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Using Anti-Stress Compounds as Spray on Cucumber Plants Grown Under Greenhouses to Mitigate The Effects of Water Deficit

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Abstract

Water and nutrients are vital environmental factors affecting cucumber growth and productivity. This study, conducted at the Vegetable Research Farm, Faculty of Agriculture, Benha University, during 2022/2023 and 2023/2024, examined the effects of water deficit and foliar anti-stress treatments on growth, chemical composition, and yield of cucumber (var. Bright VZ). Three irrigation levels (100%, 80%, 60% of water needs) were applied using the Class A evapotranspiration method. Foliar sprays included potassium silicate (2 mL/L), salicylic acid (0.5 g/L), calcium + boron (2 mL/L), and a control (tap water). Reduced irrigation negatively affected vegetative growth (plant height, leaves number, fresh and dry weights) and yield traits (total yield, fruit count, water use efficiency), especially at 60%. No significant differences appeared between 100% and 80% irrigation for leaf number, average fruit weight, diameter, or length. The 80% level yielded the highest N, P, K, Ca, and B in tissues. While fruit quality was mostly stable, TSS increased under 60% irrigation. Moderate deficit (80%) did not harm growth or yield and, combined with potassium silicate or salicylic acid, improved outcomes.

Keywords: **C**ucumber, Irrigation, Water productivity Silicat, Salcylic, Calcium, Boron, Potassium.

Introduction

Cucumber (Cucumis sativus L.), a member of the Cucurbitaceae family, is widely cultivated for its edible fruit in open fields and protected systems (Mugwanya et al., 2023). Comprising approximately 95% water, cucumber plays a role in preventing dehydration (Sahin et al., 2015). In Egypt, it is grown in both old and newly reclaimed lands. According to the Egyptian Ministry of Agriculture (2022), old lands accounted for 33,579 feddans with a total production of 357,890 tons (10.658 tons/fed), while new lands comprised 26,181 feddans yielding 236,011 tons (9.015 tons/fed), totaling 59,760 feddans and 593,901 tons with an average productivity of 9.938 tons/fed.

Efficient water and nutrient management is crucial for optimal crop productivity. However, excessive fertilizer use and poor irrigation contribute to environmental degradation **(Li *et al.*, 2024).** Integrating diverse agricultural practices into water-saving strategies, such as reducing irrigation frequency and volume, can regulate soil moisture, reduce transpiration, and improve water use efficiency **(Yan *et al.*, 2019).** Drought is a major abiotic stress that adversely affects cucumber growth and yield **(Rasheed *et al.*, 2020; Sári *et al.*, 2024),** reducing stem length, fruit number, and total yield **(Sahin *et al.*, 2015; Salama *et al.*, 2025; Ezzo *et al.*, 2020).** In cantaloupes, drought stress also reduces chlorophyll content (Moustafa et al., 2024). Enhancing drought tolerance in cucumbers is therefore a key scientific and economic priority in arid regions **(Penella *et al.*, 2014).**

Salicylic acid (SA), a phenolic plant hormone, modulates defense mechanisms against biotic and abiotic stresses **(González-Villagra *et al.*, 2022; El Refaey *et al.*, 2022).** It enhances metabolic efficiency under stress (**Rashad, 2020; Khan *et al.*, 2022),** boosts tolerance to drought (**Nada *et al.*, 2019; Salama *et al.*, 2025),** and promotes synthesis of osmoprotectants like proline, improving growth and yield **(Elhakem, 2020; Mohamed *et al.*, 2023; Halawa *et al.*, 2024).**

Calcium, constituting 60–70% of plant cell walls, is essential for fruit quality and shelf life, helping prevent disorders such as bitter pit and internal breakdown **(Siddique *et al.*, 2017).** Boron supports cell wall formation, sugar transport, hormone regulation, and reproductive development **(Bommesh *et al.*, 2017).** Together, calcium and boron enhance cucumber growth and fruit quality **(Elsisi *et al.*, 2025).**

Silicon (Si), the second most abundant soil element, is a quasi-essential nutrient that improves structural strength, stress resistance, and productivity, especially in cucumbers **(Meunier *et al.*, 2022).** Applied via foliar spray, soil incorporation, or fertigation, it strengthens cell walls and improves plant integrity **(Savvas and Ntatsi, 2015; Colla *et al.*, 2015).** In the form of potassium silicate, it enhances vegetative growth, yield, and storage capacity **(Tahany *et al.*, 2022).**

This study aims to evaluate the effects of different irrigation levels (100%, 80%, and 60%) on cucumber growth, yield, and quality, supported by foliar applications of anti-stress compounds (potassium silicate, salicylic acid, and calcium + boron) to promote sustainability.

