fresh weight did not differ significantly among the biochar rates. Similarly, shoot fresh weights under high irrigation were comparable to those observed under medium irrigation across all biochar treatments (Fig. 4a). Although shoot dry weight, root dry weight, and total dry weight showed statistically significant differences, these results were interpreted with caution due to variation in the relationship between fresh and dry biomass. Therefore, the dry weight-derived result was considered supplementary.

For tomato plants, WUE was significantly influenced by biochar rates and irrigation levels, with different trends

Table 4 Summary of the statistical significance of biochar rates (0, 15, and 25%, by vol.) and irrigation levels (low, medium, and high) on fruit fresh weight, shoot and root fresh and dry weight (wt, g), total dry weight, and water use efficiency (WUE) at 8 weeks after transplanting for tomato plants

Factors	Fruit fresh wt (g)	Shoot fresh wt (g)	Shoot dry wt (g)	Root fresh wt (g)	Root dry wt (g)	Total dry wt (g)
Biochar Rate (%)						
0	48 ± 1.1 a ^z	47 ± 1.5 b	10 ± 0.33 b	10 ± 0.27 b	0.59 ± 0.02 a	15 ± 0.40 b
15	52 ± 1.1 a	54 ± 1.4 ab	11 ± 0.30 ab	14 ± 0.41 a	0.63 ± 0.02 a	16 ± 0.34 ab
25	50 ± 1.2 a	61 ± 1.4 a	12 ± 0.37 a	15 ± 0.45 a	0.82 ± 0.05 a	18 ± 0.42 a
Irrigation Level						
low	54 ± 0.9 a	60 ± 1.5 a	11 ± 0.38 a	14 ± 0.42 a	0.76 ± 0.02 a	17 ± 0.43 a
med	49 ± 1.2 a	54 ± 1.5 ab	11 ± 0.33 a	13 ± 0.47 a	0.70 ± 0.02 a	16 ± 0.38a
high	47 ± 1.2 a	49 ± 1.5 b	11 ± 0.33 a	13 ± 0.39 a	0.58 ± 0.05 a	16 ± 0.39a
<i>P</i> value						
Biochar	0.41	<0.01	0.01	<0.01	0.07	0.02
Irrigation	0.17	0.02	0.55	0.48	0.23	0.36
Biochar × Irrigation	0.41	<0.01	<0.01	<0.01	0.90	<0.01

^z Means within a column, followed by the different alphabet letters, indicate significant differences according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$

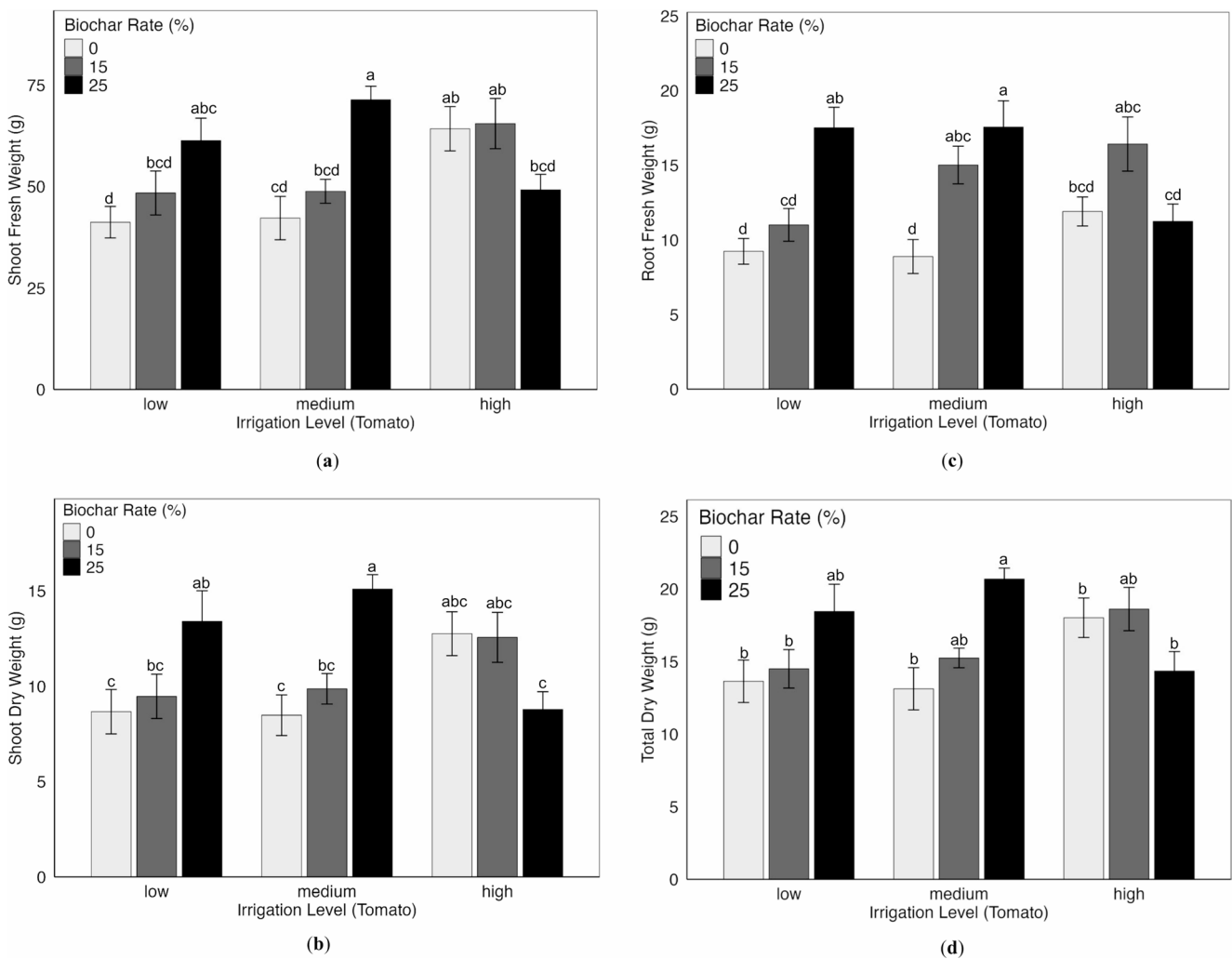


Fig. 3 The effect of biochar rate (0, 15, and 25%, by vol.) and irrigation level (low, medium, and high) on (a) shoot fresh weight, (b) shoot dry weight, (c) root fresh weight, and (d) total dry weight of tomato plants (mean $\pm$ standard error) at 8 weeks after transplanting (WAT) respec-

tively. Means indicated by different alphabet letters are significantly different according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$

