ISPEC Tarım Bilimleri Dergisi, 8(2): 310-327, 2024
ISPEC Journal of Agricultural Sciences, 8(2): 310-327, 2024
DOI: https://doi.org/10.5281/zenodo.11124802

Impact of Salicylic Acid Foliar Application on Growth, Nutrient Uptake, and Physiological Responses of Pepper Plants under Deficit Irrigation

Kemal Yalçın GÜLÜT [1*], Gamze TAZE[1]
[1] Cukurova University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Adana
*Corresponding author: kygulut@cu.edu.tr

Research Article

Abstract

This study examines the impact of foliar application of salicylic acid (SA) at various concentrations on the growth, nutrient uptake, and physiological responses of pepper plants (*Capsicum annuum* L.) subjected to different levels of deficit irrigation. Pepper plants were exposed to three irrigation regimes (full irrigation, 75% field capacity, and 50% field capacity) and four SA concentrations (0 mM, 0.25 mM, 0.50 mM, and 1.0 mM). Decreasing irrigation levels led to significant reductions in fresh shoot weight, dry shoot weight, root dry weight, and plant height, with reductions of up to 66% observed under severe drought conditions. However, foliar application of SA mitigated these reductions, with an 18% increase in fresh shoot weight and up to 50% increase in root dry weight observed at the highest SA concentration (1.0 mM). Analysis of nutrient contents in fresh shoots revealed higher concentrations of several macro and micronutrients under reduced irrigation levels, attributed to the dilution effect. SA application positively correlated with increased uptake of essential nutrients, particularly potassium, magnesium, and calcium. Chlorophyll and carotenoid contents remained unaffected by SA application or irrigation levels. Relative water content varied across SA treatments and irrigation levels, indicating potential alterations in water status. Electrical conductivity measurements showed variability among treatments, suggesting changes in membrane permeability. Overall, our findings underscore the potential of SA foliar application to mitigate the adverse effects of deficit irrigation on pepper plant growth and nutrient uptake, offering insights for enhancing plant productivity and resilience to drought stress in arid and semi-arid regions.

Article History

Received	:20.12.2023
Accepted	:29.01.2024

Keywords

Salicylic acid
foliar application
water stress
plant physiology
macronutrients
micronutrients
drought tolerance

1. Introduction

Climate change poses a significant threat to global food security, with rising temperatures and reduced water availability jeopardizing crop productivity. Future projections indicate that water shortages will affect a staggering 50% of agricultural land by 2050 (Hasanuzzaman et al., 2019). Water scarcity remains a critical impediment to plant productivity and soil fertility, hindering plant growth, development, and ultimately, yield (Dietz et al., 2021; Özdoğan et al., 2021). Drought stress, a consequence of water scarcity, presents multifaceted challenges for plants, including water deficiency, hampered transpiration, and disrupted physiological metabolism. These factors ultimately lead to decreased yield and increased vulnerability to biotic stresses (Farooqi et al., 2020). The detrimental effects are observed across diverse crop species, including wheat, cotton, and pepper (Alotaibi et al., 2023; Zafar et al., 2023; Işık, 2012). Understanding plants responses to drought stress is crucial for developing effective strategies to mitigate its impact.

Salicylic acid (SA), a key phytohormone, has emerged as a promising regulator of plant physiological processes and stress responses, including drought tolerance (Zhang et al., 2016; Maruri-López et al., 2019), acting as a crucial plant signaling molecule in the defense response (Gorni et al., 2017). SA exhibits a multifaceted role in plant resilience, not only mitigating abiotic stresses but also enhancing resistance to biotic stress factors (Wei et al., 2018; Pasternak et al., 2019). Research suggests that SA application can modulate plant growth and development under both normal and stress conditions, highlighting its potential for agricultural applications (Kim and Hwang 2011; Sadeghi et al. 2013; Chakma et al., 2021; Shaukat et al., 2022). Additionally, SA's antioxidative properties play a crucial role in alleviating oxidative stress in plants, thereby enhancing their resilience to environmental challenges (Li et al., 2019). Furthermore, SA application has been linked to increased production of nitric oxide (NO), which aids in mitigating reactive oxygen species (ROS)-induced damage in plant cells (Rai et al., 2020).

Numerous studies have documented SA's role in mitigating various stresses (Kereçin and Öztürk, 2024). For instance, Shemi et al., (2021) have shown that SA application counters the negative effects of water deficit by increasing gas exchange characteristics in plants, while water deficit alone reduces stomatal conductance, transpiration, and CO_2 assimilation. SA application has been found to alleviate the adverse effects of boron toxicity in maize plants (Nawaz et al., 2020) and mitigate heavy metal stress-induced damage (Sharma et al., 2020). SA's beneficial effects have also been observed in enhancing yield and quality parameters in crops such as garlic (Shama et al., 2016) and basil (Kaya and İnan, 2017) under stress conditions. Furthermore, SA application has been linked to improved growth, biomass accumulation, and maintenance of photosynthetic pigments in Portulaca oleracea plants under water deficit stress (Saheri et al., 2020).

In the context of pepper cultivation, where water availability significantly influences yield and quality, understanding the interaction between SA application and water stress becomes paramount. Studies evaluating the response of red pepper plants to limited irrigation levels have underscored the importance of water management in pepper production, emphasizing the need for sustainable irrigation practices (Gençoğlan et al., 2006). Furthermore, investigations into the effects of SA application on pepper plants under drought stress have provided valuable insights into its potential for enhancing plant resilience and mitigating the adverse effects of water scarcity (Dorji et al., 2005).

This study aims to investigate the impact of foliar SA application on the growth, nutrient uptake, and stress tolerance of pepper plants under different water regimes. By examining the physiological and biochemical responses of pepper plants to SA under varying water levels, we aim to provide insights into strategies for improving pepper production under water-limited conditions.

2. Materials and Methods

2.1. Experimental soil

The soil used in the experiment was obtained from Arıklı Series located in the research and application farm of the Faculty of Agriculture of Çukurova University. The soil used in the greenhouse experiment exhibited specific physical and chemical properties, as outlined in Table 1. The soil was characterized by a clay content of 17.5%, indicating a moderate presence of fine particles. Additionally, the soil contained a significant proportion of silt, constituting 62.5% of its composition. The soil had a lime content of 29.1 g kg^{-1}, indicating a neutral to slightly alkaline pH environment. This pH level of 7.6 is within the optimal range for most crops, facilitating nutrient availability and uptake by plants. Organic matter (OM) content in the soil was 1.29%, indicating a moderate level of organic material. Electrical conductivity (EC) of the soil was 0.21 dS m^{-1}, indicating low levels of soluble salts. This is favorable for plant growth as excessive salt levels can inhibit nutrient uptake and lead to physiological stress in plants. The soil was rich in potassium (K), with a concentration of 1489.5 g kg^{-1}. Phosphorus (P) content in the soil was 23.2 g kg^{-1}, indicating an adequate supply of this essential nutrient for plant growth and development. Iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) were present in the soil at concentrations of 2.9 g kg^{-1}, 0.53 g kg^{-1}, 8.8 g kg^{-1}, and 1.6 g kg^{-1}, respectively. Overall, the soil used in the greenhouse experiment exhibited favorable physical and chemical properties conducive to plant growth and development.

Table 1. Some of physical and chemical properties of soil used in the greenhouse experiment (Gülez and Şenol, 2002)

Clay	Silt	Sand	Lime	OM	pH	EC	K	P	Fe	Zn	Mn	Cu
%						ds m^{-1}	g kg^{-1}					
17.5	62.5	20.0	29.1	1.29	7.6	0.21	1489.5	23.2	2.9	0.53	8.8	1.6

2.2. Plant material and experimental design

The experiment was conducted at the Research and Application Greenhouses of the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Çukurova University. Temperature, relative humidity and light density in the greenhouse fluctuated between 25 and 35 °C, 70 and 85% and 25 and 28 klux, respectively, during the experiment. The experiment was set up in a randomized complete block design with 7 replications. The experimental treatments consisted of three drought stress levels (full irrigation, 100% of field capacity; moderate stress, 75% of field capacity; and severe stress, 50% of field capacity) assigned to main plot and four exogenous foliar applications (control, water; SA1, 0.25 mM SA (SA2), 0.50 mM SA(SA3) and 1.0 mM SA (SA4)) as subplot.