2. Materials and Methods

This study was conducted in a greenhouse at the Vegetable Research Farm, Faculty of Agriculture, Benha University, during winter seasons to evaluate the effects of irrigation water deficit and foliar application of anti-stress compounds on cucumber growth, chemical composition, and yield. The commercial cultivar 'Bright VZ' (Vitazad Company, Egypt) was used. Seedlings were transplanted in early November on six ridges (1.2 m wide × 40 m long), each with two rows and 50 cm spacing between plants. Pre-planting soil analysis showed clay soil with 24% silt, 21% sand, and 55% clay. Soil pH was 8.2, EC was 1.5 dS/m, and organic matter content was 2.4%. Available N, P, and K were 28.3, 10.0, and 100.0 mg/kg, respectively.

Irrigation water deficiency levels

Three irrigation levels (100%, 80%, and 60% of water requirements) were determined using the Class A pan evaporation method, based on data from a local meteorological station near Moshtohor. The E_o values recorded for November, December, January, and February were 2.90, 2.26, 2.56, and 3.07 mm/day, respectively. The full irrigation treatment (100%) was estimated according to the following steps:

Etcrop = Eto × K.C. × HR, where, K.C=Crop Coefficient, HR= Housing Reduction= 0.7 (Abou-Hadid et al 1988)

WR = Et crop × L%, WR = Water requirements, L % = Leaching requirement percentage = 1.25.

IR = WR × R,where, WR= Water requirement, R = Reduction factor for drip irrigation= 0.41 (FAO, 1977).

WD = IR × Plant area × EIS, Plant area= 0.375 m2 (1.5 m in width x 0.5 m of the distance between plants /2, EIS= Efficiency of irrigation system= 0.80

Spraying with anti-stress compounds

Foliar applications of potassium silicate (2 ml/L), salicylic acid (0.5 g/L), calcium + boron (2 ml/L), and tap water (control) were applied three times, starting 21 days after planting and repeated at 10-day intervals. The compounds were obtained from Al-Nasr, Al-Fardous, and Al-Gomhoria companies, respectively.

Experimental Design

The experiment followed a split-plot design with three replicates. Deficit irrigation treatments were assigned to main plots, while foliar spray treatments were randomly distributed within sub-plots. Each ridge was divided into four spray treatments. The experimental plot measured 12 m², consisting of a 10 m long and 1.2 m wide ridge, with plants spaced 50 cm apart on both sides.

Evaluation measurements

1. Vegetative growth measurements: At 60 days after planting, three plants per replicate were selected to measure plant height and number of leaves. Fresh weight was estimated by weighing the top three fully expanded leaves and extrapolating based on total leaf number per plant. For dry weight, the sampled leaves were oven-dried at 70°C until constant weight.
2. Chemical contents of leaves: Pre-dried leaves were used and their nitrogen, phosphorus, potassium, calcium and boron contents were estimated based on the methods described by **ADAS/MAFF (1987), Watanabe and Olsen (1965), ADAS/MAFF (1987)** and **Chapman and Paratt (1961)**, respectively.
3. Fruit quality characteristics: The average diameter, length, weight and content of dissolved solids (TSS) of the fruit were measured.
4. Yield characteristics and water productivity : The number of fruits and the total yield of each plant throughout the growing season were estimated, then the water productivity was estimated based on the following equation: WP = Total yield (kg/ m^3)/ Total water consumption (m^3 /fed.) according to **Howell *et al.* (1990).**

Statistical analysis

The Duncan method was used to differentiate between averages based on **Gomez and Gomez (1984).**

Results and Discussion

1. Vegetative growth of cucumber plants

a. Leaves number / plant

As shown in Table 1, deficit irrigation significantly influenced the total number of leaves in both seasons. The highest leaf numbers were recorded at 80% irrigation (35.9 and 34.8 leaves/plant), followed by 100% irrigation (35.1 and 33.5 leaves/plant), while the lowest values were observed under 60% irrigation (32.8 and 32.1 leaves/plant). Foliar application of anti-stress compounds significantly increased leaf numbers compared to the control(tap water). The highest values were obtained with salicylic acid (36.3 and 35.1), calcium + boron (36.0 and 35.3), and potassium silicate (34.5 and 33.0 leaves/plant), whereas the control recorded the lowest (32.6 and 31.4 leaves/plant).

