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Compost Amendment Enhances Leaf Gas Exchange, Growth, and Yield in Water-challenged 'Crimson Giant' Red Radish (*Raphanus sativus* L.)

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***Abstract.* Red radish is a nutritious root vegetable crop that has a short production cycle. Water deficit limits plant productivity, affecting its quantity and quality. Compost amendment offers a potential solution to mitigate water deficit effects. This study assessed the impact of compost manure rates (0%, 50%, 75%, and 100%) and irrigation treatments (40%, 60%, 80%, and 100% of evapotranspiration) on 'Crimson Giant' red radish production. Significant differences in growth and quality were observed among these treatments. Compost rates of 75% and 100% improved leaf gas exchange, plant growth (leaf count, fresh weight, dry weight, and area; stem length), root development, total yield (root fresh weight, dry weight, diameter, and length), and root quality (vitamin C and total soluble solid and titratable acidity). The 100% compost and 100% irrigation combination achieved the highest yields. Under water deficit, applying 75% or 100% compost with 80% irrigation conserved 20% of water while maintaining radish output. Overall, compost amendment effectively enhanced red radish growth and production under water deficit.**

The root vegetable red radish (*Raphanus sativus* L.), belonging to the family Brassicaceae, is globally cultivated owing to its high nutritional content and distinctive pungent flavor. Red radish storage roots contain abundant phenolic and antioxidant chemicals (Li et al. 2022) known for their anticancer and anti-inflammatory properties in humans (Li et al. 2022; Wang et al. 2010). Its short production cycle and excellent sink capacity make red radish an ideal model for studying biomass allocation patterns under stress (Henschel et al. 2022; Stagnari et al. 2018). Water availability significantly influences radish biomass, as water stress prompts modifications in source–sink interactions and reduced leaf development, posing a significant challenge for growers (Abdalla et al. 1992; Henschel et al. 2022; Stagnari et al. 2018). Water scarcity and other environmental factors markedly impact plant growth and development, posing a significant challenge for crop growers (Abdalla et al. 1992; Feng et al. 2013; Miyashita et al. 2005; Siddique et al. 2016; Stagnari et al. 2018). To cope with water shortage, plants adapt their life cycles, either avoiding drought periods or developing tolerance mechanisms to enhance water uptake and utilization (Mukarram et al. 2021; Rao and Chaitanya 2016; Reddy et al. 2004). These tolerance mechanisms involve morphophysiological responses, such as reduced leaf expansion and stomatal conductance, and biochemical responses, including enhanced antioxidant systems and osmotic adjustment, allowing plants to remain within their genetic capacity (Lata et al. 2015; Mukarram et al. 2021). Root vegetables, including sugar beets (Sabreen et al. 2018), carrots (Zhang et al. 2021), and radishes (Henschel et al. 2022; Stagnari et al. 2018), experience reduced growth and biomass allocation among their organs when faced with water deficiency. Water scarcity often leads to an excess of reactive oxygen species (ROS), causing oxidative stress (Chaichi et al. 2017; Jaleel et al. 2008; Martinez et al. 2016; Shahid et al. 2020), which can harm proteins, RNA, DNA, and biological membranes. To counteract this, plants use enzymatic and nonenzymatic antioxidant systems to detoxify and regulate cellular ROS levels (Devireddy et al. 2021; Miller et al. 2010). Vitamin C (ascorbic acid), a potent nonenzymatic antioxidant with self-recycling abilities, is used to scavenge ROS (Paciolla et al. 2019). Nevertheless, previous studies have demonstrated a series of deteriorations in the physiomorphological traits of radish plants under water shortage (Henschel et al. 2022; Stagnari et al. 2018).

Global water scarcity is a pressing issue due to factors such as climate change, population growth, and urbanization. The demand for water exceeds the available supply, leading to water scarcity in many regions (Shemer et al. 2023). Water scarcity has economic impacts at a global scale, considering factors such as population, agricultural productivity, and climate trajectories (Dolan et al. 2021). Agricultural water scarcity will intensify in more than 80% of global croplands due to decreased water availability (Liu et al. 2022). Compost amendments have the potential to improve soil water retention. The addition of compost to soil plots resulted in improved soil water content (Wright et al. 2022). A study on sandy soil found that coamending with water treatment residual and compost increased plant biomass, indicating improved water retention (Clarke et al. 2019). Another study on olive orchards showed that compost amendment improved soil water status and reduced water stress in plants (Amel et al. 2023). Short-term effects of compost amendments on soil water retention characteristics were observed, with compost and vermicompost-based amendments increasing soil water holding capacity and water use efficiency (WUE). Overall, the research suggests that compost amendments can enhance soil water retention and improve plant water availability (Rivier et al. 2022). Conventionally, chemical treatments and agronomical crop management techniques have been used to address water deficiency and mitigate its negative impacts (Askari and Ehsanzadeh 2015; Ghani et al. 2022). However, compost, as an organic fertilization method, plays a vital role in reducing the use of chemical fertilizers, which have adverse effects on the environment, soil,