Table 5 Summary of the statistical significance of biochar rates (0, 15, and 25%, by vol.) and irrigation levels (low, medium, and high) on shoot and root fresh weight (wt, g) at 8 weeks after transplanting (WAT) for kale plants

Factors	Shoot fresh wt (g)	Root fresh wt (g)
Biochar Rate (%)		
0	181 $\pm$ 3.95 a ^z	30 $\pm$ 0.89 a
15	196 $\pm$ 2.22 a	31 $\pm$ 0.55 a
25	197 $\pm$ 3.09 a	33 $\pm$ 1.1a
Irrigation Level		
Low	195 $\pm$ 3.90 a	36 $\pm$ 0.73 a
Medium	192 $\pm$ 2.68 a	31 $\pm$ 0.55 ab
High	186 $\pm$ 2.90 a	27 $\pm$ 0.73 b
P value		
Biochar	0.14	0.57
Irrigation	0.53	<0.01
Biochar $\times$ Irrigation	<0.01	0.25

observed across treatments. Under low irrigation, the irrigation events increased from 716 (0% biochar) to 957 (15%) and 1928 (25%, Table 6). This corresponded to an increase in irrigation volume by 33.80% and 169.27% as biochar rates increased from 0% to 15% and 25%, respectively. Therefore, 0% biochar treatments used the water most efficiently under low irrigation levels ($3.81 \text{ g} \cdot \text{L}^{-1}$, Fig. 5a). Moderate WUE was found at 15% biochar under low irrigation ($3.03 \text{ g} \cdot \text{L}^{-1}$, Fig. 5a). Under the medium irrigation level, the total irrigated events had increased from 1005 (0% biochar) to 1122 (15% biochar) and 1659 (25% biochar), representing 11.64% and 65.07% increase in irrigation volume as biochar rate increased from 0% to 15% and 25%, respectively (Table 6). However, no significant difference in WUE was observed among biochar rates under medium irrigation. Under high irrigation, 15% biochar treatments were not shown due to mechanical issues. The

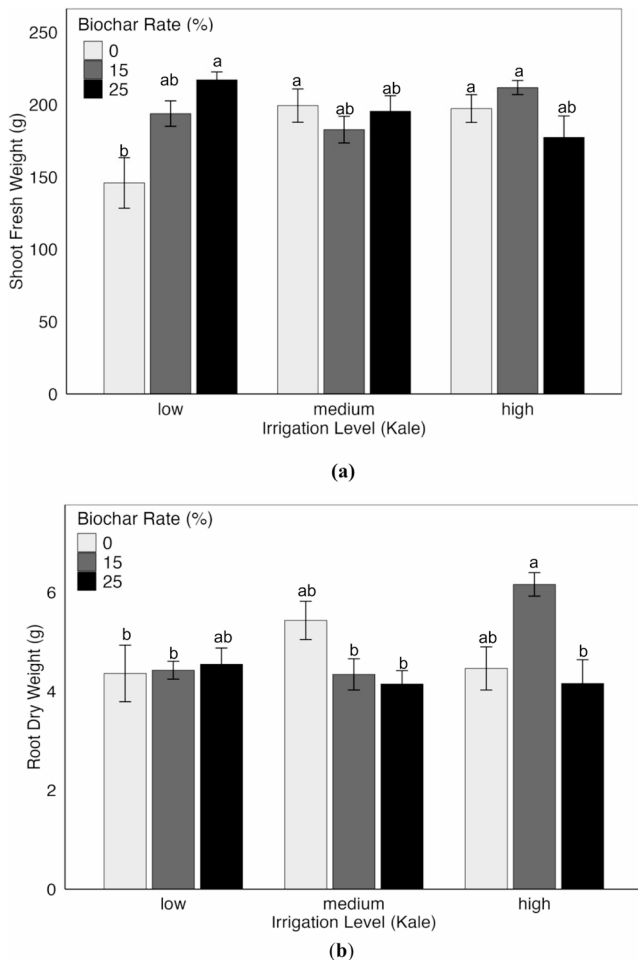


Fig. 4 The effect of biochar rate (0, 15, and 25%, by vol.) and irrigation level (low, medium, and high) on (a) shoot fresh weight, (b) root fresh weight (mean $\pm$ standard error) of kale at 8 weeks after transplanting (WAT) respectively. Means indicated by different alphabet letters are significantly different according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$

25% biochar treatments had the lowest irrigation volume at 4.41 L (Table 6). The WUE of 0% and 25% biochar treatments were statistically similar at $3.11 \text{ g} \cdot \text{L}^{-1}$ and $3.26 \text{ g} \cdot \text{L}^{-1}$, respectively (Fig. 5a).