In this study, Demre pepper variety was used as the plant material. Pepper (*Capsicum annuum* L.) were provided by South Fidagro seed company. The seedlings were carefully transplanted into individual plastic pots filled with 2 kg of soil. The initial fertilization applied to the soil used consisted of; 200 mg kg-1 N ($CaNO_3.4H_2O$), 100 mg kg^{-1} P, and 125 mg kg^{-1} K (KH_2PO_4), 2 mg kg^{-1} Zn ($ZnSO_4.7H_2O$), and 1 mg kg^{-1} Fe (Fe-EDTA). One plant was planted in each pot. Drought treatment was started 17 days after planting. During the following days, the water levels of the plants in the control were maintained at field capacities by weighing the plants 2 or 3 times a day. Water requirement was met with distilled water. Salicylic acid applications were prepared as solutions of 0, 0.25, 0.50, and 1.0 mM (% 0.01 Tween-20) applied foliarly. When preparing salicylic acid, the weighed SA amount for each dose was dissolved in 1 ml of ethanol and a small amount of distilled water was added. Then, the pH of SA was adjusted to a value between 5.5-6.0 using 0.1 N NaOH, and the solution was made up to 1 liter. Tween-

20 was added to the prepared SA solution to a concentration of 0.01%. The first salicylic acid application was made 14 days after planting, and the second application was made 26 days after planting. Pure water (% 0.01 Tween-20) was used for the control dose of salicylic acid.

The plants were harvested at 41st day of the experiment. Before harvesting the plants, the heights of the plants were measured, and they were harvested as root and fresh parts. Roots were carefully washed by removing the soils in each pot with tap water. The fresh parts and roots of the plants were dried in an oven at 70°C for at least 48 hours. The dried fresh parts and roots were weighed, and the fresh parts were ground in an agate mill to prepare them for analysis.

2.3. Plant analysis

2.3.1. Plant nutrient analysis

The ground plant samples were incinerated by microwave digestion method to determine the concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), cupper (Cu), manganese (Mn), iron (Fe), and zinc (Zn) (Jones and Case, 1990). Accordingly, 0.2 g of ground samples were weighed and digested with 2 ml of H_2O_2 and 5 ml of HNO_3 in a microwave digestion set. After cooling, 13 ml of distilled water was added to the samples, and the final volume was adjusted to 20 ml and filtered. The concentrations of K, Ca, Mg, Cu, Mn, Fe, and Zn in the filtrate were determined by Atomic Absorption Spectrometry (AAS). The phosphorus concentration in the plant sample were determined using a vanado molybda phosphoric acid method with a spectrophotometer (Kuo, 1996).

2.3.2. Chlorophyll and carotenoid content

Approximately 0.1 g of fresh leaf samples were homogenized in 12 ml of 80% acetone in a ceramic mortar. After this process, the samples were filtered through coarse filter paper, and the absorbances at 652 nm wavelength were determined spectrophotometrically (Wellburn, 1994).

Leaf fresh weights (LFW) totaling 0.05 g were meticulously gathered from each treatment, followed by thorough mixing with an extraction solution comprising an 80% acetone to absolute ethanol ratio (1:1). Subsequently, this mixture was transferred into a 1.5 ml microcentrifuge tube and centrifuged at 10,000 rpm. The resulting transparent extract underwent analysis using a UV-Vis spectrophotometer (Hitachi U-2000; Hitachi, Tokyo, Japan), with absorbance values for chlorophyll A, B, and carotenoids recorded at wavelengths of 663 nm, 645 nm, and 470 nm, respectively. The calculations were carried out using the following equations (Eq.1 – 4):

$$\text{Chlorophyll A} = [(12.25 \times A663) - (2.55 \times A645)] \times [1/(100 \times LFW)] \quad \text{Eq. 1}$$

$$\text{Chlorophyll B} = [(20.30 \times A645) - (4.91 \times A663)] \times [1/(100 \times LFW)] \quad \text{Eq.2}$$

$$\text{Total Chlorophyll (A + B)} = [(7.34 \times A663) + (17.76 \times A645)] \times [1/(100 \times LFW)] \quad \text{Eq.3}$$

$$\text{Carotenoids} = [(4.46 \times A441) - (\text{Total Chlorophyll})] \times [1/(100 \times LFW)] \quad \text{Eq.4}$$

2.3.3. Membrane permeability

Membrane permeability was conducted according to Cakmak and Marschner (1987). Accordingly, leaves cut with a 1 cm diameter disc were incubated in deionized water at room temperature for 24 hours, and then the electrical conductivity (EC, %) of the medium was measured. After this measurement, the same medium was heated with leaf samples up to 105°C, and after heating, the EC of the medium was measured again. Membrane permeability was expressed as a percentage by comparing the initial EC1 value with the second EC2 value (Eq. 5).

$$\text{Membrane Permeability (\%)} = [1 - (EC1/EC2)] \times 100 \quad \text{Eq.5}$$

2.3.4. Relative water content

Relative water content (RWC, %) serves as a valuable tool for identifying drought-tolerant varieties. RWC reflects a plant's water status by comparing the weight of a fresh leaf sample to the combined weights of the same leaf when fully hydrated (turgid) and completely dried. The RWC was assessed by extracting leaf discs from both treated and untreated plants, and their respective fresh weights were measured. Subsequently, these leaf discs were immersed in Petri dishes filled with distilled water for a duration of 1 hour to attain full turgidity. Upon achieving turgid weight, the leaf discs were subjected to oven-drying at 80°C for a period of 24 hours to determine their dry weight. The RWC of pepper plants was calculated according to Smart and Bingham (1974) using the following equation (Eq. 6):

$$\text{RWC (\%)} = \text{Fresh Weight} - \text{Dry Weight}/\text{Turgid weight} - \text{Dry Weight} \times 100 \qquad \text{Eq.6}$$

2.4. Statistical analysis

JMP statistical software was used for the statistical analysis of data. Analysis of variance (ANOVA) was performed, and LSD test was applied to determine the significance of differences between means. All statistical analyses were set at a significance level of $P < 0.05$.

3. Results and Discussion

3.1. Results

In this study, the effects of foliar application of different doses of salicylic acid (0mM SA-SA1, 0.25 mM SA- SA2, 0.50 mM SA-SA3, 1.0 mM SA- SA4) on the growth and nutrient uptake of pepper plants grown under different irrigation levels were investigated to determine the optimal water requirement for pepper plants.

3.1.1. Growth parameters of pepper plants

Irrigation levels significantly influenced (P=0.001) all growth parameters measured, including fresh shoot weight, dry shoot weight, root dry weight, and plant height (Table 2). Plants subjected to decreasing irrigation levels (Irr1 > Irr2 > Irr3) exhibited a consistent and gradual reduction in all growth parameters. For instance, compared to full irrigation, the average fresh shoot weight decreased by approximately 66% under 50% of field capacity irrigation. Similarly, root dry weight and plant height also exhibited significant reductions of approximately 36% and 27%, respectively, under the lowest irrigation level (Irr3). Salicylic acid (SA) application also significantly affected the most growth parameters, except for plant height (P=0.443). Increasing SA doses (SA1 < SA2 < SA3 < SA4) generally led to an increase in fresh shoot weight, dry shoot weight, and root dry weight (Table 2). For instance, the highest SA dose (SA4) resulted in an approximately 18% increase in average fresh shoot weight compared to no SA application (SA1). Additionally, the dry shoot weight and root dry weight showed increases of approximately 34% and 50%, respectively, with the highest SA concentration. However, the interaction between irrigation levels and SA concentrations was not significant for any of the measured parameters.