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and sustainable agriculture (Pergola et al. 2018; Sequi 1996). Compost offers numerous benefits, including improved soil aggregation, enhanced microbial diversity and activity, increased water holding capacity, field capacity, soil water content, elevated soil electrical conductivity (EC), and enriched organic material and nutrient content, all of which promote plant growth and boost crop yield (Ghorbani et al. 2023; Gosling et al. 2006; Kranz et al. 2020; Sequi 1996). Better soil aggregation has positive effects on root growth and seedling emergence, which are influenced by soil moisture, aeration, temperature, and physical impedance (Kranz et al. 2020; Viator et al. 2002; Wang and Lin 2002).

Given the evidence of abiotic stressors negatively affecting plant growth, our study aimed to determine whether compost, as a soil supplement, could mitigate the detrimental effects of water deficit on red radish plants. Consequently, we investigated the effects of compost on leaf gas exchange, yield, vitamin C content, and total soluble solids.

Materials and Methods

Experimental site. The field experiment was conducted in 2020 at the Research Farm of the Plant Production Department, College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia (24°43′N, 46°36′E). The soil at the experimental field is classified as sandy loam, and its physicochemical characteristics are listed in Table 1. The irrigation water used had an EC of 0.89 $dS \cdot m^{-1}$ and the following ion contents ($mEq \cdot L^{-1}$): $Na^{+} = 3.52$; $Ca^{++} = 0.74$; $Mg^{++} = 0.17$; $HCO_3^{-} = 0.32$; $Cl^{-} = 2.31$; and $SO_4^{-2} = 1.80$.

Plant materials and experimental design. Seeds of 'Crimson Giant' red radish (*R. sativus*) were obtained from Emerald Seed Company (El Centro, CA, USA) and sown manually under field conditions on 4 Oct 2020. The air temperature, relative humidity, and solar radiation during the culture period are presented in Table 2. The seeds were planted in lines with a row-to-row distance of 100 cm. The experimental design used was a randomized complete block design with a split-plot layout, comprising four replicates that included combinations of four irrigation treatments and four compost fertilizers (Fig. 1). There were 64 experimental plots (four irrigation treatments × four compost treatments × replicates) and the area of each plot was 10 m^2. The main plots were randomly assigned to the irrigation treatments, and the subplots were allocated to the compost fertilizer treatments.

Compost and irrigation treatments. Organic fertilization (compost; Table 3) was applied at rates of 0%, 50%, 75%, and 100% of 20 $m^3 \cdot ha^{-1}$. Irrigation treatments commenced 10 d after planting using a drip irrigation system, with four treatments implemented: 40%, 60%, 80%, and 100% of evapotranspiration (ETc). The amount of irrigation water applied was determined based on the FAO Penman–Monteith method (Allen et al. 1998; Table 4) using data from the nearby meteorological station. Irrigation scheduling was monitored using class A pan (mm) evaporation, and the total irrigation water supply was estimated using the following crop coefficients equation (Allen et al. 1998):

$$\text{ET crop} = \text{Kc} \times \text{ET}_0,$$

where ET crop is the maximum daily crop evapotranspiration in mm; Kc is the crop coefficient, ranging from 0.7 to 1.0 for different growth stages; and ET_0 is the reference crop evapotranspiration ET, measured using a class A pan (mm). The irrigation treatments were applied for 50 days, with the following total amounts of water applied for each treatment: 1125, 900, 675, and 450 $m^3 \cdot ha^{-1}$ for treatments T1, T2, T3, and T4 (control), respectively.

Leaf gas exchange. The photosynthetic rate, stomatal conductance, and transpiration of the plants were measured using an LI-6400 photosynthesis system (Li-6400XT; LI-COR, Lincoln, NE, USA). Three plants were used for each measurement, and the third fully expanded leaf (from the apex) was exposed to 1200 μmol (photon) $m^{-2} \cdot s^{-1}$ photosynthetic photon flux density, a chamber temperature of 25 °C, a CO_2 concentration of 350 ± 10 $\mu mol \cdot mol^{-1}$, and a relative humidity of 50% to 55%.

Measurements of root growth and physical characteristics. At harvest, shoot height, leaf count, leaf area, fresh and dry plant weights, and leaf dry matter content were recorded. The total root of each plot was hand-harvested 60 d after planting, and all harvested roots from each plot were weighted before global yield was calculated in tons per hectare. WUE ($kg \cdot m^{-3}$) was calculated using the following equation:

WUE ($kg \cdot m^{-3}$) = total fruit yield ($kg \cdot ha^{-1}$)/ applied water ($m^3 \cdot ha^{-1}$). Root quality, including dimensions (length and diameter in centimeters) and root fresh and dry weights (in grams), was also measured. For dry weight determination, fresh samples were oven-dried at 70 °C until a constant weight was achieved.