In this connection the highest number of leaves was recorded with calcium + boron foliar application under 80% irrigation (40.7 and 40.0 leaves/plant), followed by salicylic acid under 100% irrigation (37.7 and 36.7 leaves/plant) in the first and second seasons, respectively. Conversely, the lowest values (30.0 and 29.0 leaves/plant) were observed in control plants irrigated at 60% of water requirements.

b. Leaves fresh weight of plant

Table 1 indicates that leaf fresh weight was significantly affected by irrigation levels. Fresh weight declined progressively with reduced irrigation, reaching 250.1 and 346.1 g/plant at 80%, and 213.5 and 299.6 g/plant at 60%, compared to 269.0 and 370.6 g/plant under full irrigation (100%) during both growing seasons, respectively.

Data presented in Table 1 show clearly that the differences between anti-stress compounds were not significant for leaves fresh weight of cucumber plant in 2022/2023 and 2023/2024 seasons. Even so, using salicylic acid as foliar application recorded the highest values compared with other treatments in both seasons.

Leaves fresh weight was significantly influenced by anti-stress compounds under different irrigation levels in both seasons. The highest values were recorded with salicylic acid at 80% irrigation (288 g/plant) in the first season and potassium silicate at 100% irrigation (411.2 g/plant) in the second one . The lowest values were observed in control plants (201.9 and 281.4 g/plant) under 60% irrigation**.**

c.Leaves dry weight of plant

Results in Table 1 show that there is a significant difference among the deficit irrigation water treatments on leaves dry weight of cucumber plant as it decreased gradually with increasing the deficit of irrigation water. This decrease was significant with medium level “80%” (22.7, and 40.4 g/ plant) and high deficit level “60%” (16.7, and 37.1 g/ plant) in comparison with full water requirements “100%” (26.0, and 47.5 g/ plant) of irrigation water in both seasons.

The differences between used anti-stress compounds were significant for leaves dry weight of cucumber plant in both seasons. Where, using Calcium+Boron (23.8 and 46.5 g / plant) recorded the highest values compared to control treatment (19.1 and 37.0 g / plant) in the first and the second seasons, respectively.

Leaves dry weight were significantly affected by anti-stress compounds combined with irrigation levels in both seasons. The highest values (27.9 and 57.2 g/plant) were recorded with calcium + boron under full irrigation (100%), while the lowest (16.0 and 31.1 g/plant) were observed in the control under 60% irrigation (Table 1).

Table 1. Effect of deficit irrigation rates and spraying with anti-stress compounds on leaves number, fresh weight and dry weight of cucumber plants during winter seasons of 2022/2023 and 2023/2024.

Anti-stress	1st season				2nd season			
	100 %	80 %	60 %	Mean	100 %	80 %	60 %	Mean
				Leaves number				
Control (tapwater)	37.0ab	31.0b	30.0b	32.67B	34.0ab	31.3ab	29.0b	31.4B
Potassium silicate	35.7ab	36.0ab	32.0ab	34.56A	35.0ab	33.7ab	30.3ab	33.0A
Salicylic acid	37.3ab	37.0ab	34.7ab	36.33A	36.7ab	34.3ab	34.3ab	35.1A
Calcium Boron	33.7ab	40.7a	33.7ab	36.00A	31.3ab	40.0a	34.7ab	35.3A
Mean	35.9A	35.9A	32.8B		34.3A	34.8A	32.1B	
				Total leaves fresh weight (g)				
Control (tapwater)	280.3ab	237.5ac	201.9c	239.5A	337.4ab	395.7ab	281.4b	337.5A
Potassium silicate	260.0ac	238.5ac	209.8ac	236.5A	411.2a	323.9ab	295.2b	344.5A
Salicylic acid	252.3ac	288.0a	233.4ac	257.9A	374.8ab	346.8ab	326.5ab	349.4A
Calcium Boron	283.3ab	236.3ac	208.7bc	242.8A	359.1ab	317.8ab	295.2b	324.0A
Mean	269.0A	250.1AB	213.5B		370.6A	346.1B	299.6C	
				Total leaves dry weight (g)				
Control (tapwater)	23.3ab	17.8bc	16.0c	19.1B	39.7ab	39.7ab	31.1b	37.0B
Potassium silicate	25.9ab	21.6ab	16.5c	21.4AB	48.2ab	37.4ab	36.2ab	40.4AB
Salicylic acid	27.0a	25.4ab	16.6c	23.0A	45.1ab	41.5ab	41.8ab	42.8AB
Calcium Boron	27.9a	26.1ab	17.6bc	23.8A	57.2a	42.9ab	39.4ab	46.5A
Mean	26.0A	22.7B	16.7B		47.5A	40.4AB	37.1B	

The values that take lowercase letters and similar have no significant difference between them.
The general average values that are capitalized and similar have no significant difference between them..