Table 2. Effects of irrigation levels and salicylic acid application levels on growth parameters of pepper plants (mean value ± standard deviation)

Treatments	Fresh Shoot Weight (g)	Dry Shoot Weight (g)	Dry Root Weight (g)	Plant Height (cm)
Irr1xSA1	29.6±9.5 cd	5.7±1.7 bcd	1.5±0.41 b-e	37.8±7.1 bc
Irr1xSA2	32.9±6.2 bc	6.1±1.2 bc	1.6±0.55 bc	42.0±6.3 ab
Irr1xSA3	36.6±3.0 ab	6.8±1.0 ab	1.8±1.52 ab	45.1±3.0 a
Irr1xSA4	40.7±2.8 a	7.5±0.5 a	2.1±0.29 a	43.0±3.1 ab
Irr2xSA1	27.8±5.4 cd	5.3±1.0 cd	1.5±0.38 bcd	37.3±5.1 bc
Irr2xSA2	24.0±5.5 d	4.5±1.2 d	1.3±0.33 cde	34.0±6.2 cd
Irr2xSA3	29.1±3.3 cd	5.5±0.6 cd	1.5±0.12 bcd	38.6±4.3 bc
Irr2xSA4	31.7±4.5 bc	5.9±0.7 bc	1.6±0.20 bcd	38.3±2.4 bc
Irr3xSA1	15.8±4.1 e	3.1±0.7 e	1.1±0.30 ef	29.1±3.2 de
Irr3xSA2	12.7±3.7 e	2.5±0.6 e	0.9±0.32 f	27.4±4.3 e
Irr3xSA3	12.3±2.0 e	2.3±0.4 e	0.8±0.20 f	25.9±3.9 e
Irr3xSA4	15.4±2.1 e	3.0±0.4 e	1.2±0.21 def	27.4±1.8 e
Irr (P: LSD value)	0.001:2.693	0.001:0.512	0.001:0.175	0.001:2.562
SA (P: LSD value)	0.001:3.110	0.005:0.601	0.018:0.202	0.443:2.959
IrrxSA (P: LSD value)	0.074:5.386	0.112:1.041	0.121:0.35	0.115:5.124

* The difference between letters bearing the same symbols in the same column is not significant ($p<0.05$). Irr1: Full Irrigation, Irr2: 75% of Field capacity, Irr3: 50% of Field capacity: SA: Salicylic acid, SA1: 0 mM, SA2: 0.25 mM, SA3: 0.5 mM, SA4: 1 mM

3.1.2. Macro and micronutrient contents (mg plant^{-1}) of fresh shoots

The analysis of variance revealed significant differences in nutrient concentrations among different irrigation levels (Table 3). Plants subjected to full irrigation (Irr1) exhibited higher concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) compared to those subjected to reduced irrigation levels (Irr2 and Irr3). Among the irrigation treatments, plants under Irr1 consistently displayed the highest nutrient concentrations across all measured elements. In contrast, plants subjected to 75% field capacity (Irr2) and 50% field capacity (Irr3) exhibited progressively lower nutrient concentrations, with the most pronounced reductions observed in Mg, Cu, Zn, Fe, and Mn Compared to plants under full irrigation (Irr1), those subjected to reduced irrigation levels (Irr2 and Irr3) exhibited an increase in the content of N by 11.1% and 14.2%, P by 13.3% and 16.7%, K by 5.1% and 12.9%, Ca by 3.0% and 15.3%, Mg by 2.7% and 10.8%, and Fe by 7.8% and 24.3% for Irr2 and Irr3, respectively. Notably, Cu content also significant increased with Irr2 showing a 27.0% rise and Irr3 exhibiting a substantial 134.6% increase compared to Irr1 (P=0.001). Interestingly, Mn content displayed the opposite trend, exhibiting a decrease with decreasing irrigation levels. Plants under Irr2 and Irr3 showed reductions of 12.9% and 34.5%, respectively, compared to Irr1.

While most measured nutrients were not significantly affected by SA application, N and Mn content showed a significant increase (0.001) across all irrigation levels and SA doses compared to the control (Table 3 and Figure 1). Across the different treatments, N concentrations ranged from 1.62±0.25 mg kg^{-1} (Irr1xSA2) to 2.80±0.63 mg kg^{-1} (Irr2xSA1). There appears to be a discernible trend suggesting that at the same irrigation level, increasing SA levels caused a significant decrease in the N concentration, while in the SA4 application, the N concentration has been higher at each irrigation level compared to SA2 and SA3 (Figure 1). Moreover, different irrigation levels also exerted influence on N concentration, with Irr1 generally displaying higher N concentrations compared to Irr2 and Irr3 under the same SA treatment. The ANOVA results underscore significant differences (p=0.001) among the treatments for N concentration, implying that both irrigation levels and SA treatments play crucial roles in modulating N uptake of pepper plants. Phosphorus (P) concentration varied significantly across different irrigation and SA treatments. The mean P content ranged from 0.09±0.01% to 0.17±0.03%, indicating notable fluctuations under various experimental conditions (Figure 1). The statistical analysis revealed significant differences in phosphorus concentration among irrigation treatments (P=0.001). However, no significant differences were observed for phosphorus content concerning SA application (P=0.205) or the interaction between irrigation and SA treatments (P=0.413).

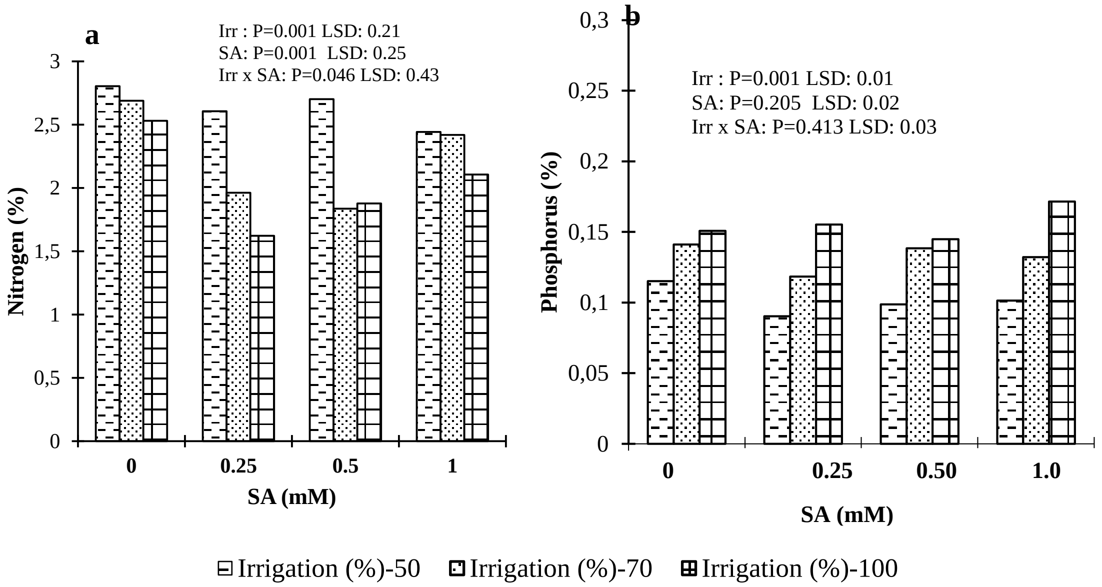

Figure 1. Effects of irrigation and salicylic acid treatments on total nitrogen (a) and phosphorus (b) contents of pepper plants.

Irr1: Full Irrigation, Irr2: 75% of Field capacity, Irr3: 50% of Field capacity: SA: Salicylic acid, SA1: 0 mM, SA2: 0.25 mM, SA3: 0.5 mM, SA4: 1 mM.

Plants treated with SA (SA2, SA3, and SA4) exhibited 22.5% to 41.5% higher Mn concentrations compared to the control. When comparing the effect of SA concentration within each irrigation level, it is evident that the highest SA concentration (1 mM) generally resulted in decreased nutrient levels compared to lower SA concentrations (0.25 mM, 0.5 mM, and 0 mM). This trend was particularly noticeable in plants subjected to Irr1, where higher SA concentrations led to decreased nutrient uptake, indicating a potential inhibitory effect of SA on nutrient absorption. Plants treated with SA (SA2, SA3, and SA4) showed a 22.5% to 41.5% increase in Mn concentration compared to the control (SA1). This suggests a potential role of SA in enhancing Mn uptake or translocation within the plant.