Measurements of root chemical characteristics. Vitamin C content was measured using the classical titration method with a 2,6-dichlorophenolindophenol solution and expressed in milligrams of ascorbic acid per 100 g fresh weight (Association of Official Agricultural Chemists 2005). Total soluble solids were determined using a Portable Digital Refractometer (PR-101; Palette Series, Atago Co., Ltd., Tokyo, Japan). Titratable acidity was determined through titration of the root homogenate (5.0 g) using 0.1 M sodium hydroxide at pH 8.1, with citric acid as control.

Statistical analysis. The data obtained for the different measurements were subjected to analysis of variance appropriate for a randomized complete block split-plot design. Tukey's multiple range test via SAS (version 6.12; SAS Institute, Cary, NC, USA) was used to compare mean differences for the different measurements among experimental treatments at a significance level of $P \leq 0.05$. Pearson's correlation analysis was conducted to elucidate the extent of correlation between yield and parameters under various irrigation and compost treatments. Principal component analysis (PCA) with clustering was performed to integrate growth and yield parameters with different treatments and explain the largest proportion of variability among variables. This analysis was carried out using the XLSTAT statistical package software (Version 2019.1, Excel Add-ins soft SARL, New York, NY, USA).

Results and Discussion

Leaf gas exchange of red radish in response to water deficit and compost amendment. The leaf gas exchange parameters, including net CO_2 assimilation (Fig. 2A), stomatal conductance (Fig. 2B), and transpiration rate (Fig. 2C), exhibited a significant decrease with reduced irrigation levels. Conversely, the application of different percentages of compost to the soil resulted in higher leaf gas exchange parameters compared with untreated plants. Notably, the 100% compost treatment resulted in the highest level of leaf gas exchange across all irrigation levels. Increasing the compost rate led to an enhancement in leaf gas exchange parameters under different irrigation levels. Net CO_2 assimilation, stomatal conductance, and transpiration rate were markedly decreased by reducing the irrigation level. These findings align with previous studies (Benyahia et al. 2023; Miyashita et al. 2005). A shortage of irrigation water can induce various detrimental effects on plant growth and development, including inhibited photosynthesis (Ji et al. 2023; Siddique et al. 2016), stomatal closure, cell membrane damage, and plant metabolic process disruption (Siddique et al. 2016).

In this study, water deficit significantly reduced red radish growth parameters compared with well-irrigated red radish plants.

Table 1. Soil characteristics of the experimental soil.

Soil texture				pH	EC $ds \cdot m^{-1}$	Cations ($mEq \cdot L^{-1}$)				Anions ($mEq \cdot L^{-1}$)		
Clay %	Silt %	Sand %	Texture			K^{+}	Na^{+}	Mg^{++}	Ca^{++}	HCO_3^{-}	Cl^{-}	SO_4^{-}
8.43	7.82	83.75	Sandy Loam	7.9	1.05	1.30	6.95	4.48	10.48	2.28	2.62	18.31

pH = acid or alkaline; EC = electrical conductivity; K= potassium; Na = sodium; Mg = magnesium; Ca = calcium; HCO_3 = bicarbonate; Cl = chloride; SO_4 = sulfate.

Table 2. Air temperature, relative humidity, and solar radiation during October and November 2020 at the experimental site.

Parameters Month	T max (°C)	T min (°C)	RH max (%)	RH min (%)	Solar LY	WS ($m \cdot s^{-1}$)	ET_0 (mm)
October	35.98	22.41	42.51	14.89	342.15	2.45	8.79
November	28.15	15.96	51.86	21.52	279.26	2.42	5.49

T max and T min = maximum and minimum air temperature; RH max and RH min = maximum and minimum air relative humidity; solar LY = Langley; WS = wind speed; ET_0 = reference evapotranspiration.

Fig. 1. Experimental site and layout (**A**) and harvest of 'Crimson Giant' red radish (**B**).

However, the application of compost positively influenced leaf gas exchange in these plants, regardless of whether they experienced water deficit or were well-irrigated. This effect was more pronounced when the 75% and 100% compost levels were applied to the soil. Compost plays a dual role by increasing soil moisture availability in the root zone and acting as organic matter (Duong et al. 2012; Qian et al. 2023). Under drought or osmotic stress conditions, applied compost has been found to enhance the growth of various plant species, such as quinoa and pea (Hirich et al. 2014), common bean (Rady et al. 2016), tomato and cabbage (Goswami et al. 2017), and pepper (Yu et al. 2019). Compost serves as organic matter that improves soil fertility and water holding capacity, and it has been shown to enhance growth and yield parameters in pea, tomato, and cabbage (Goswami et al. 2017; Hirich et al. 2014).