For kale plants, biochar rates and irrigation levels interactively affected irrigation volume, and frequency, and ultimately influenced fresh weight based-WUE (Table 6; Fig. 5b). Under low irrigation, the total irrigation events increased from 1491 (0% biochar) to 1765 (15% biochar) and 1828 (25% biochar). This irrigation event corresponded to 18.28% and 22.6% higher irrigated volume for the 15% and 25% biochar treatments, respectively, compared to 0% biochar. Interestingly, 25% biochar treatments resulted in the highest fresh weight-based WUE under low irrigation, at $13.7 \text{ g} \cdot \text{L}^{-1}$ (Fig. 5b). Under medium irrigation, total irrigated volumes varied considerably across treatments: 20.55 L (0% biochar), 11.93 L (15% biochar), and 27.91 L

(25% biochar). The 15% biochar treatments had the most efficient water usage at $17.8 \text{ g} \cdot \text{L}^{-1}$. Under high irrigation, the total irrigation volumes were 19.07 L (0% biochar), 24.35 L (15% biochar), and 17.90 L (25% biochar). Fresh weight based-WUE was not significantly different between 0% and 25% biochar treatment, while 15% biochar was lower than both (Fig. 5b).

For both tomato and kale plants, the WUE declined as total water application increased. In tomato, the relationship was described as a power function: $\text{WUE} = 7.2$

$\times (\text{total water applied})^{-0.564}$ (Fig. 6a) with $R^2 = 0.255$ and $P < 0.01$, indicating the total volume of water explained 25.5% of variation in WUE. In kale, the relationship was also described as a power function: $\text{FreshWUE} = 86.9$

$\times (\text{total water applied})^{-0.684}$ (Fig. 6b), with $R^2 = 0.382$ and $P < 0.01$, indicating total volume of water explained 38.2% of variation in FreshWUE.

3.3 Plant Physiological Responses

For both tomato and kale plants, all the treatments had similar photosynthesis rates, transpiration rates, and stomatal conductance rates at 4, 6, and 8 WAT regardless of biochar rates and irrigation levels (Tables S2 and S3). At 8 WAT, biochar had significant effects on maximum fluorescence for tomato plants (Table S2). Specifically, the 25% biochar treatments had the significantly highest maximum fluorescence at 0.83, and 0% biochar treatments showed a moderate photosynthetic efficiency at 0.82. The biochar rate at 15% showed the lowest maximum fluorescence at 0.80 (Fig. 7).

4 Discussion

Addition of biochar influences both physical and chemical properties in soilless substrates, which in turn affects plant growth. Amending biochar in the substrates could result in a higher pH due to its liming effects from high ash content during pyrolysis (Tomczyk et al. 2020). This neutral to alkaline substrate provided an optimal growing condition for Brassicaceae family plants (kale, optimal pH 6.0 to 7.5), yet not optimal pH for growing tomato plants (optimal pH 6.2 to 6.8) (Westerfield 2021; Schuh 2022).

Biochar effects on water-holding capacity varies depending on biochar pyrolysis temperature, particle sizes, rates, and feedstock materials (Huang and Gu 2019). This study observed an increase in water-holding capacity (though not significantly) with an increasing biochar rate from 0% to 25% (Table 2; Fig. 1). The pyrolysis process breaks biochar

Table 6 The total irrigated volume, irrigation events, and water use efficiency (WUE) of tomato and fresh weight-based WUE of kale plants under three rates of biochar (0, 15, and 25%, by vol.) and three levels of irrigation (low, medium, and high). The total irrigated volume and irrigation events were recorded starting from 2 weeks after transplanting

Biochar (%)	Irrigation levels	Tomato			Kale		
		Total irrigated volume per container (L)	Total irrigation events	WUE (g·L ⁻¹)	Total irrigated volume (L)	Total irrigation events	Fresh WUE (g·L ⁻¹)
0	Low	3.58	716	3.8 a ^z	14.91	1491	11.3 bcd
	Medium	5.03	1005	2.6 bc	20.55	2055	11.3 bcd
	High	5.79	1158	3.1 ab	19.07	1907	12.2 bc
15	Low	4.79	957	3.0 ab	17.65	1765	12.5bc
	Medium	5.61	1122	2.7 bc	11.93	1193	17.8a
	High	- ^x	-	-	24.35	2435	10.2 cd
25	Low	9.64	1928	1.9 c	18.28	1828	13.7b
	Medium	8.30	1659	2.5 bc	27.91	2791	8.5d
	High	4.41	881	3.3 ab	17.9	1790	11.9 bc
<i>P</i> value							
Biochar		- ^y	-	<0.01	-	-	<0.01
Irrigation		-	-	<0.01	-	-	0.078
Biochar × Irrigation		-	-	<0.01	-	-	<0.01

^x Data was not shown due to mechanical issues^z Means within a column, followed by the different alphabet letters, indicate significant differences according to Tukey–Kramer's Honestly Significant Difference (HSD) test at $P \leq 0.05$ ^y ANOVA was not performed since only one soil moisture sensor for each treatment, Biochar × Irrigation, was used

into different sizes of particles and generates pore spaces, which could improve water-holding capacity when it is amended with substrates mixes (Jaafar et al. 2015; Leng et al. 2021 b; Weber and Quicker 2018). A study found that 50% deinking sludge biochar (by volume, pyrolyzed under 300 °C) in brown peat-based substrates improved water-holding capacity, compared with 100% peat substrates (Méndez et al. 2015). Similarly, increasing switchgrass biochar (pyrolyzed at 1000 °C) rates from 0% to 10 to 25% (by volume) increased the water holding capacity of pine bark-based substrate significantly (Jahromi et al. 2018). However, hardwood biochar pyrolyzed at 1000 °C showed no significant differences in water holding capacity when incorporated at 20% or 40% (by volume) biochar into a commercial substrate mix consisting of 55% aged pine bark and 45% Canadian sphagnum peat moss, perlite, and vermiculite. Moreover, incorporation of 60% biochar (by volume) significantly reduced water holding capacity compared to the 100% commercial substrate (Chen et al. 2024).