Table 3. Nutrient concentrations of pepper plants under different irrigation and salicylic acid treatments (mean value ± standard deviation)

	K	Ca	Mg	Cu	Zn	Fe	Mn
	mg kg^{-1}						
Irr1xSA1	2.78±0.22c	2.68±0.50b-e	0.74±0.13abc	21.39±12.47b	16.65±5.65c	93.73±9.60bc	82.46±7.20abc
Irr1xSA2	2.93±0.14bc	2.17±0.15e	0.64±0.05c	19.53±7.43b	18.39±2.16bc	91.30±8.80c	69.66±11.69de
Irr1xSA3	3.02±0.23ab	2.67±0.16b-e	0.71±0.03c	17.31±4.45b	16.33±1.92c	103.09±29.97abc	68.64±8.92e
Irr1xSA4	3.00±0.11ab	2.46±0.22cde	0.70±0.05c	14.41±5.0b	18.90±6.26bc	96.55±16.09abc	77.52±7.37b-e
Irr2xSA1	2.92±0.07bc	2.76±0.27a-d	0.72±0.06bc	27.04±11.79b	19.77±5.08bc	101.07±9.83abc	88.60±7.38a
Irr2xSA2	2.95±0.11abc	2.54±0.57cde	0.67±0.08c	26.97±11.30b	18.87±4.87bc	98.87±8.74abc	76.71±4.38cde
Irr2xSA3	3.07±0.07ab	2.30±0.64de	0.69±0.07c	29.93±6.47b	19.66±5.14bc	103.80±28.55abc	80.15±11.17a-d
Irr2xSA4	2.88±0.17bc	2.61±0.12b-e	0.72±0.01bc	30.43±7.22b	17.11±4.05c	97.77±5.97abc	76.21±3.84cde
Irr3xSA1	3.13±0.13a	2.84±0.21abc	0.80±0.08ab	61.47±19.15a	27.09±7.15a	117.078.44±a	90.39±8.21a
Irr3xSA2	3.02±0.10ab	3.09±0.40ab	0.80±0.05ab	53.97±31.80a	24.65±5.95ab	110.60±10.69abc	78.31±4.73b-e
Irr3xSA3	3.04±0.11ab	3.21±0.40a	0.82±0.07a	63.67±17.88a	27.74±5.03a	114.19±15.96ab	87.51±7.20ab
Irr3xSA4	2.99±0.09ab	3.05±0.30ab	0.80±0.09ab	57.27±20.32a	23.98±4.78ab	116.01±14.22ab	88.95±9.41a
Irr (P:LSD)	0.023:0.08	0.001:0.21	0.001:0.04	0.001:8.75	0.001:2.93	0.001:9.18	0.001:4.58
SA (P:LSD)	0.186:0.09	0.715:0.25	0.192: 0.05	0.863:10.10	0.875:3.79	0.670:10.61	0.001:5.29
IrrxSA (P:LSD)	0.041:0.16	0.050:0.42	0.753: 0.08	0.948:17.51	0.713:5.85	0.974:18.37	0.278:9.16

* The difference between letters bearing the same symbols in the same column is not significant ($p<0.05$). Irr1: Full Irrigation, Irr2: 75% of Field capacity, Irr3: 50% of Field capacity: SA: Salicylic acid, SA1: 0 mM, SA2: 0.25 mM, SA3: 0.5 mM, SA4: 1 mM

The interaction between irrigation level and SA concentration was significant for N, K, and Ca content (Table 3). The highest nitrogen (N) concentration was recorded in plants treated with Irr3xSA1 (2.69%), which was approximately 67% higher than the lowest concentration observed in plants treated with Irr1xSA2 (1.62%). Generally, increasing SA application level resulted in a decrease in N concentration, except for the plants treated with Irr1 where the N concentration slightly increased with the increase in SA application level. The highest potassium concentration was observed in the plants treated with Irr3xSA1 (3.13%), while the lowest was recorded in Irr1xSA2 (2.93%). Salicylic acid application did not have a significant effect on potassium concentration. Similar trends were observed for other nutrients, such as P, Ca, Mg, Cu, Zn, Fe, and Mn, with notable differences between treatments.

3.1.3. Total chlorophyll, chlorophyll A and B and carotenoid contents

The analysis revealed that SA application did not significantly affect the chlorophyll content of pepper plants, regardless of irrigation level. This means that across all treatments, the measured values for chlorophyll A (ChlA), chlorophyll B (ChlB), carotenoids, and total chlorophyll did not exhibit any statistically significant increases or decreases compared to the control group (SA1) that received no SA. For Chl A content, the mean values ranged from 1.00±0.19 to 1.39±0.22 mg/g fresh weight, while Chl B content ranged from 0.49±0.05 to 0.74±0.24 mg/g fresh weight (Table 4). Similarly, total chlorophyll content varied from 0.66±0.11 to 0.92±0.24 mg/g fresh weight, and carotenoid content ranged from 1.07±0.12 to 1.50±0.29 mg/g fresh weight (Table 4). Despite some fluctuations in the mean values, the differences were not statistically significant based on the ANOVA results ($P > 0.05$), which could be due to natural variations within the plant population or random error. This suggests that within the tested range, irrigation amount did not have a substantial impact on the concentration of these pigments in the plants, which indicates that the effect of SA on pigment concentrations was not dependent on the irrigation level, and vice versa. The ANOVA revealed no statistically significant interactions between irrigation and SA treatments for any of the measured pigments (ChlA, ChlB, total chlorophyll, and carotenoids). The results indicate that the combined effects of irrigation and SA on chlorophyll content did not vary depending on the specific combination of treatments used (Table 4).

Relative water content (RWC) exhibited variations across different SA treatments and irrigation levels. The RWC values ranging from 79.84±10.42% (Irr2xSA2) to 88.73±2.86% (Irr2xSA4) across treatments suggest varying degrees of water availability and hydration levels in the plants. The relatively lower RWC values in Irr2xSA2 treatment suggest potential water stress under these conditions (Table 4). Electrical conductivity (EC), a measure of membrane permeability, also showed variability among treatments. The EC values ranged from 18.81±0.02% (Irr1xSA1) to 25.24±2.13% (Irr3xSA3), indicating differences in membrane integrity across treatments. Relatively higher EC values suggest increased membrane permeability, possibly due to stress-induced damage. Conversely, lower EC values indicate better membrane integrity under these conditions.

Table 4. Effect of salicylic acid treatment on chlorophyll, carotenoid content and relative water content and electrical conductivity (membrane permeability) in pepper plants under different irrigation levels (mean value ± standard deviation)

Treatments	ChlA	ChlB	Total Chl	Carotenoid	RWC	EC
	mg g^{-1} fresh weight				%	
Irr1xSA1	1.00±0.19	0.52±0.08	0.66±0.11	1.12±0.15	88.26±5.86	18.81± 0.02
Irr1xSA2	1.14±0.30	0.64±0.20	0.77±0.21	1.23±0.27	84.74±3.81	22.02±0.51
Irr1xSA3	1.07±0.11	0.53±0.07	0.68±0.08	1.09±0.12	81.26±1.78	23.30± 2.64
Irr1xSA4	1.26±0.23	0.67±0.14	0.84±0.16	1.27±0.19	81.67±4.17	21.12±2.54
Irr2xSA1	1.18±0.08	0.57±0.05	0.74±0.06	1.27±0.06	85.39±0.55	22.99±3.56
Irr2xSA2	1.39±0.22	0.74±0.24	0.92±0.24	1.50±0.29	87.57±0.82	20.09±2.17
Irr2xSA3	1.08±0.07	0.57±0.01	0.71±0.03	1.21±0.08	87.38±6.34	22.03±1.05
Irr2xSA4	1.12±0.13	0.58±0.05	0.73±0.07	1.27±0.13	88.73±2.86	24.07±3.05
Irr3xSA1	1.09±0.14	0.49±0.05	0.66±0.07	1.07±0.12	84.89±1.86	21.21±1.75
Irr3xSA2	1.29±0.03	0.59±0.01	0.79±0.02	1.37±0.08	79.84±10.42	19.66±0.14
Irr3xSA3	1.22±0.23	0.56±0.10	0.74±0.13	1.32±0.15	86.21±1.67	25.24±2.13
Irr3xSA4	1.35±0.10	0.63±0.07	0.83±0.08	1.41±0.13	85.21±1.25	19.37±1.33
Irr (P: LSD)	0.403:0.177	0.707:0.114	0.229:0.128	0.809:0.168	0.256:4.57	0.726:2.23
SA (P: LSD)	0.210:0.204	0.175:0.132	0.219:0.148	0.180:0.194	0.871:5.28	0.155:2.57
IrrxSA (P: LSD)	0.670:0.353	0.854:0.228	0.685:0.256	0.779:0.337	0.489:9.14	0.152:4.46