Vegetative growth parameters of red radish in response to water deficit and compost amendment. The impact of compost treatments and water deficit on plant growth and biomass is summarized in Table 5. The lowest values of plant growth and biomass were observed under a 40% irrigation level without compost application, whereas the highest values were recorded in plants treated with compost under both natural and water deficit conditions. Notably, the use of compost resulted in a significant increase in stem length under drought stress conditions. Stem length reached 16.60 cm under the 100% irrigation level without compost, whereas it reached 19.39 and 17.65 cm under 80% water deficit with application of the 100% and 75% compost treatments, respectively. In addition, fresh and dry weight increased with increasing compost application under water deficit conditions. Leaf area was recorded as 508.1 cm^2 without compost at the 100% water level, but it was 494.2 and 463.1 cm^2 under 80% water deficit with the 75% and 100% compost treatments, respectively. The number of leaves did not differ significantly with compost application levels (75% and 100%) under the 80% irrigation level compared with the 100% irrigation level without compost. Under water deficit conditions, red radish stem length, leaf fresh and dry weight, leaf number, leaf area, and total yield were significantly decreased at different critical stages without using compost. These findings are consistent with previous research (More et al. 2023; Siddique et al. 2016), which also reported adverse effects of water deficit on stem length (Widuri et al. 2018) and fresh and dry weight (Bocchini et al. 2018; Widuri et al. 2018). The highest values for stem length, leaf fresh and dry weight, leaf number, leaf area, and total yield were observed under the 100% irrigation level, whereas these traits exhibited a decline with increasing water deficit levels. The results suggest that increasing soil moisture availability in the root zone by applying water at the 100% irrigation level may enhance water assimilation, leading to increased photosynthesis activity, cell division, and cell enlargement (Abd El-Mageed et al. 2019). In the present study, leaf gas exchange under water deficit was associated with a decrease in leaf area, number, and fresh and dry weight (Feng et al. 2013; Liu and Stützel 2004; Stagnari et al. 2018).

Root growth characteristics were also influenced by irrigation levels and compost amendment (Table 6). Root diameter reached its highest level under the 80% water level, measuring 4.6 and 4.2 cm with 100% and 75% compost application, respectively, compared with 3.9 cm recorded under the 100% water level without compost. In addition, root length was greater when 100% and 75% compost were applied under the 80% irrigation level compared with the 100% irrigation level without compost. Root fresh weight exhibited the highest values of 42.8 and 38.9 g with compost application under the 80% irrigation level and the 100% irrigation level without compost, respectively, and the same trend was observed in root dry weight. Total yield was increased when using a higher compost rate at all levels of irrigation. WUE was lowest when 75% compost was applied. These results suggest more efficient water uptake and improved growth and WUE under water deficit and well-irrigated conditions. Moreover, these findings indicate that both irrigation level and compost rate treatments imposed significant effects on all parameters, with a significant interaction between irrigation level and compost rate also observed. A well-developed root system plays a vital role in plant growth and serves as a storage organ in red radish. Our study showed that red radish root length, diameter, and fresh and dry weight decreased with lower irrigation levels. Similar findings have been reported for the root length, diameter, and yield of sugar beet under water stress (Abd El-Mageed et al. 2019; Sabreen et al. 2018). However, the negative effects of water deficit on red radish root biomass traits were alleviated by the addition of compost, which positively influenced root biomass. This improvement can be attributed to the ameliorative effect of compost on soil physiochemical characteristics and soil–water relations,

Table 3. The chemical analysis of compost used in this study.

	pH	H (%)	OM (%)	N	P	K	Ca^{++}	Mg^{++}	Fe	Mn	Zn	C/N ratio	Wt of m^3 manure (kg)
				(%)					ppm				
Compost	6.23	24	45	1.46	0.88	1.14	0.53	0.43	671	280	135	12:1	380

ppm = $mg \cdot kg^{-1}$; H = humidity; pH = acid or alkaline; OM = organic matter; N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Fe = iron; Mn = manganese; Zn = zinc.

Table 4. Water use for the irrigation treatments of ‘Crimson Giant’ red radish.

Treatments	Description	Water consumptive use (m^3/ha)
T1	Irrigation at 100% of ETc	1,125
T2	Irrigation at 80% of ETc	900
T3	Irrigation at 60% of ETc	675
T4	Irrigation at 40% of ETc	450

Etc = evapotranspiration.