This increase in water-holding capacity corresponds to an enhancement in plant-available water. The moisture release curve of 15% and 25% biochar substrates had higher volumetric water content than 0% biochar between −1 kPa and −10 kPa, indicating that biochar amended substrate provided higher plant-available water (Fig. 1). This result was consistent with findings by Kafle (2024), who found that the incorporation of biochar and compost (12.5% biochar+12.5%

hemp compost, and 25% biochar+25% hemp compost, v/v) into soilless substrates enhanced water retention compared to the control medium composed of peat: perlite: vermiculite (50:25:25, v/v)(Kafle et al. 2024). Additionally, 25% switchgrass biochar (pyrolyzed at 100 °C) held more water at lower tension (−1 kPa) but held less water at higher tension (−10 kPa), compared with 100% pine bark-based substrates (Basiri Jahromi et al. 2020), shared similar results with our study.

Although substrate-specific calibration of the soil moisture sensors was performed in this study, the sensor-controlled irrigation system didn't work consistently. As a result, irrigation frequency and total applied water did not follow the expected treatment pattern, which limited our ability to interpret the system as a fully demand-driven irrigation approach. In addition, only one substrate moisture sensor was used per treatment, resulting in a less accurate reading of VWC of each replicate due to the variability of moisture in each individual container. Furthermore, the unusual low total irrigation volume observed in 25% biochar treatment under high irrigation may be due to a non-linear calibration curve in biochar-amended substrate, resulting sensor's reading consistently higher than the actual VWC, causing a lower total irrigation volume (Gómez-Astorga et al. 2024). Future calibration should enable the collection of more data points at higher volumetric water contents for the biochar-amended substrate calibration curve (Gómez-Astorga et al.

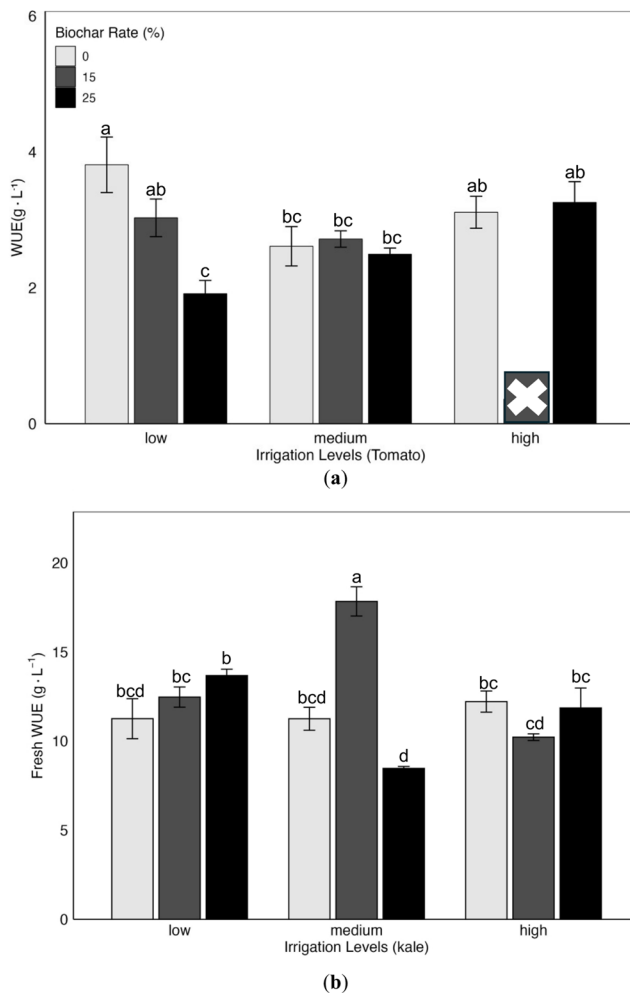


Fig. 5 The effect of biochar rates (0, 15, and 25%, by vol.) and irrigation levels (low, medium, and high) on water use efficiency (WUE) (mean ± standard error) of tomato (a) and fresh weight based-WUE of kale (b) plants at 8 weeks after transplanting (WAT), respectively. Treatments with 25% biochar under high irrigation data of tomato plants were not shown due to mechanical issues. Means indicated by different alphabet letters are significantly different according to Tukey–Kramer’s Honestly Significant Difference (HSD) test at $P \leq 0.05$

2024; Rasheed et al. 2022). Therefore, water application and WUE results should be interpreted cautiously, and fresh weight-based WUE of kale plants in this study should be viewed as a practical productivity indicator rather than a precise demand-driven water use efficiency metric.

Because the fresh weight to dry weight ratio of kale varied disproportionately across treatments, dry weight measurements were considered less reliable for interpreting kale productivity. Although total dry weight is commonly used to calculate water use efficiency, fresh weight was used as the primary yield indicator for kale, as it represents the economically relevant product. Based on fresh weight, WUE suggested that biochar may improve productivity under low irrigation for kale. However, these benefits