* The difference between letters bearing the same symbols in the same column is not significant ($p<0.05$). Irr1: Full Irrigation, Irr2: 75% of Field capacity, Irr3: 50% of Field capacity: SA: Salicylic acid, SA1: 0 mM, SA2: 0.25 mM, SA3: 0.5 mM, SA4: 1 mM, Chl: Chlorophyll, RWC: Relative water content, EC: Electrical conductivity (membrane permeability)

3.2. Discussion

3.2.1. Effects of deficit irrigation and salicylic acid treatment of plant growth parameters of pepper plants

This study investigated the effects of foliar application of salicylic acid (SA) on pepper plants grown under different drought stress (irrigation) levels and its impact on growth and nutrient uptake. The findings demonstrated complex responses in pepper plants to foliar SA application under varying irrigation levels, offering valuable insights into their physiological and nutritional adaptations to drought stress. Drought stress led to a significant decrease in fresh shoot dry matter production, indicating limitations in plant biomass accumulation under water-deficient conditions. This highlights the crucial role of maintaining adequate water availability for optimal pepper plant growth, as water deficiency restricts essential physiological processes. For instance, under control conditions (Irr1xSA1), the fresh shoot dry matter production averaged 29.6±9.5 g plant^{-1}, while it decreased to 27.8±5.4 and 15.8±4.1 g plant^{-1} under 75 and 50% drought stress conditions. Intriguingly, SA application at 1.0 mM (SA4) mitigated this reduction, particularly under severe drought, where dry matter production increased to 40.7±2.8 g plant^{-1} in Irr1xSA4 and 31.7±4.5 g plant^{-1} in Irr2xSA2 demonstrating a notable enhancement in plant biomass under SA treatment. Our findings are in accordance with observations of Ghahremani et al. (2023) regarding the positive impact of SA application on pepper plants under varying irrigation levels. Ghahremani et al. (2023) demonstrated that SA foliar application enhanced drought tolerance in pepper plants by regulating stomatal conductance, increasing leaf chlorophyll content, and improving water use efficiency. These mechanisms likely contributed to the observed increase in fresh shoot dry matter production, nutrient uptake, and yield in our study, particularly at the optimal SA dose of 1.0 mM.

The findings unveiled valuable insights into the morphological adaptations of pepper plants to drought stress and SA treatment, focusing on plant height responses. We observed substantial constraints in vertical growth under water-deficient conditions, with increasing drought stress leading to significant reductions in plant height. For instance, average plant height was 37.8±7.1 cm under control conditions (Irr1xSA1), but it decreased to 29.1±3.2 cm under 50% drought stress (Irr3xSA1). The observed reduction in plant height under drought stress aligns with previous research attributing it to adverse effects on cell turgor pressure, cell expansion rates, metabolic activity, photosynthesis, and nutrient accumulation. SA application may mitigate these effects by enhancing cell turgor pressure, promoting cell expansion, and modulating metabolic processes, thereby supporting plant growth and development even under water-limited conditions (Mahdi Zamaninejad et al. 2013). Mahdi Zamaninejad et al. (2013) found significant mitigation of the reduction in plant height with SA application in corn, while our findings did not show a statistically significant influence of SA on plant height in pepper plants under drought stress. This discrepancy could be attributed to variations in plant species, experimental conditions, SA application methods, or drought severity. In line with the present study, which found that 1.0 mM salicylic acid (SA) application improved fresh shoot dry matter production under 100% drought stress compared to no SA application, Mostafa et al. (2024) reported similar positive effects of SA on pepper plants grown under deficit irrigation (60% of crop evapotranspiration). They observed that 1.0 mM SA application significantly enhanced various growth parameters, including plant height, total chlorophyll content, fruit yield, and total dry matter content, compared to control groups without SA application. These findings collectively suggest that SA application has the potential to alleviate the detrimental effects of drought stress on pepper plants by improving various aspects of their growth and yield.

The results indicated a significant decrease (P=0.01) in dry shoot production with increasing drought stress levels in pepper plants (from 5.7 g in Irr1xSA1 to 3.1 g in Irr3xSA1), while SA application did not substantially influence plant height (P=0.443). This aligns with the findings of Abbaszadeh et al. (2020) on leaf yield being significantly affected by SA in rosemary cultivation, suggesting that SA's impact may vary across different plant growth parameters and crop types. Moreover, the study by Chen et al. (2014) highlights SA's role in enhancing stress tolerance in zoysiagrass, indicating potential variations in SA effects across different crops. However, our findings differ in terms of the optimal SA concentration, with our study showing the highest dry shoot and root matter productions at the 1.0 mM SA dose under severe drought conditions in peppers, while Abbaszadeh et al. (2020) found the highest leaf yield at the 2 mM SA level in rosemary. Overall, the findings of our study highlight the importance of irrigation management and SA application in influencing plant growth. optimizing irrigation levels and utilizing SA treatments could significantly enhance plant productivity and resilience to environmental stressors in agricultural practices.

Based on the ANOVA results provided in Table 2, it is noteworthy that the interaction between irrigation level and SA application levels did not yield significant differences for any of the measured parameters (P>0.05). This implies that, within the examined ranges, the impacts of irrigation and SA on plant growth were not influenced by each other. In other words, the beneficial effects of SA were observed irrespective of the irrigation level, and conversely. This outcome holds promise for practical agricultural applications, as it suggests that growers can optimize irrigation and SA treatments independently to enhance growth without being concerned about intricate interactions.

3.2.2. Effects of deficit irrigation and salicylic acid treatments on nutrient contents of pepper plants

The examination of plant nutrient concentrations in pepper plants grown under different drought stress levels revealed the complexity of nutrient uptake and accumulation in plant organs. Generally, an increase in stress levels was associated with increased concentrations of N, P, K, Fe, and Zn in plant organs. The increase in nutrient content under deficit irrigation conditions can be attributed to the interplay of water uptake and dilution effects (Faloye et al. 2020; Zhao et al. 2020). Under lower irrigation levels (Irr2 and Irr3), reduced water uptake led to a smaller dilution effect within the plant tissues, resulting in higher concentrations of most measured nutrients in the plant tissues, except P and Mn. Overall, phosphorus concentration exhibited a trend of increasing with higher irrigation levels. Pepper plants subjected to full irrigation (Irr1) consistently displayed higher P content compared to those under moderate (Irr2) and severe (Irr3) stress conditions. This observation suggests that water availability positively influences P uptake, as well as Mn uptake, and accumulation in pepper plants. The observed decrease in P and Mn concentrations at lower irrigation levels suggests different uptake or translocation mechanisms specific to these elements.

Salicylic acid has the potential to boost plant resilience against drought. This is achieved by influencing various physiological and biochemical processes within the plant (Khalvandi et al. 2021). However, the influence of SA applications on nutrient concentrations varied, with some nutrients showing decreases and others increases. In general, SA application positively correlated with increased uptake of essential nutrients (K, Mg, and Ca), while drought stress led to significant reductions or increases in nutrient contents, particularly under severe stress levels. The potassium concentrations in pepper plants were influenced by both irrigation levels (P=0.023) and interaction of irrigation level and SA applications (P=0.041). Generally, higher K concentrations were observed with increasing levels of SA application, particularly under severe drought conditions. For instance, under full irrigation (Irr1), the mean K concentration ranged from 2.78±0.22 to 3.13±0.13 mg kg^{-1} across different SA treatments. Interestingly, the highest K concentration was observed under Irr3xSA1 treatment, where the plants received 50% of field capacity irrigation along with 0 mM SA application, suggesting a potential compensatory mechanism in response to water stress. Conversely, under severe drought conditions (Irr3), K concentrations tended to decrease, with the lowest mean value of 2.99±0.09 mg kg^{-1} recorded under Irr3xSA4 treatment. The findings suggest that while SA application may enhance K uptake in pepper plants, the magnitude of this effect is influenced by the level of water availability.