Vegetative growth traits (leaf number, fresh and dry weight) significantly declined under deficit irrigation, especially at 60% of crop water needs. These results align with **Rahil and Qanadillo (2015), Nada and Abd El-Hady (2019), Masria *et al.* (2021), Parkash *et al*. (2021), Bello *et al.* (2023), and Abd El-Fattah *et al.* (2024).** The decline is likely due to reduced water uptake and limited nutrient availability (N, P, K). Water stress disrupts physiological functions like photosynthesis, and prolonged drought can stunt growth or cause plant death **(Lisar *et al.*, 2012).**

Conversely, adequate soil moisture improves nutrient mobility, enhancing mineral uptake and carbohydrate assimilation, which promotes vegetative growth and fruit development **(Ezzo *et al.*, 2010).** Cucumber plants at 60% irrigation showed weaker growth than those at 80% or 100%, likely due to limited water during critical processes like cell expansion and photosynthesis, reducing carbohydrate accumulation and yield **(Kumar, 2011; Ali, 2016).**

Higher irrigation levels boost gibberellins and auxins, promoting cell division and expansion, thus enhancing vegetative growth **(Rahil and Qanadillo, 2015).** At 60% irrigation, reduced water content lowers leaf turgor, impairing nutrient uptake and cell expansion **(Eltarabily *et al.*, 2019).** Water stress also hinders root development and micronutrient absorption, affecting chlorophyll synthesis **(Farouk and Ramadan, 2012).** Drought lowers photosynthetic efficiency through reduced pigment synthesis and stomatal closure, which limits CO_2 diffusion and Rubisco activity **(Akács *et al.*, 2020; Nematpour *et al.*, 2020; Romdhane *et al.*, 2020; Putti *et al.*, 2023; Murtaza *et al.*, 2016).**

Foliar application of anti-stress compounds notably improved vegetative traits stem length, leaf number, and shoot biomass under both full (100%) and moderate (80%) irrigation. Even at 60% irrigation, treatments with potassium silicate, salicylic acid (SA), or calcium + boron outperformed the unsprayed control. SA enhances stress tolerance by regulating nutrient uptake, cell elongation, pigments, and photosynthesis **(González-Villagra *et al.*, 2022; El Refaey *et al.*, 2022; Khan *et al.*, 2022; Rashad, 2020).** It also boosts carbon metabolism, antioxidant defenses, membrane stability, and protein function, while promoting proline accumulation for stress resilience **(Sharma *et al.*, 2017; Elhakem, 2020).**

2. Chemical composition of cucumber plant leaves:-

a. Nitrogen (N %) content

Table 2 reveal significant differences in N% of cucumber leaves between deficit irrigation water treatments in both seasons , with the highest values at 80% followed by in a decreasing trend 100% and 60% of irrigation requirtment.

The application of several anti-stress compound spraying had a substantial impact on the N content of cucumber leaves in the both seasons.

Using anti-stress compounds as interacted with irrigation water deficit rates during both growing seasons had a substantial impact on the N percentags of cucumber leaves. However, applying potassium silicate topically and irrigating the plants with 80% of the irrigation water in both seasons resulted in the highest values of the nitrogen percentags of cucumber leaves. In contrast, the control treatment, which was irrigated at 60% of the deficit irrigation rates in both seasons, produced the lowest values.

b. Phosphorus (P %) content

Significant variations between the deficit irrigation water treatments on the P% of cucumber leaves over the winter seasons are displayed in Table 2. In both seasons,whereas the maximum P% values were achieved with 80% followed by100% as compared to 60%. The P% concentration of cucumber leaves in both growing seasons was significantly impacted by the spraying application of several anti-stress agent types, as indicated in Table 2. Using salicylic acid produced the highest P% content levels in both seasons. In contrast, the control treatment produced the lowest P% content values in both seasons.

Using anti-stress substances with irrigation water deficit rates during both growing seasons had a substantial impact on the P percentages of cucumber leaves. However, using salicylic acid topically and watering the plants with 80% of the irrigation water in both seasons resulted in the highest values of the P percentage of cucumber leaves. Conversely, the control treatment, which was irrigated with 60% of the deficit irrigation rates in both seasons produced the lowest results.

c. Potassium (K %) content

Significant variations in the K% of cucumber leaves during the winter seasons are evident in the results presented in Table 2 regarding the deficit irrigation water treatments. The mediest level (80%) produced the greatest K% values, followed by 100% compared to 60% in both seasons as shown in Table 2, whereby spraying plants with all of the anti-stress compounds did not significantly affect the K % content of cucumber leaves in the first season. Even so, the highest values were recorded with using Calcium+Boron or salicylic acid in both seasons.