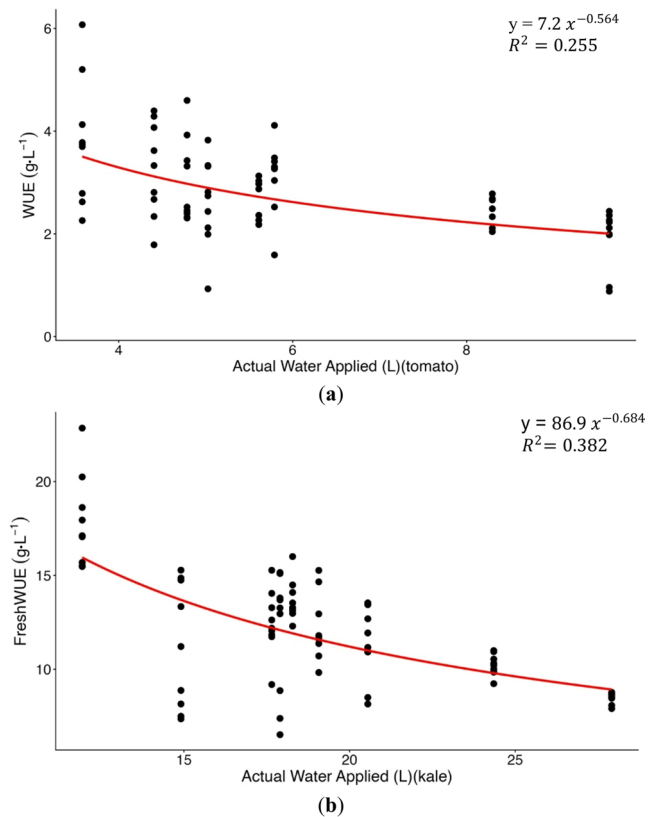


Fig. 6 The relationship between water use efficiency (WUE) and actual water applied in tomato (a) and kale (b) plants at 8 weeks after transplanting (WAT), respectively. Water use efficiency was calculated on a dry-weight basis for tomato (WUE) and on a fresh-weight basis for kale (FreshWUE)

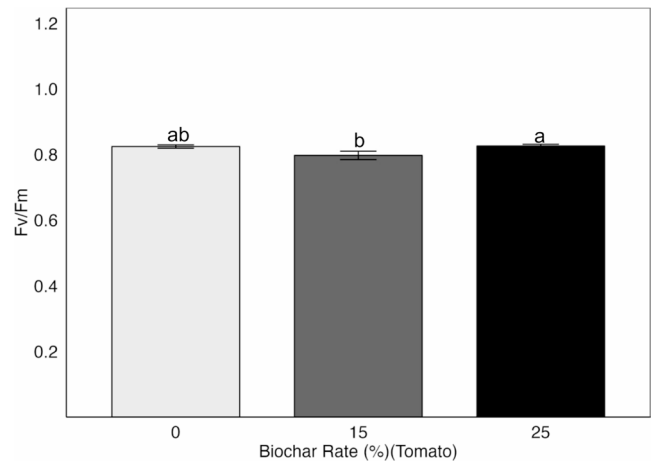


Fig. 7 The effects of biochar rates (0, 15, and 25%, by vol.) on the maximum fluorescence (Fv/Fm)(mean ± standard error) of tomato plants at 8 weeks after transplanting (WAT). Means indicated by different alphabet letters are significantly different according to Tukey–Kramer’s Honestly Significant Difference (HSD) test at $P \leq 0.05$

were limited under sufficient water conditions, likely due to biochar-induced changes in substrate hydraulic properties and water dynamics (Liu et al. 2017). Under high irrigation, substrates were maintained in a relatively wet state, with biochar-amended substrates exhibiting consistently higher volumetric water content. These wetter conditions may have reduced substrate aeration by limiting air-filled porosity, thereby diminishing the positive effects of biochar on plant growth (Liu et al. 2017).

The biomass response to biochar may also have been partially associated with the higher VWC setpoints to biochar-amended substrate, which triggered more frequent irrigation events (Table 6). For example, under medium irrigation, the 25% biochar treatment (VWC setpoint at $0.367 \text{ cm}^3 \cdot \text{cm}^{-3}$) had 65.07% more irrigation events and volume compared to the 0% biochar treatment (VWC setpoint at $0.287 \text{ cm}^3 \cdot \text{cm}^{-3}$), despite both substrates being maintained at the same matric potential (at -3.5 kPa). This interpretation may also help explain why previous studies have reported inconsistent biomass responses to biochar. For instance, green velvet boxwood (*Buxus sempervirens* L. $\times$ *Buxus microphylla*) biomass was not significantly affected by switchgrass (*Panicum virgatum* L.) biochar rates at 10 or 25% (by vol.) in pine bark-based substrate (Jahromi et al. 2018). Conversely, hydrangea (*Hydrangea paniculata*) total dry weight was reduced by 50% as the biochar rate increased from 0% (56.4 g) to 25% (27.8 g) in a pine-bark-based substrate (Jahromi et al. 2018). In that study, VWC of both 0% and 25% biochar-amended pine bark substrates was maintained at $0.25 \text{ m}^3 \cdot \text{m}^{-3}$. Fewer irrigation events were triggered in 25% biochar treatments due to higher water content in the biochar-amended substrate. However, biochar tends to hold water in higher tension, reducing plant-available water. In contrast, our study determined the irrigation threshold based on specific substrate matric potential which ensures the same water availability across the same irrigation level. Biochar can also improve plant biomass. For instance, the total dry weight of chestnut-leaved oak (*Quercus castaneifolia*) seedlings decreased as substrate field capacity declined from 100% to 70% and 40%. In contrast, dry weight increased as increasing hornbeam (*Carpinus betulus* L.) wood chip biochar (pyrolyzed between 450°C and 500°C) from 10 to 20 and $30 \text{ g} \cdot \text{kg}^{-1}$ soil (Zoghi et al. 2019).