which promoted root elongation and development, facilitating water and nutrient uptake in red radish plants. These results are consistent with previous studies on several crops, including sugar beet (Abd El-Mageed et al. 2019; Sabreen et al. 2018), quinoa and pea (Hirich et al. 2014), common bean (*Phaseolus vulgaris*) (Rady et al. 2016), and pepper (Yu et al. 2019). Water deficit limits CO_2 assimilation and stomatal conductance (Miyashita et al. 2005; Sabreen et al. 2018); however, in our study, the application of 75% and 100% compost significantly improved these parameters. WUE indicates the ratio of water used in metabolic processes to the water lost via transpiration, and it has been reported to increase with increasing drought levels (Jaleel et al. 2008; Liu and Stützel 2004). In addition, compost amendment has been shown to significantly enhance WUE (Abd El-Mageed et al. 2018; Jaleel et al. 2008); however, compost amendment effects can vary due to factors such as compost quality, application rates, crop type, and environmental conditions. Different compost amendments have been found to have varying effects on soil characteristics and plant growth. For example, in the study by Kissler (2022), the effectiveness of compost amendment in modifying soil physical and hydrological attributes was found to depend on the pore size distribution obtained from adsorption and desorption experiments. Similarly, Duddigan et al. (2021) found that different compost amendments resulted in significantly different soil environments and nitrogen budgets, leading to variable effects on plant yield and biometrics. In addition, the effects of compost amendment on wheat yield and quality were dependent on weather conditions, with different outcomes observed in drier and wetter years (Deakin 2021). Overall, the variability in compost amendment effects highlights the need for careful consideration of factors such as compost type, application rates, and specific environmental conditions when implementing compost amendments in agricultural practices.

Vitamin C content, titratable acidity, and total soluble solids of red radish in response to water deficit and compost amendment. Both water deficit and compost amendment significantly influenced the vitamin C content, titratable acidity, and total soluble solids of red radish roots (Table 7). Vitamin C content increased with higher compost rates, reaching its peak value under the 40% irrigation level with the application of 50%, 75%, and 100% compost. Similarly, titratable acidity increased as irrigation level decreased and compost rate increased. The data showed that