The K% of cucumber leaves were significantly affected by using anti-stress compounds with deficit rates of irrigation water in addition, when the plants were irrigated with 80% of the irrigation water when combined with foliar spray of either calcium + boron or salicylic acid resulted in the highest content of K%.

Table 2. Effect of deficit irrigation rates and spraying with anti-stress compounds on the contents of nitrogen, phosphorus , potassium , calcium and boron of cucumber foliage during winter seasons of 2022/2023 and 2023/2024.

Anti-stress	1st season				2nd season			
	100 %	80 %	60 %	Mean	100 %	80 %	60 %	Mean
				N%				
Control (tapwater)	1.58ad	1.63ab	1.33d	1.58A	1.33ab	1.46ab	1.20b	1.33B
Potassium silicate	1.58ad	1.73a	1.42bd	1.58A	1.54ab	1.69a	1.39ab	1.54A
Salicylic acid	1.51ad	1.66ab	1.36cd	1.51A	1.44ab	1.59ab	1.30ab	1.44AB
Calcium Boron	1.47ad	1.62ac	1.42bd	1.47A	1.44ab	1.58ab	1.30ab	1.44AB
Mean	1.54B	1.69A	1.38C		1.44B	1.58A	1.29C	
			P%					
Control (tapwater)	0.17ac	0.17ac	0.13c	0.15B	0.15ab	0.17ab	0.14b	0.15B
Potassium silicate	0.24ac	0.26ac	0.22ac	0.24AB	0.14ab	0.16ab	0.13b	0.14B
Salicylic acid	0.27ab	0.30a	0.24ac	0.27A	0.21ab	0.23a	0.19ab	0.21A
Calcium Boron	0.16c	0.15bc	0.16bc	0.16B	0.20ab	0.22a	0.18ab	0.20A
Mean	0.21B	0.23A	0.19C		0.18B	0.19A	0.16C	
				K%				
Control (tapwater)	1.06a	1.17a	0.95a	1.06A	0.67cd	0.73bd	0.60d	0.67B
Potassium silicate	1.00a	1.10a	0.90a	1.00A	0.64cd	0.71cd	0.58d	0.64B
Salicylic acid	0.94a	1.04a	0.85a	0.94A	0.90ab	0.99a	0.81ac	0.90A
Calcium Boron	0.97a	1.07a	0.87a	0.97A	0.82ac	0.90ab	0.74bd	0.82A
Mean	0.99B	1.09A	0.89C		0.76B	0.83A	0.68C	
				Ca%				
Control (tapwater)	4.18bc	4.59ac	3.76c	4.18B	3.76cd	4.13bd	3.38d	3.76B
Potassium silicate	4.36bc	4.80ac	3.92c	4.36B	4.83ad	5.31ac	4.83ad	4.83A
Salicylic acid	4.54ac	4.99ac	4.08bc	4.54B	5.67ab	6.23a	5.10ad	5.67A
Calcium Boron	5.73ab	6.30a	5.15ac	5.73A	5.67ab	6.23a	5.10ad	5.67A
Mean	4.70B	5.17A	4.23C		5.63B	6.19A	5.06C	
				B (ppm)				
Control (tapwater)	62.77a	69.04a	56.49a	62.77A	60.73ac	66.81ab	54.66ac	60.73AB
Potassium silicate	49.27a	54.19a	44.34a	49.27A	44.23	48.66ac	39.81c	44.23C
Salicylic acid	60.00a	66.00a	54.00a	60.00A	48.87ac	53.75ac	43.98bc	48.87BC
Calcium Boron	56.47a	62.11a	50.82a	56.47A	63.73ac	70.11a	57.36ac	63.73A
Mean	57.13B	62.84A	51.41C		54.39B	59.83A	48.95C	

The values that take lowercase letters and similar have no significant difference between them.
The general average values that are capitalized and similar have no significant difference between them..

d. Calcium (Ca %) content.

The findings in Table 2 demonstrate that the deficit irrigation water treatments had a substantial impact on the calcium percentage of cucumber leaves in both seasons . In both seasons, 80% gave the highest Ca% values, followed by 100% as compared to 60%.

The Ca content of cucumber leaves throughout both growing seasons was considerably impacted by the spraying application of several anti-stress representative types, as indicated in Table 2. Calcium+Boron produced the greatest values in both seasons, while the control treatment produced the lowest values.