The study observed species-specific differences in WUE, which may be driven by biochar-induced changes in water availability. In present study, tomato showed lower WUE in biochar-amended substrates relative to the control, whereas kale showed higher fresh weight-based WUE with biochar amendment. This difference may be related to the greater responsiveness of kale biomass to increased substrate water content compared with tomato. Biochar-amended substrates exhibited greater water-holding capacity and higher VWC

at the same matric potential than the non-amended substrate, which likely contributed to enhanced kale growth under low irrigation. Similarly, Barickman et al. (2020) reported that amending 15% and 25% biochar increased WUE of kale by 111.76% and 57.22%, respectively, compared to the control. Notably, the 15% biochar rate under medium irrigation was the highest WUE. In addition, Fidler and Gomez (2025) reported that increasing VWC from 0.15 to $0.33 \text{ m}^3 \cdot \text{m}^{-3}$ increased tomato shoot dry weight by 6.78%, but enhanced kale shoots dry weight by 16.66% (Barickman et al. 2020; Fidler and Gomez 2025). Similar species-dependent responses to biochar have been reported in other crops. For instance, 0% coniferous wood biochar substrate had the highest WUE for two cultivars of lavender (*L. angustifolia*) and (*L. dentata*) compared to biochar amended mixes at 25%, 50% or 75% at the same substrate matric potential (Fascella et al. 2020). Conversely, hydrangea (*Hydrangea paniculata*), a heavy water user like kale, 25% biochar (switchgrass pyrolyzed at 1000°C) had significantly higher WUE than 0% biochar treatment (Jahromi et al. 2018).

To further explore the relationship between WUE and total water application, regression analysis was performed. The result showed an inverse relationship between WUE and total water input, with exponent values of -0.564 and -0.684 for tomato and kale, respectively. This indicated that WUE declined as total water applied increased, suggesting diminishing effects at higher water inputs for both plants. This pattern has been widely reported, where biomass production is proportional to transpiration under water-limited condition but becomes less responsive when water supply exceeds plant demand (Steduto et al. 2007). Consequently, additional irrigation did not result in proportional increase in biomass, leading to reduced efficiency (Feres and Soriano 2007). In addition, the exponent value for both plants was greater than -1 , indicating not all the water was wasted. Instead, part of water applied was likely contributed to support physiological processes such as adjusting leaf temperature, stomatal conductance (Jones 2004a).

The chlorophyll content (indicated by SPAD value) was unaffected by either biochar or irrigation level for both tomato and kale plants. This suggests that foliar nutrients were likely unaffected by biochar and irrigation. For instance, Jahromi et al. (2018) reported foliar concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium were not significantly different between the 0% and 25% biochar treatments, and no significant effect of hardwood biochar (0% or 25%) on SPAD values in ‘Silver Dollar’ hydrangea (*Hydrangea paniculata*) grown in a pine bark-based substrate. In another study, Fascella et al. (2020) found no statistical difference in plant height or SPAD readings between 0% and 25% coniferous wood biochar in a

peat-based substrate for two lavender species (*Lavandula angustifolia* and *L. dentata*) 90 days after transplanting.

Physiological performance of kale and tomato plants was not affected by biochar rates, with the exception that 25% biochar improved the chlorophyll fluorescence of tomato plants. Plants perform differently in physiological performance due to differences in biochar particle sizes, biochar application rates, feedstock materials, pyrolysis conditions, and plant species (Chrysargyris et al. 2020). For instance, Chrysargyris et al. (2020) noted increased chlorophyll fluorescence in lettuce (*Lactuca sativa* L. var. Nogal) grown in a 7.5% forest-wood biochar substrate (pyrolyzed at 700 °C), compared to pure peat. Conversely, lettuce grown in 7.5% fresh wood screenings biochar (particle size 0–20 mm, pyrolyzed between 500 and 600 °C) exhibited significantly lower chlorophyll fluorescence than the control. Similar results were reported by Liu et al. (2022), who found significantly higher chlorophyll fluorescence in tomato (*Solanum lycopersicum* L.) grown in soil amended with 3% maize straw biochar compared to a control (100% soil) (Liu et al. 2022). This increase was accompanied by an enhancement in photosynthesis and stomatal conductance rates.

Physiological performance of kale and tomato plants was not affected by irrigation thresholds. Under lower water level conditions, plants reduce stomatal conductance rate, thereby limiting photosynthesis and transpiration rate (Zhou et al. 2013). In this study, the irrigated VWC threshold was set within easily available water potential (between −1 kPa and −5 kPa), which may not impose severe stress to trigger stomatal closure response (Zhou et al. 2013). This result was similar to Currey et al. (2019), who reported that the photosynthesis, transpiration, and stomatal conductance rate of parsley grown in 75% sphagnum peat moss and 25% perlite were not significantly influenced by increasing VWC from 0.15 to 0.45 m³·m^{−3} (Currey et al. 2019). This increase in VWC didn't affect the Fv/Fm or gas exchange of sage and basil either but has increased Fv/Fm of parsley from 0.82 to 0.84 (Currey et al. 2019). Additionally, lowering VWC from 0.45, 0.39, and 0.32 m³·m^{−3} did not affect the Fv/Fm values of hebe (*Hebe andersonii*) grown in peat, coconut fiber, and perlite mixes (Bañón et al. 2022).

5 Conclusion

Both tomato and kale plants exhibited species-specific growth and water use responses to biochar-amended substrates under lower water level conditions (at −5 kPa), indicating that the hypothesis of this study was partially supported. The reduced water use efficiency (WUE) in tomato suggested that biochar amendment is not a universally effective strategy. In contrast, the enhanced fresh

weight based-water use efficiency and yield of kale grown in biochar-amended substrate and medium irrigation level suggested biochar can be an effective growing amendment for high water-consuming crops under moderate deficit irrigation. This research demonstrated that biochar can partially replace peat in soilless substrates without reducing crop productivity and may provide greater benefit for water-demanding crops under limited irrigation, supporting its potential as more sustainable substrate amendment in nursery production. More studies are needed to investigate biochar effects at different rates and different types, which have a strong influence on substrate hydraulic properties, using sensor-based irrigation systems under deficit irrigation conditions.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42729-026-03320-7>.

Author contributions Conceptualization, P.Y., L.C.; methodology, P.Y., K.Q., and L.C.; software, L.C. and K.Q.; validation, L.C. and K.Q.; formal analysis, L.C.; investigation, L.C. and Y.C.; resources, P.Y.; data curation L.C.; writing—original draft preparation, L.C.; writing—review and editing, L.C. K.Q. and P.Y.; visualization, L.C.; supervision, P.Y.; project administration, L.C. and P.Y.