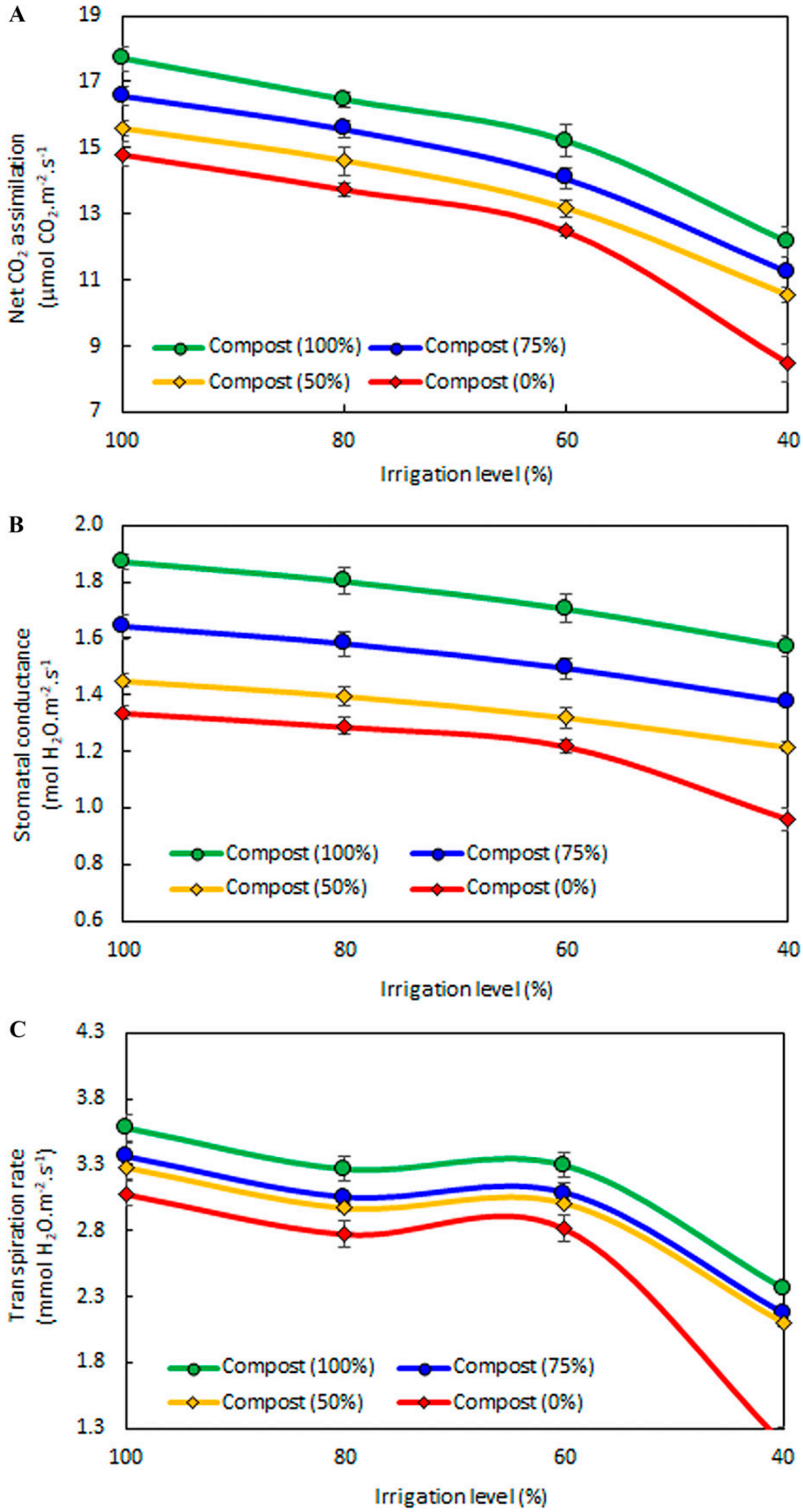

Fig. 2. Net CO_2 assimilation (**A**), stomatal conductance (**B**) and transpiration rate (**C**) of ‘Crimson Giant’ red radish in response to irrigation levels and compost amendment.

total soluble solids reached the highest values of 5.51% and 5.03% with 50% to 100% compost under the lowest irrigation level, respectively. A previous study by Favati et al. (2009) suggested that vitamin C levels increase with higher drought levels, but other studies, such as that of Shao et al. (2014), have shown no significant increase in vitamin C content in stressed plants. Moreover, compost amendment has been reported to enhance vitamin C

Table 5. Effects of irrigation levels and compost rate on stem length, leaf number, leaf area, and leaf fresh and dry weight of 'Crimson Giant' red radish.

Irrigation rate (%)	Compost rate (%)	Stem length (cm/plant)	No. of leaves	Leaf area (cm^2/plant)	Leaf fresh wt (g/plant)	Leaf dry wt (g/plant)
100	100	22.58 a[i]	10.5 a	600.7 a	42.53 a	4.50 a
	75	20.35 b	10.2 b	573.8 b	40.79 b	4.26 b
	50	18.55 d	9.7 c	544.0 c	38.84 c	4.11 c
	0	16.60 f	9.0 d	508.1 d	36.59 d	3.85 d
80	100	19.39 c	9.3 d	494.2 e	35.52 e	3.83 d
	75	17.65 e	8.6 d	463.1 f	33.20 f	3.56 e
	50	15.95 g	8.1 gf	435.9 g	31.31 g	3.36 f
	0	14.52 i	7.5 i	405.0 i	29.15 i	3.17 h
60	100	17.55 e	8.5 e	442.6 g	31.73 g	3.39 f
	75	16.47 f	8.1 f	421.2 h	30.22 h	3.28 g
	50	15.34 h	7.6 ih	385.2 j	27.78 j	3.04 i
	0	14.05 j	7.0 j	354.1 l	25.61 l	2.83 j
40	100	15.55 h	8.1 gf	382.1 j	27.56 j	3.02 i
	75	14.72 i	7.8 gh	365.5 k	26.40 k	2.87 j
	50	13.57 k	7.4 i	342.6 m	24.81 m	2.75 k
	0	10.60 l	6.7 k	312.7 n	20.47 n	2.17 l
Significance						
Irrigation level		*	*	*	*	*
Compost rate		*	*	*	*	*
Irrigation level × Compost rate		*	NS	*	*	*

[i] Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test.
NS, * indicate not significant or significant at $P \leq 0.05$, respectively.
1 cm = 0.3937 inch; 1 cm^2 = 0.1550 $inch^2$; 1 g = 0.0353 oz.

content in habanero-type pepper (*Capsicum chinense*) (Premamali et al. 2019) and lettuce (Santos et al. 2016). Titratable acidity was found to increase in the fruit of tomato plants grown under salt stress conditions (Carbajal-Vázquez et al. 2020). In our study, titratable acidity increased as irrigation levels decreased, and this response also had an impact on total soluble solids. Similarly, total soluble solids increased with higher water stress levels, which aligns with findings in tomato plants, where vitamin C content, titratable acidity, and total soluble solids increased under water deficit conditions (Al-Selwey et al. 2021). Compost usage was also found to increase the values of titratable acidity and total soluble solids in sweet pepper fruits (Al-Harbi et al. 2020) and strawberries (Wang and Lin 2002). The perception of taste in fresh root vegetables, such as radish, is influenced by factors such as total acidity and sweetness (measured by Brix). Consumers consider both total acidity and Brix as important factors when evaluating the taste of radish fresh root (Wieczorek et al. 2018). In addition, the sensory characteristics of Brassica vegetables, which include radish, are known to have a characteristic sharp and bitter taste (Bell et al. 2018). The perception of taste in radish fresh root is influenced by both the levels of total acidity and sweetness (Brix), as well as the presence of bitter compounds like glucosinolates and isothiocyanates (Chang et al. 2010).

Principal component analysis. The PCA biplot visually represents that the first and second components account for 94.16% variability observed among all parameters when considering both compost and irrigation treatments (Fig. 3). Specifically, the first component accounts for 78.38% of the variability, and the second component accounts for 15.78% of the variability among the parameters. Furthermore, the biplot from the PCA analysis demonstrates that the vegetative growth and leaf gas exchange traits exhibit positive correlation with one another, with the exception being the biochemical traits such as vitamin C, titratable acidity, total soluble solids, and WUE. Root fresh weight exhibited strong correlation with 100% compost and 80% irrigation rate.