When anti-stress compounds were used with irrigation water deficit rates in both growing seasons, the Ca% of cucumber leaves was considerably impacted. However, the highest calcium percentage values were obtained when calcium and boron were applied topically and the plants were irrigated with 80% of the irrigation water in both seasons. Nevertheless,plants sprayed only with tapwater (control) when irrigated with 60% of the deficit irrigation rates, produced the lowest values in this respect.

E. Boron (B ppm) content.

The findings in Table 2 demonstrate that there were notable variations in the B (ppm) of cucumber leaves under the deficit irrigation water treatments in both growing seasons . In both seasons, the highest B(ppm) values were achieved with 80% irrigation water, followed by 100% and 60%. The types of the anti-stress compounds significantly affected the B (ppm) of cucumber leaves in second season only.

The plants that were irrigated with 80% of the irrigation water and sprayed with calcium+boron had the highest B (ppm) levels. Using potassium silicate as a foliar spray on plants that were irrigated at 60% of deficit irrigation rates produced the lowest B values.

The 80% irrigation level recorded the highest leaf contents of nitrogen, phosphorus, potassium, calcium, and boron, followed by full irrigation, consistent with **Mousavi *et al.* (2009), Nada and Abd El-Hady (2019), and Shehata *et al.* (2019).** Reduced soil moisture often impairs nutrient uptake, as seen in declines of N, K, Ca, and Mg under water stress **(Kaya *et al.*, 2005; Kirnak and Demirtas, 2006; Saffan *et al.*, 2024).** This may result from changes in soil solution chemistry affecting mineral absorption **(Sahin *et al.*, 2015).** The 80% level likely maintained a favorable water–air balance in the root zone, supporting nutrient uptake and growth. Thus, 80% irrigation appears optimal, as water deficits limit cell division, root development, and uptake of key nutrients like nitrogen and magnesium, essential for chlorophyll synthesis (**Yavas and Unay, 2016).**

3. Physical quality of cucumber fruits.

The findings in Table 3 indicate that there were no appreciable variations in either fruit diameter,length or weight between the deficit irrigation water treatments over the winter seasons of 2022–2023 and 2023–2024. Additionally, sucb fruit traits in both seasons were not significantly impacted by any of the anti-stress compounds types that were tested. It is evident from the data in Table 3 that the use of anti-stress chemicals with different irrigation water rates in both seasons had no discernible effects.This could be due to heritability or harvest practices.

As for the effect on TSS persentages,data in Table 3 reveals significant differences in total soluble solids (TSS) between deficit irrigation water treatments during 2022/2023 and 2023/2024, with a significant increase in 60%.

The use of anti-stress compounds significantly impacted TSS in both seasons.Spraying cucumber plants with potassium silicate showing the highest values, while control or Calcium+Boron had the lowest values in this respect.

It is evident from the data in Table 3 that the use of anti-stress compounds with irrigation water deficit rates had a substantial impact on total soluble solids. However, applying potassium silicate topically and irrigating the plants with 60% of the irrigation water in both seasons resulted in the highest values of total soluble solids.

Irrigation treatments did not significantly affect fruit physical traits as length, diameter, and weight likely because cucumbers were harvested at the same maturity stage, aligning with **El-Sisi *et al.* (2025).** Given their rapid growth cycle, cucumbers may tolerate short-term irrigation variations without major impacts on fruit size if baseline water needs are met **(Nikolaou *et al.*, 2017).** The tested variety may also possess genetic resilience to water fluctuations, and sufficient soil moisture across treatments may have buffered differences in physical fruit characteristics.

Interestingly, total soluble solids (TSS) in cucumber fruits increased under 60% irrigation and decreased at 100%, consistent with findings by **Arshad *et al.* (2017) and Nada and Abd El-Hady (2019).** Reduced water uptake limits dilution, concentrating solutes in the fruit. Though cucumber is water-rich, water stress at 60% reduced growth and yield **(Chala and Quraishi, 2015).** However, 80% irrigation supported optimal leaf hydration and greener foliage **(Abou El-Khair, 1999; Mohammed *et al.*, 2021).** The rise in TSS and proline at 60% irrigation may result from enhanced proline biosynthesis and inhibited degradation **(Kishor *et al.*, 2005),** as part of osmotic adjustment. Water deficit can also trigger sugar accumulation and organic acid transformation (**Nahar and Gretzmacher, 2002),** showing irrigation strongly affects cucumber fruit quality traits.