Funding This research received no external funding.

Data Availability The data can be made available on reasonable request.

Declarations

Competing Interests Authors declare no competing interests that are directly or indirectly related to the work submitted for publication.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Atkinson CJ (2018) How good is the evidence that soil-applied biochar improves water-holding capacity? *Soil Use Manag* 34:177–186. <https://doi.org/10.1111/SUM.12413>
- Bañón D, Lorente B, Bañón S et al (2022) Control of substrate water availability using soil sensors and effects of water deficit on the

- morphology and physiology of potted *Hebe andersonii*. *Agronomy* 12:206. <https://doi.org/10.3390/agronomy12010206>
- Barickman TC, Ku KM, Sams CE (2020) Differing precision irrigation thresholds for kale (*Brassica oleracea* L. var. acephala) induces changes in physiological performance, metabolites, and yield. *Environ Exp Bot* 180:104253. <https://doi.org/10.1016/j.envexpbot.2020.104253>
- Basiri Jahromi N, Fulcher A, Walker F, Altland J (2020) Photosynthesis, growth, and water use of *Hydrangea paniculata* ‘Silver Dollar’ using a physiological-based or a substrate physical properties-based irrigation schedule and a biochar substrate amendment. *Irrig Sci* 38:263–274. <https://doi.org/10.1007/s00271-020-00670-7>
- Belayneh BE, Lea-Cox JD, Lichtenberg E (2013) Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. *Horttechnology* 23:760–769. <https://doi.org/10.21273/HORTTECH.23.6.760>
- Blum A (2009) Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Res* 112:119–123. <https://doi.org/10.1016/j.fcr.2009.03.009>
- Chen L, Rycyna J, Yu P (2024) Investigating the effect of hydrafiber and biochar as a substitute for peat-based substrate for zinnia (*Zinnia elegans*) and snapdragon (*Antirrhinum majus*) production. *Horticulturae* 10:589. <https://doi.org/10.3390/horticulturae10060589>
- Chrysargyris A, Prasad M, Kavanagh A, Tzortzakakis N (2020) Biochar type, ratio, and nutrient levels in growing media affects seedling production and plant performance. *Agronomy* 10:1421. <https://doi.org/10.3390/agronomy10091421>
- Cifre J, Bota J, Escalona JM et al (2005) Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.): An open gate to improve water-use efficiency? *Agric Ecosyst Environ* 106:159–170. <https://doi.org/10.1016/j.agee.2004.10.005>
- Currey CJ, Flax NJ, Litvin AG, Metz VC (2019) Substrate volumetric water content controls growth and development of containerized culinary herbs. *Agronomy* 9:667. <https://doi.org/10.3390/agronomy9110667>
- Demirbaş A, Arin G (2002) An overview of biomass pyrolysis. *Energy Sources* 24:471–482. <https://doi.org/10.1080/00908310252889979>
- Fascella G, Mammano MM, D’Angiolillo F et al (2020) Coniferous wood biochar as substrate component of two containerized lavender species: effects on morpho-physiological traits and nutrients partitioning. *Sci Hortic* 267:109356. <https://doi.org/10.1016/j.scienta.2020.109356>
- Fereres E, Soriano MA (2007) Deficit irrigation for reducing agricultural water use. *J Exp Bot* 58:147–159. <https://doi.org/10.1093/JXB/ERL165>
- Ferreira CSS, Soares PR, Guilherme R et al (2024) Sustainable water management in horticulture: problems, premises, and promises. *Horticulturae* 10:951. <https://doi.org/10.3390/horticulturae10090951>
- Fidler M, Gomez C (2025) Evaluating the effect of fertilization and substrate volumetric water content on compact tomato and pepper plants. *HortTechnology* 35:39–51. <https://doi.org/10.21273/HORTTECH05529-24>
- Fonteno W, Hardin C, Brewster J (1995) Procedures for determining physical properties of horticultural substrates using the NCSU porometer; horticultural substrates laboratory, North Carolina State University: Raleigh, NC, USA,
- Food and Agriculture Organization of the United Nations (2017) Water for Sustainable Food and Agriculture. FAO
- Fukumori Y, Takeuchi H, Ando Y (2018) Structural Control of Nanoparticles. *Nanoparticle Technology Handbook*. Elsevier, pp 49–107
- Gómez-Astorga MJ, Villagra-Mendoza K, Masís-Meléndez F et al (2024) Calibration of low-cost moisture sensors in a biochar-amended sandy loam soil with different salinity levels. *Sensors (Basel)* 24:5958. <https://doi.org/10.3390/s24185958>
- Huang L, Gu M (2019) Effects of biochar on container substrate properties and growth of plants—a review. *Horticulturae* 5(1):14. <https://doi.org/10.3390/HORTICULTURAE5010014>
- Jaafar NM, Clode PL, Abbott LK (2015) Soil microbial responses to biochars varying in particle size, surface and pore properties. *Pedosphere* 25:770–780. [https://doi.org/10.1016/S1002-0160\(15\)30058-8](https://doi.org/10.1016/S1002-0160(15)30058-8)
- Jahromi NB, Walker F, Fulcher A et al (2018) Growth response, mineral nutrition, and water utilization of container-grown woody ornamentals grown in biochar-amended pine bark. *HortScience* 53:347–353. <https://doi.org/10.21273/HORTSCI12643-17>
- Jones H (2004a) Water Use Efficiency in Plant Biology. BlackWell Publishing Ltd, 550 Swanston Street, Carlton, Victoria 3053, Australia, ISBN: 0-8493-2354-1, Chapter 5, page 113–115
- Jones HG (2004b) Irrigation scheduling: advantages and pitfalls of plant-based methods. *J Exp Bot* 55:2427–2436. <https://doi.org/10.1093/JXB/ERH213>
- Kafle A, Singh S, Singh M et al (2024) Effect of biochar-compost amendment on soilless media properties and cucumber seedling establishment. *Technology in Horticulture* 4:0–0. <https://doi.org/10.48130/tihort-0023-0029>
- Lamichhane B, Dunn BL, Singh H et al (2024) Determining Eastern Red Cedar biochar soilless-media supplementation rates for potted geranium and petunia production. *Horticulturae* 10:467. <https://doi.org/10.3390/horticulturae10050467>
- Leng L, Xiong Q, Yang L et al (2021) An overview on engineering the surface area and porosity of biochar. *Sci Total Environ* 763:144204. <https://doi.org/10.1016/J.SCITOTENV.2020.144204>
- Lichtenberg E, Majsztrik J, Saavoss M (2013) Profitability of sensor-based irrigation in greenhouse and nursery crops. *HortTechnology* 23:770–774. <https://doi.org/10.21273/horttech.23.6.770>
- Liu Z, Dugan B, Masiello CA, Gonnermann HM (2017) Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS One* 12:e0179079. <https://doi.org/10.1371/journal.pone.0179079>
- Liu X, Zhang J, Wang Q et al (2022) Improvement of photosynthesis by biochar and vermicompost to enhance tomato (*Solanum lycopersicum* L.) yield under greenhouse conditions. *Plants Basel* 11:3214. <https://doi.org/10.3390/plants11233214>
- McCarter CPR, Wilkinson SL, Moore PA, Waddington JM (2021) Ecophysiological trade-offs from multiple peatland disturbances: the interactive effects of drainage, harvesting, restoration and wildfire in a southern Ontario bog. *J Hydrol (Amst)* 601:126793. <https://doi.org/10.1016/j.jhydrol.2021.126793>
- Méndez A, Paz-Ferreiro J, Gil E, Gascó G (2015) The effect of paper sludge and biochar addition on brown peat and coir based growing media properties. *Sci Hortic* 193:225–230. <https://doi.org/10.1016/j.scienta.2015.07.032>
- Montesano FF, Van Iersel MW, Parente A (2016) Timer versus moisture sensor-based irrigation control of soilless lettuce: effects on yield, quality and water use efficiency. *Hortic Sci* 43:67–75. <https://doi.org/10.17221/312/2014-HORTSCI>
- Munoth P, Tiwari K, Goyal R, Scholar PD (2016) Sensor based Irrigation System: A Review. *International Journal of Engineering Research & Technology (IJERT)*, NCACE-2016 conference proceedings, 4 (23):86–90. https://scholar.googleusercontent.com/scholar?q=cache:Cznox41cMsJ:scholar.google.com/+Sensor+based+Irrigation+System:+A+Review,+International+Journal+of+Engineering+Research+%26+Technology+&hl=en&as_sdt=0,11
- O’Meara L, Chappell MR, van Iersel MW (2014) Water use of *Hydrangea macrophylla* and *Gardenia jasminoides* in response