Table 6. Effects of irrigation levels and compost rate on root diameter and length, root fresh and dry weight, total yield and water use efficiency (WUE) of 'Crimson Giant' red radish.

Irrigation rate (%)	Compost rate (%)	Root diam (cm)	Root length (cm)	Root fresh wt (g/plant)	Root dry wt (g/plant)	Total yield ($t\cdot ha^{-1}$)	WUE
100	100	5.4 a[i]	5.6 a	49.2 a	5.7 a	31.651 a	28.13 ji
	75	4.8 b	5.1 b	47.2 b	5.5 b	30.528 b	27.13 k
	50	4.4 d	4.7 d	44.6 c	5.2 c	29.088 c	25.86 l
	0	3.9 f	4.2 f	41.2 e	4.8 d	27.229 e	24.20 m
80	100	4.6 c	4.9 c	42.8 d	5.1 c	28.134 d	31.26 h
	75	4.2 e	4.5 e	38.9 f	4.5 e	25.987 f	28.87 i
	50	3.8 g	4.0 g	36.2 g	4.2 f	24.514 g	27.24 jk
	0	3.4 i	3.7 i	33.6 i	3.9 h	23.076 i	25.64 l
60	100	4.2 e	4.4 e	38.8 f	4.6 e	25.893 f	38.36 d
	75	3.9 f	4.2 f	36.4 g	4.2 f	24.582 g	36.42 e
	50	3.6 h	3.9 h	33.8 i	3.9 h	23.154 i	34.30 f
	0	3.3 j	3.6 j	31.1 j	3.6 i	21.670 j	32.11 hg
40	100	3.7 h	3.9 h	36.3 g	4.2 f	24.518 g	54.49 a
	75	3.5 i	3.7 i	35.0 h	4.0 g	23.828 h	52.95 b
	50	3.2 k	3.5 k	32.7 i	3.8 h	22.584 i	50.19 c
	0	2.7 l	2.9 l	24.2 k	2.9 j	14.555 k	32.34 g
Significance							
Irrigation level		*	*	*	*	*	*
Compost rate		*	*	*	*	*	*
Irrigation level × Compost rate		*	*	*	*	*	*

[i] Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey's multiple range test.
*Significant at $P \leq 0.05$.
1 cm = 0.3937 inch; 1 g = 0.0353 oz; 1 $t\cdot ha^{-1}$ = 0.4461 ton/acre.

Table 7. Effects of irrigation levels and compost on vitamin C, titratable acidity, and total soluble solids of ‘Crimson Giant’ red radish.

Irrigation rate	Compost rate (%)	Vitamin C (mg/100 g fresh wt)	Titratable acidity (%)	Total soluble solids (%)
100	100	12.67 i[i]	0.256 j	3.58 k
	75	12.36 j	0.248 k	3.50 l
	50	12.25 j	0.236 l	3.24 m
	0	11.40 k	0.216 n	3.06 n
80	100	14.54 e	0.268 h	4.36 f
	75	14.19 f	0.259 i	4.26 g
	50	14.06 f	0.247 k	3.97 i
	0	13.07 g	0.226 m	3.76 j
60	100	15.21 c	0.357 c	4.73 d
	75	14.82 d	0.347 d	4.63 e
	50	14.68 ed	0.334 e	4.30 g
	0	12.86 h	0.297 g	4.08 h
40	100	16.02 a	0.372 a	5.51 a
	75	15.59 b	0.362 b	5.39 b
	50	15.44 b	0.348 d	5.03 c
	0	13.17 g	0.308 f	4.63 e
Significance				
Irrigation level		*	*	*
Compost rate		*	*	*
Irrigation level × Compost rate		*	*	*

[i] Values followed by the same letter in the same column are not significantly different at $P \leq 0.05$ level, according to Tukey’s range test.
*Significant at $P \leq 0.05$.
1 mg/100 g = 10 ppm.

Pearson’s correlation coefficient between yield and all studied parameters under different rates of compost and irrigation treatments. Pearson’s correlation analysis was conducted to elucidate the association between yield and various factors of vegetative growth, leaf gas exchange, and WUE of the ‘Crimson Giant’ red radish, under different compost and irrigation treatments (as presented in Table 8). All factors demonstrated a high degree of correlation and displayed a robust and positive relationship (r = 0.84–0.98; $P \leq 0.001$), with the exception of WUE, total soluble solids, vitamin C, and titratable acidity, which exhibited insignificant correlations.