Table 3. Effect of deficit irrigation rates and foliar spray with anti-stress compounds on fruit diameter, length, weight and TSS of cucumber plants during winter seasons of 2022/2023 and 2023/2024.

Anti-stress	1st season				2nd season			
	100 %	80 %	60 %	Mean	100 %	80 %	60 %	Mean
Average fruit diameter (cm)								
Control (tapwater)	2.4a	2.4a	2.4a	2.4A	2.8a	2.5a	2.6a	2.6A
Potassium silicate	2.5a	2.3	2.3a	2.4A	2.6a	2.6a	2.8a	2.7A
Salicylic acid	2.5a	2.6a	2.2a	2.4A	2.6a	2.7a	2.5a	2.6A
Calcium Boron	2.5a	2.7a	2.3a	2.5A	2.8a	2.7a	2.7a	2.7A
Mean	2.5A	2.5A	2.3A		2.7A	2.6A	2.7A	
Average fruit length (cm)								
Control (tapwater)	13.50ab	13.87ab	13.9a	13.51A	14.1ab	14.8a	12.9c	13.9A
Potassium silicate	12.47b	12.03b	12.73b	12.41A	13.7ab	11.8c	13.6ab	13.0A
Salicylic acid	13.10b	12.23b	12.57b	12.63A	14.4ab	14.5ab	13.7ab	14.2A
Calcium Boron	12.77b	12.03	13.60ab	12.80A	13.5ac	13.9ab	14.7a	14.1A

Mean	**12.96A**	**12.54A**	**13.7A**		**13.9A**	**13.7A**	**13.7A**	
				Average fruit weight (g)				
Control (tapwater)	**62.8cd**	**70.6ac**	**64.1bd**	**65.8A**	**70.4ab**	**70.8ab**	**73.8a**	**71.8A**
Potassium silicate	**75.8a**	**64.0bd**	**69.0ad**	**69.6A**	**67.5ab**	**66.2ab**	**62.9ab**	**65.5A**
Salicylic acid	**73.4ab**	**69.6ad**	**67.1ad**	**70.0A**	**60.9b**	**69.0ab**	**68.9ab**	**66.2A**
Calcium Boron	**72.8ac**	**74.8a**	**59.7d**	**69.1A**	**68.6ab**	**68.9ab**	**68.7ab**	**68.8A**
Mean	**71.2A**	**69.7A**	**65.0A**		**66.8A**	**68.7A**	**68.7A**	
				TSS (%)				
Control (tapwater)	**3.7ce**	**3.2e**	**4.3ad**	**3.7B**	**5.2de**	**5.5b**	**4.9f**	**5.2B**
Potassium silicate	**4.6ab**	**4.5ac**	**4.8a**	**4.6A**	**5.4bc**	**5.1e**	**5.8a**	**5.4A**
Salicylic acid	**3.5de**	**4.3ad**	**4.6ab**	**4.1B**	**4.5h**	**4.5h**	**5.3cd**	**4.8C**
Calcium Boron	**3.8be**	**4.2ad**	**4.3ad**	**4.1B**	**4.5h**	**4.7g**	**4.6gh**	**4.6D**
Mean	**3.9B**	**4.0AB**	**4.5A**		**4.9B**	**5.0B**	**5.2A**	

The values that take lowercase letters and similar have no significant difference between them.
The general average values that are capitalized and similar have no significant difference between them..

4. Yield and water productivity

a. Fruit number.

The findings in Table 4 demonstrate that the number of fruits produced per plant throughout the winter seasons varied significantly depending on the deficit in irrigation water treatments. In contrast to 100% (36.9 and 42.3 fruits / plant) in both seasons, there was a considerable reduction in the number of fruits per plant of 60% (24.8 and 36.7 fruits per plant) and 80% (34.2 and 39.3 fruits per plant).

The number of fruits per plant in both seasons was greatly impacted by the types of anti-stress substances. The highest results were obtained with potassium silicate (33.0 and 42.4 fruits /plant) and salicylic acid (33.1 / 40.9 fruits per plant). The control treatment, on the other hand, had the lowest results in both seasons (29.2 / 34.4 fruits per plant).

Table 4 shows that applying anti-stress compounds under irrigation deficit significantly affected fruit number per plant. The highest values (41.3 and 45.3 fruits/plant) were recorded with potassium silicate and 100% irrigation. The lowest (25.0 and 31.3 fruits/plant) occurred under 60% irrigation without compounds.

b. Total yield of cucumber plant (g. /plant).

Results in Table 4 show significant differences among the deficit irrigation water treatments on total fruit yield during winter seasons.