- to a gradually drying substrate. *HortScience* 49:493–498. <https://doi.org/10.21273/HORTSCI.49.4.493>
- Page SE, Siegert F, Rieley JO et al (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420(6911):61–65. <https://doi.org/10.1038/nature01131>
- Page SE, Rieley JO, Banks CJ (2011) Global and regional importance of the tropical peatland carbon pool. *Glob Chang Biol* 17:798–818. <https://doi.org/10.1111/J.1365-2486.2010.02279.X>
- Rasheed MW, Tang J, Sarwar A et al (2022) Soil moisture measuring techniques and factors affecting the moisture dynamics: a comprehensive review. *Sustainability* 14(18):11538. <https://doi.org/10.3390/su141811538>
- Schuh M (2022) Growing collards and kale in home gardens. Univ Minn Ext, <https://extension.umn.edu/vegetables/growing-collards-and-kale>
- Sradnick A, Werner M, Körner O (2023) Make a choice: a rapid strategy for minimizing peat in horticultural press pots substrates using a constrained mixture design and surface response approach. *PLoS One*. <https://doi.org/10.1371/JOURNAL.PONE.0289320>
- Steduto P, Hsiao TC, Fereres E (2007) On the conservative behavior of biomass water productivity. *Irrig Sci* 25(3):189–207. <https://doi.org/10.1007/S00271-007-0064-1>
- Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Rev Environ Sci Biotechnol* 19:191–215. <https://doi.org/10.1007/S1157-020-09523-3/TABLES/3>
- Weber K, Quicker P (2018) Properties of biochar. *Fuel* 217:240–261. <https://doi.org/10.1016/j.fuel.2017.12.054>
- Westerfield RR (2021) B1721, Georgia Homegrown Tomatoes. <https://fieldreport.caes.uga.edu/publications/B1721/georgia-homegrown-tomatoes/>
- Wright RD (1986) The pour-through nutrient extraction procedure. *HortScience* 21:227–229. <https://doi.org/10.21273/hortsci.21.2.227>
- Yu P, Qin K, Niu G, Gu M (2023) Alleviate environmental concerns with biochar as a container substrate: a review. *Front Plant Sci* 14:1176646. <https://doi.org/10.3389/FPLS.2023.1176646/BIBTEX>
- Zhou S, Duursma RA, Medlyn BE et al (2013) How should we model plant responses to drought? An analysis of stomatal and non-stomatal responses to water stress. *Agric For Meteorol* 182–183:204–214. <https://doi.org/10.1016/j.agrformet.2013.05.009>
- Zoghi Z, Hosseini SM, Kouchaksaraei MT et al (2019) The effect of biochar amendment on the growth, morphology and physiology of *Quercus castaneifolia* seedlings under water-deficit stress. *Eur J For Res* 138:967–979. <https://doi.org/10.1007/s10342-019-01217-y>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.