Drought stress induced contrasting responses in micronutrient uptake, with increases in Cu content and decreases in Zn, Fe, and Mn contents. Interestingly, SA application did not significantly influence micronutrient contents, suggesting that its effects may be more focused on macro nutrient dynamics rather than micronutrient uptake.

The observed significant increase in Mn content across all irrigation levels and SA concentrations compared to the control highlights a potential role of SA in influencing Mn uptake or translocation within pepper plants. While most measured nutrients were not significantly affected by SA application, the increase in Mn concentrations suggests a specific responsiveness of pepper plants to SA treatment in terms of Mn assimilation. The plants treated with SA2, SA3, and SA4 exhibited substantial increases ranging from 22.5% to 41.5% in Mn concentrations compared to the control, indicating a dose-dependent effect of SA on Mn uptake or utilization. The findings from Shi and Zhu (2008) align closely with the observations from our study regarding the effect of SA on Mn accumulation in pepper plants. They found that the application of SA mitigated reduced Mn transport from roots to shoots, alleviating the inhibition of Ca, Mg, and Zn absorption induced by excess Mn, and promoted cucumber growth.

The total chlorophyll concentration did not increase with SA applications, but drought stress treatments had similar effects. SA doses did not have a significant effect on RWC, but drought stress treatments did. Although SA application did not significantly affect total chlorophyll concentration or RWC, it induced changes in EC values compared to control conditions, implying potential alterations in ion uptake and water relations in response to SA treatment. Our findings parallel those of Khazaei and Estaji (2020), illustrating the adverse impact of drought stress on sweet pepper plants. Like their study, we observed decreases in shoot and root fresh weight, dry weight, relative leaf water content, fruit dimensions, chlorophyll index, and leaf area under drought conditions. Additionally, both studies noted increases in electrical conductivity in response to drought stress. After foliar application of SA, our results mirrored theirs, showing a decrease in electrical conductivity. However, unlike their study, we did not find statistically significant increases in shoot dry weight, root fresh weight, or chlorophyll index post-SA application. These findings suggest consistent outcomes regarding the detrimental effects of drought stress and the potential mitigating effects of SA, contributing valuable insights for crop management under stress conditions.

3.2.3. Effects of deficit irrigation and salicylic acid treatments on chlorophyll and carotenoid content of pepper plants

Salicylic acid application, at the concentrations and irrigation levels tested, did not have a significant impact on the overall chlorophyll content in pepper plants (P=0:685). The lack of significant differences suggests that SA application did not exert a discernible effect on the chlorophyll and carotenoid concentrations in pepper plants under the experimental conditions tested. This indicates that SA, at the concentrations applied in this study, may not significantly alter the photosynthetic pigment composition in pepper plants. However, it is essential to note that other factors, such as environmental conditions and plant physiological responses, could influence the efficacy of SA treatment, warranting further investigation. While we did not observe significant changes in chlorophyll content upon SA application, our findings differ from those reported by the researchers who observed increased chlorophyll content in pepper plants (Khazaei et al. 2015), basil (Damalas 2019), okra (Ayub et al. 2020), and others treated with SA under drought stress conditions.

Our findings align with observations from Saheri et al. (2020) who investigated the impact of drought stress and SA application on purslane. Both studies observed a negative impact of water limitations on pigment content. Several other studies have proved that drought stress led to significant reductions in chlorophyll A, B, and carotenoid content in purslane leaves (Saheri et al. 2020), rice plants (Kunpratum et al. 2023; El-Okkiah et al. 2022), while SA application improved the content of chlorophyll A, B, and carotenoids in purslane leaves (Saheri et al. 2020), rice plants (Kunpratum et al. 2023; El-Okkiah et al. 2022) and lettuce leaves (Shehata et al. 2020) compared to drought-stressed plants alone.

While we did not find a statistically significant difference between irrigation levels, the overall trend suggests a decrease in chlorophyll and carotenoid content with decreasing irrigation (increased drought stress). This aligns with Ayub et al. (2020) where drought stress (25% field capacity) significantly reduced chl A, B, and total chlorophyll in okra plants. Both studies also hint at the potential benefits of SA in mitigating the negative effects of drought stress on plants. Ayub et al. (2020) observed improvements in various parameters like fresh weight, dry weight, and chlorophyll content in SA-treated okra plants under drought stress. Although our study did not show a significant interaction between irrigation and SA on pigments, the absence of a substantial decrease in pigment concentrations even at lower irrigation levels might suggest some protective effect from SA. However, key differences exist between the studies. The plant species (pepper vs. okra) might have varying responses to drought stress and SA application. Additionally, the SA application method (foliar sprays vs. seed priming) and the severity of drought stress levels differed between the studies, which could explain the observed variations in responses. Several potential mechanisms for SA's positive effects on pigments under drought stress have been suggested including reduced chlorophyll degradation (Saheri et al. 2020), enhanced ROS scavenging (Saheri et al. 2020; Gujjar et al. 2020), increased chlorophyll synthesis (Saheri et al. 2020; Alharbi et al. 2021), and improved water relations (El-Okkiah et al. 2022). These mechanisms could potentially explain why pepper plants in our study maintained pigment levels even under some drought stress when treated with SA.

3.2.4. Effects of deficit irrigation and salicylic acid treatments on relative water content and membrane permeability of pepper plants

The relative water content (RWC) and electrical conductivity (EC) measurements provide insights into the water status and membrane integrity of pepper plants under SA treatments and irrigation levels. The findings on RWC and EC suggest that SA treatment and irrigation levels influence the water status and membrane permeability of pepper plants, highlighting the importance of these factors in plant physiology and stress response mechanisms. As a measure of plant leaf water deficits compared to full turgid pressure, the RWC has been widely used to evaluate plants under varying levels of drought stress, which focus on drought-resistant crops to identify drought-tolerant individuals (Hu and Xiong 2014). Although statistically not significant, we observed a general trend of decreasing RWC with decreasing irrigation levels (increased drought stress). This indicates that plants subjected to greater drought stress had lower water content in their tissues. This finding aligns with well-established knowledge that drought stress disrupts water uptake and transport in plants, leading to cellular dehydration. The findings highlight the importance of maintaining adequate soil moisture for optimal plant growth and physiological function. The lack of a significant effect of SA on RWC in our study suggests that under the conditions employed, SA application might not directly influence water uptake or retention in pepper plants. However, it is important to consider that SA might exert its protective effects through other mechanisms, such as improved stomatal regulation or enhanced antioxidant activity (Khalvandi et al. 2021), which could indirectly contribute to maintaining cellular water content under drought stress. Ghahremani et al. (2023) reported similar findings, observing no significant impact of SA application on water content (not directly measured) in pepper plants under drought stress. However, they suggested that SA might enhance drought tolerance through other mechanisms. The researchers reported that SA application increased the number, size, and total yield of pepper fruits, potentially by regulating stomatal conductance and increasing leaf chlorophyll content (Ghahremani et al. 2023). This aligns with the possibility that SA application, even if not directly affecting RWC, might improve overall plant growth and stress tolerance in pepper plants under drought conditions.