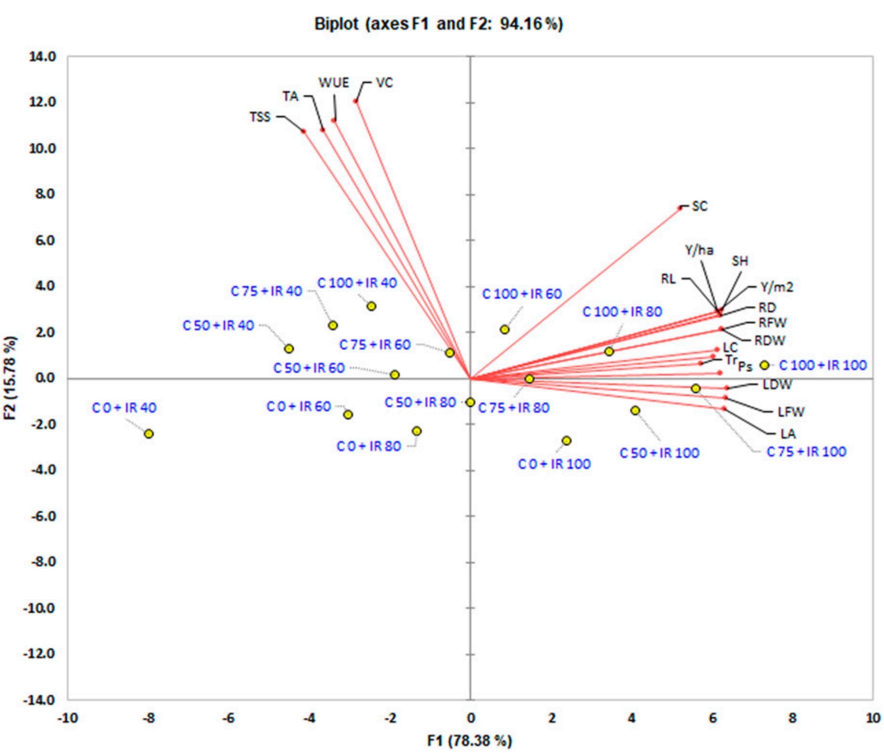

Fig. 3. Biplot of principal component analysis of different parameters of ‘Crimson Giant’ red radish under different treatments of compost and irrigation rates. Abbreviations in the figure indicate total soluble solids (TSS), titratable acidity (TA), water use efficiency (WUE), vitamin C (VC), stomatal conductance (SC), yield per hectare (Y/ha), yield per square meter (Y/m^2), root length (RL), shoot height (SH), root diameter (RD), root fresh weight (RFW), root dry weight (RDW), leaf count (LC), transpiration rate (Tr), photosynthesis (Ps), leaf dry weight (LDW), leaf fresh weight (LFW), leaf area (LA), compost rate (C0, C50, C75, and C100), and irrigation rate (IR40, IR60, IR80, and IR100).

Table 8. Pearson’s correlation coefficients between yield and all the studied parameters of ‘Crimson Giant’ red radish.

Parameters	Yield/ha	
Shoot height	0.956	<0.0001*
Leaf count	0.937	<0.0001*
Leaf fresh weight	0.944	<0.0001*
Leaf area	0.917	<0.0001*
Leaf dry weight	0.958	<0.0001*
Root fresh weight	0.985	<0.0001*
Root dry weight	0.977	<0.0001*
Root diameter	0.938	<0.0001*
Root length	0.942	<0.0001*
Water use efficiency	−0.288	0.279 NS
Total soluble solids	−0.480	0.060 NS
Vitamin C	−0.258	0.335 NS
Titratable acidity	−0.404	0.120 NS
Photosynthetic rate	0.908	<0.0001*
Transpiration rate	0.866	<0.0001*
Stomatal conductance	0.842	<0.0001*

NS, * indicate not significant or significant at $P \leq 0.001$, respectively.

In conclusion, the current investigation offers insights into the beneficial effects of applying compost to mitigate the diverse impacts of water deficit and enhance production qualities in red radish plants. Water deficit notably decreased the WUE, physiological responses, and growth traits of red radish plants. However, the use of compost mitigated the harmful effects of water deficit and improved plant growth characteristics. Compost appears to be a viable substitute for improving soil water availability and fertility. Our results demonstrate that compost rates of 75% and 100% significantly improve total yield, vitamin C content, total soluble solids, and titratable acidity. Moreover, the treatment combining 100% compost and 100% irrigation proved to be the most effective, providing the highest yields under the experimental conditions. In cases of water shortage, the application of the 75% and 100% compost with 80% irrigation yielded promising results, saving 20% of irrigation water while providing nearly the same red radish yield. Our findings suggest that the use of compost may serve as a potential growth stimulant to enhance plant growth and production when water resources are limited. Future investigations ought to direct their attention toward the anatomical characteristics and antioxidative capacity of radish when subjected to water scarcity and compost amendment. Furthermore, it is imperative to consider the performance of radish when exposed to a dual condition of elevated irrigation level (125%) and an increased rate of compost application (120%).

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