The findings from both our study and Ghehremani et al. (2023) suggest that foliar application of SA holds promise as a practical technique to alleviate drought stress and enhance the productivity of pepper plants, particularly in arid and semi-arid regions. This conclusion is further supported by the research of Damalas (2019), whose findings align with our observations. In his study, Damalas (2019) reported a significant impact of drought stress on sweet basil, leading to a substantial reduction in its relative water content (RWC) by 29.2%. However, they also noted that SA application emerged as a potential solution to mitigate the effects of drought stress. Specifically, sweet basil plants treated with SA exhibited a significant increase in RWC compared to untreated plants, indicating an improvement in water retention under drought conditions. These consistent findings across different plant species underscore the effectiveness of SA as a drought mitigation strategy and highlight its potential for broader application in agricultural settings.

The EC is a measure of the leakage of electrolytes from damaged cell membranes (Bajji et al. 2002). While drought stress can eventually lead to membrane damage (López-Serrano et al. 2019), the lack of a significant increase in EC in our study suggests that the imposed drought stress levels might not have been severe enough to cause widespread membrane disruption in the pepper plants. Additionally, SA application, at the concentrations used in this study, did not significantly alter EC.

4. Conclusion

In this study, we investigated the effects of deficit irrigation and salicylic acid (SA) treatments on the growth parameters and nutrient contents of pepper plants. The results revealed complex effects of SA on pepper plants under varying irrigation levels, offering valuable insights into the physiological and nutritional adaptations of pepper plants to drought stress. As expected, drought stress significantly reduced the dry weight of fresh shoots, highlighting the critical role of adequate water availability for optimal plant growth. However, applying SA at a concentration of 1.0 mM mitigated this reduction, particularly under severe drought conditions. This suggests a significant enhancement in plant biomass accumulation, underlining the potential of SA as a tool to alleviate the detrimental effects of water deficiency on pepper productivity.

Additionally, our examination of nutrient contents revealed intriguing dynamics influenced by both drought stress severity and SA application. As drought stress intensified, concentrations of certain nutrients increased. This can be attributed to the complex interplay between reduced water uptake and the concentration of solutes within the plant. The SA application displayed a positive correlation with the uptake of essential macronutrients, particularly potassium, magnesium, and calcium. This suggests a targeted effect by SA on these crucial nutrients. While the influence of SA on micronutrients was less prominent, a significant increase in manganese (Mn) content was observed across all irrigation levels with SA treatment. This finding suggests a potential mechanism by which SA might enhance Mn uptake or translocation within pepper plants.

While SA application did not significantly alter pigment content, the overall trend suggested a decline in pigment concentrations with increasing drought stress. This decline suggests potential protective role of SA under stress conditions. In summary, our study underscores the importance of optimizing irrigation management and SA application to enhance pepper plant growth and productivity, particularly in water-limited environments. These findings offer valuable guidance for sustainable agricultural practices aimed at mitigating the adverse impacts of drought stress on crop yields.

Declaration of Author Contributions

KYG conceived and designed the experiments, analyzed the data, prepared tables, authored or reviewed drafts of the article, and approved the final draft. GT conceived and designed the experiments, performed the experiments, analyzed the data and approved the final draft.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

References

Abbaszadeh, B., Layeghhaghighi, M., Azimi, R., Hadi, N., 2020. Improving water use efficiency through drought stress and using salicylic acid for proper production of *Rosmarinus officinalis* L. *Industrial Crops and Products*, 144: 111893.

Alharbi, B.M., Abdulmajeed, A.M., Hassan, H.A., 2021. Biochemical and molecular effects induced by triacontanol in acquired tolerance of rice to drought stress. *Genes* 12(8): 1119.

Alotaibi, M., El-Hendawy, S., Mohammed, N., Alsamin, B., Al-Suhaibani, N., Refay, Y., 2023. Effects of salicylic acid and macro- and micronutrients through foliar and soil applications on the agronomic performance, physiological attributes, and water productivity of wheat under normal and limited irrigation in dry climatic conditions. *Plants*, 12(12): 2389.

Ayub, Q., Khan, S.M., Mehmood, A., Haq, N.U., Ali, S., Ahmad, T., Shoukat, M.F., 2020. Enhancement of physiological and biochemical attributes of okra by application of salicylic acid under drought stress. *Journal of Horticultural Science and Technology*, 3(4): 113-119.

Bajji, M., Kinet, J.M., Lutts, S., 2002. The use of the electrolyte leakage method for assessing cell membrane stability as a water stress tolerance test in durum wheat. *Plant Growth Regulation*, 36: 61-70.

Chakma, R., Biswas, A., Saekong, P., Ullah, H., Datta, A., 2021. Foliar application and seed priming of salicylic acid affect growth, fruit yield, and quality of grape tomato under drought stress. *Scientia Horticulturae* 280: 109904.

Chen, Z.L., Li, X.M., Zhang, L.H., 2014. Effect of salicylic acid pretreatment on drought stress responses of zoysiagrass (*Zoysia japonica*). *Russian Journal of Plant Physiology*, 61: 619-625.

Damalas, C.A., 2019. Improving drought tolerance in sweet basil (*Ocimum basilicum*) with salicylic acid. *Scientia Horticulturae*, 246: 360-365.

Dietz, K.J., Zörb, C., Geilfus, C.M., 2021. Drought and crop yield. *Plant Biology*, 23(6): 881-893.

Dorji, K., Behboudian, M.H., Zegbe-Domínguez, J.A., 2005. Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. *Scientia Horticulturae*, 104: b137–149.

El-Okkiah, S.A.F., El-Afry, M.M., Eldeen, S.A.S., El-Tahan, A.M., Ibrahim, O.M., Negm, M.M., Selim, D.A., 2022. Foliar spray of silica improved water stress tolerance in rice (*Oryza sativa* L.) cultivars. *Frontiers in Plant Science*, 13: 935090.

Faloye, O.T., Ajayi, A.E., Alatise, M.O., Ewulo, B.S., Horn, R., 2019. Nutrient uptake, maximum yield production, and economic return of maize under deficit irrigation with biochar and inorganic fertiliser amendments. *Biochar*, 1: 375-388.

Farooqi, Z.U.R., Ayub, M.A., ur Rehman, M.Z., Sohail, M.I., Usman, M., Khalid, H., Naz, K., 2020. Regulation of drought stress in plants. In Plant life under changing environment. Academic Press.

Gençoğlan, C., Akıncı, İ.E., Uçan, K., Akıncı, S., Gençoğlan, S., 2006. Response of red hot pepper plant (*Capsicum annuum* L.) to the deficit irrigation. *Journal of Mediterranean University, Faculty of Agriculture* 19(1): 131-138.

Ghahremani, Z., Alizadeh, B., Barzegar, T., Nikbakht, J., Ranjbar, M.E., Nezamdoost, D., 2023. The mechanism of enhancing drought tolerance threshold of pepper plant treated with putrescine and salicylic acid. *Plant Stress*, 9: 100199.

Gorni, P.H., Brozulato, M.D.O., Lourenção, R.D.S., Konrad, E.C.G., 2017. Increased biomass and salicylic acid elicitor activity in fennel (*Foeniculum vulgare* Miller). *Brazilian Journal of Food Technology*, 20: e2016172.

Gülez, M., Şenol, S., 2002. Detailed soil study and mapping of the experimental field of the soil department of the faculty of agriculture. *Çukurova University Journal of the Faculty of Agriculture*,17(3): 103-110.

Hasanuzzaman, M., Fujita, M., Oku, H., Islam, M.T., 2019. Plant tolerance to environmental stress: role of phytoprotectants. CRC Press.

Hu, H., Xiong, L., 2014. Genetic engineering and breeding of drought-resistant crops. *Annual Review of Plant Biology*, 65: 715-741.

Jones, J.B., Case, J.R., 1990. Sampling, Handling and Analyzing Plant Tissue Samples. In. R.L. Westerman, (Ed), Soil Testing and Plant Analysis, 3rd ed., SSSA Book Series Number 3, SSSA, Madison, WI, pp. 389–427.

Işık, F., 2012. Effect of irrigations based on root density images obtained by minirhizotron camera on root development, yield, and water use efficiencies of pepper. Master's Thesis, Çanakkale Onsekiz Mart University, Graduate School of Natural and Applied Sciences, Çanakkale.

Kaya, A., İnan, M., 2017. The effects of salicylic acid on some morphological, physiological, and biochemical parameters in basil (*Ocimum basilicum* L.) plants exposed to salt (NaCl) stress. *Harran Journal of Agricultural and Food Sciences*, 21(3): 332-342.

Kayabaşı, S., 2011. Investigation of some physiological parameters and proline accumulation in soybean (*Glycine* max L.) grown under drought stress. Master's Thesis, Harran University, Şanlıurfa.

Kereçin, G., Öztürk, F., 2024. The effect of salicylic acid and salt stress on seeder development of some soya (*Glycine max*. L.) cultivars. *ISPEC Journal of Agricultural Sciences*, 8(1): 25–35.

Khalvandi, M., Siosemardeh, A., Roohi, E., Keramati, S., 2021. Salicylic acid alleviated the effect of drought stress on photosynthetic characteristics and leaf protein pattern in winter wheat. *Heliyon* 7(1): e05908

Khazaei, Z., Estaji, A., 2021. Impact of exogenous application of salicylic acid on the drought-stress tolerance in pepper (*Capsicum annuum* L.). *Journal of Plant Physiology and Breeding*, 11(2): 33-46.

Kim, D.S., Hwang, B.K., 2011. The pepper receptor-like cytoplasmic protein kinase CaPIK1 is involved in plant signaling of defense and cell-death responses. *Plant Journal*, 66: 642-655.

Köşkeroğlu, S., 2006. Investigation of proline accumulation levels and stress parameters in maize (*Zea mays* L.) plants under salt and water stress. Master's Thesis, Muğla University, Muğla.

Kuo, S., 1996. Phosphorus. Methods of Soil Analysis, Part 3, Chemical Methods, SSSA Book Series Number 5, SSSA, Madison, WI.

Kunpratum, N., Phalawat, C., Thoradit, T., Kamoltheptawin, K., Thongyoo, K., Khiaokhoen, P., Tunprasert, L., Jiajitsawat, S., Pooam, M., 2023. Effect of salicylic acid on germination and seedling growth of khaorai leum pua petchabun (*Oryza sativa* L.) under combined drought stress. *Plant Physiology Reports*.

Li, Q., Wang, G., Wang, Y., Yang, D., Guan, C., Ji, J., 2019. Foliar application of salicylic acid alleviate the cadmium toxicity by modulation the reactive oxygen species in potato. *Ecotoxicology and Environmental Safety*, 172: 317-325.

López-Serrano, L., Canet-Sanchis, G., Vuletin, S. G., Penella, C., San Bautista, A., López-Galarza, S., Calatayud, Á., 2019. Pepper rootstock and scion physiological responses under drought stress. *Frontiers in Plant Science*, 10: 38.

Maruri-Lopez, I., Aviles-Baltazar, N.Y., Buchala, A., Serrano, M., 2019. Intra and extracellular journey of the phytohormone salicylic acid. *Frontiers in Plant Science*, 10: 423.

Nawaz, M., Ishaq, S., Ishaq, H., Khan, N., Iqbal, N., Ali, S., Alyemeni, M.N., 2020. Salicylic acid improves boron toxicity tolerance by modulating the physio-biochemical characteristics of maize (*Zea mays* L.) at an early growth stage. *Agronomy*, 10(12).

Özdoğan, Ç.T., Tepecik, M., Geren, H., 2021. A preliminary study on the effect of deficit irrigation application on the yield and some yield characteristics of burnet (*Poterium sanguisorba*) in early growth stage. *ISPEC Journal of Agricultural Sciences*, 5(2): 362–371.

Pasternak, T., Groot, E.P., Kazantsev, F.V., Teale, W., Omelyanchuk, N., Kovrizhnykh, V., Mironova, V.V., 2019. Salicylic acid affects root meristem patterning via auxin distribution in a concentration-dependent manner. *Plant Physiology*, 180(3): 1725-1739.

Rai, K.K., Pandey, N., Rai, S.P., 2020. Salicylic acid and nitric oxide signaling in plant heat stress. *Physiologia Plantarum*, 168(2): 241-255.

Sadeghi, M., Dehghan, S., Fischer, R., Wenzel, U., Vilcinskas, A., Kavousi, H.R., Rahnamaeian, M., 2013. Isolation and characterization of isochorismate synthase and cinnamate 4-hydroxylase during salinity stress, wounding, and salicylic acid treat- ment in Carthamus tinctorius. *Plant Signals of Behaviour*, 8: e27335.

Saheri, F., Barzin, G., Pishkar, L., Boojar, M.M.A., Babaeekhou, L., 2020. Foliar spray of salicylic acid induces physiological and biochemical changes in purslane (*Portulaca oleracea* L.) under drought stress. *Biologia*, 75(12): 2189-2200.

Shama, M.A., Moussa, S.A., El Fadel, N.I.A., 2016. Salicylic acid efficacy on resistance of garlic plants (*Allium sativum* L.) to water salinity stress on growth, yield and its quality. *Alexandria Science Exchange*, 37(2): 165-174.

Sharma, A., Sidhu, G.P.S., Araniti, F., Bali, A.S., Shahzad, B., Tripathi, D.K., Landi, M., 2020. The role of salicylic acid in plants exposed to heavy metals. *Molecules*, 25(3): 540.

Shaukat, K., Zahra, N., Hafeez, M.B., Naseer, R., Batool, A., Batool, H., Wahid, A., 2022. Role of salicylic acid–induced abiotic stress tolerance and underlying mechanisms in plants. In Emerging plant growth regulators in agriculture, Academic Press.

Shehata, S.A., Mohamed, M., Attallah, S.Y., 2020. Salicylic acid enhances growth, yield and quality of lettuce plants (*Lactuca sativa* L.) under drought stress conditions. *Journal of Plant Production*, 11(12): 1581–1586.

Shemi, R., Wang, R., Gheith, E.S.M., Hussain, H. A., Hussain, S., Irfan, M., ... Wang, L., 2021. Effects of salicylic acid, zinc and glycine betaine on morpho-physiological growth and yield of maize under drought stress. *Scientific Reports*, 11(1): 3195.

Shi, Q., Zhu, Z., 2008. Effects of exogenous salicylic acid on manganese toxicity, element contents and antioxidative system in cucumber. *Environmental and Experimental Botany*, 63(1-3): 317-326.

Smart, R.E., Bingham, G.E., 1974. Rapid estimates of relative water content. *Plant Physiology*, 53(2): 258-260.

Wei, Y., Liu, G., Chang, Y., He, C., Shi, H., 2018. Heat shock transcription factor 3 regulates plant immune response through modulation of salicylic acid accumulation and signalling in cassava. *Molecular Plant Pathology*, 19(10): 2209-2220.

Wellburn, A.R., 1994. The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. *Journal of Plant Physiology*, 144: 307-313.

Zafar, S., Afzal, H., Ijaz, A., Mahmood, A., Ayub, A., Nayab, A., Moosa, A., 2023. Cotton and drought stress: An updated overview for improving stress tolerance. *South African Journal of Botany*, 161: 258-268.

Zamaninejad, M., Khorasani, S.K., Moeini, M.J., Heidarian, A.R., 2013. Effect of salicylic acid on morphological characteristics, yield and yield components of corn (*Zea mays* L.) under drought condition. *European Journal of Experimental Biology*, 3(2): 153-161.

Zhao, Y., Chen, P., Li, Z., Casa, R., Feng, H., Yang, G., Xu, X., 2020. A modified critical nitrogen dilution curve for winter wheat to diagnose nitrogen status under different nitrogen and irrigation rates. *Frontiers in Plant Science*, 11: 549636.

Zhang, J., Wang, X., Vikash, V., Ye, Q., Wu, D., Liu, Y., Dong, W., 2016. Ros and Ros-mediated cellular signaling. *Oxidative Medicine and Cellular Longevity*, 2016: 4350965

To Cite	Gülüt, K.Y., Taze, G., 2024. Impact of Salicylic Acid Foliar Application on Growth, Nutrient Uptake, and Physiological Responses of Pepper Plants under Deficit Irrigation. *ISPEC Journal of Agricultural Sciences*, 8(2): 310-327. DOI: https://doi.org/10.5281/zenodo.11124802.