Total fruit yield decreased with reduced irrigation. At 60% irrigation, yields dropped to 1618 and 2499 g/plant, while 80% irrigation yielded 2377 and 2691 g/plant, compared to 2640 and 2813 g/plant at full irrigation (100%). Yield reductions at 60% were 38.8% and 11.2%, while 80% irrigation led to smaller declines of 9.9% and 4.3% in the first and second seasons, respectively.

During both seasons, anti-stress compounds significantly enhanced total fruit yield compared to the control. Potassium silicate (2317 and 2795 g/plant), salicylic acid (2313 and 2678 g/plant), and calcium+boron (2295 and 2736 g/plant) outperformed the control (1922 and 2461 g/plant). Yield increases over control were 20.5% and 13.5% for potassium silicate, 20.3% and 8.9% for salicylic acid, and 19.4% and 11.1% for calcium+boron in the first and second seasons, respectively.

Table 4 shows that total fruit yield was significantly influenced by anti-stress compounds under deficit irrigation in both seasons. The highest yields (3146 and 3081 g/plant) were achieved with potassium silicate and full irrigation (100%), while the lowest (1608 and 2310 g/plant) occurred in the control treatment under 60% irrigation.

c. Water productivity

Results in Table 4 show significant differences among the deficit irrigation water treatments on WP of cucumber plants during winter seasons. In first season, the highest values were obtained with 80% (31.0 kg/m^3), followed by the 60% (28.1 kg/m^3) then 100 % (27.5 kg/m^3) of irrigation water. In the second season, the highest values were obtained with 60% (43.4 kg/m^3), followed by the 80% (35.0 kg/m^3) then 100 % (29.3 kg/m^3) of irrigation water.

The types of anti-stress compounds had a major impact on the water use efficiency of cucumber plants' during both seasons, where by salicylic acid (30.4 and 36.3 kg/m3), calcium+boron (29.6 and 36.8 kg/m3), and potassium silicate (29.8 and 37.3 kg/m3) produced the greatest results in both seasons as compared to the control treatment (25.6 and 33.1 kg/m3).

Data in Table 4 show that water productivity of cucumber plants was significantly influenced by anti-stress compounds under deficit irrigation in both seasons. The highest WP values (35.1 and 44.7 kg/m^3) were recorded with salicylic acid at 80% and 60% irrigation levels in the first and second seasons, respectively. In contrast, the lowest values (21.2 and 26.8 kg/m^3) were observed in the control treatment under full irrigation (100%) in both seasons.

Table 4. Effect of deficit irrigation rates and foliar spray with anti-stress compounds on total yield and water productivity of cucumber plant during winter seasons of 2022/2023 and 2023/2024.

Anti-stress	1st season				2nd season			
	100 %	80 %	60 %	Mean	100 %	80 %	60 %	Mean
				fruit number/ plant				
Control (tapwater)	32.3ab	30.3ab	25.0b	29.2B	36.7ac	35.3bc	31.3c	34.4B
Potassium silicate	41.3a	34.3ab	23.3b	33.0A	45.3a	42.3ab	39.7ac	42.4A
Salicylic acid	34.7ab	39.0a	25.7b	33.1A	43.7ab	41.7ab	37.3ac	40.9A
Calcium Boron	39.3a	33.3ab	25.3b	32.7AB	43.3ab	38.0ac	38.3ac	39.9AB
Mean	36.9A	34.2A	24.8B		42.3A	39.3AB	36.7B	
				Total yield (g/ plant)				
Control (tapwater)	2034bd	2125bd	1608d	1922B	2576ab	2496ab	2310b	2461B
Potassium silicate	3146a	2195bd	1611d	2317A	3081a	2816ab	2489ab	2795A
Salicylic acid	2522ac	2695ab	1721cd	2313A	2625ab	2833ab	2575ab	2678A
Calcium Boron	2856ab	2494ac	1534d	2295AB	2970ab	2617ab	2622ab	2736A
Mean	2640A	2377A	1618B		2813A	2691B	2499B	
				Water productivity (kg/ m^3).				
Control (tapwater)	21.2b	27.7ab	27.9ab	25.6B	26.8e	32.5ce	40.1ac	33.1B
Potassium silicate	32.8ab	28.6ab	28.0ab	29.8A	32.1ce	36.7ad	43.2ab	37.3A
Salicylic acid	26.3ab	35.1a	29.9ab	30.4A	27.3de	36.9ac	44.7a	36.3A
Calcium Boron	29.8ab	32.5ab	26.6ab	29.6A	30.9ce	34.1be	45.5a	36.8A
Mean	27.5B	31.0A	28.1B		29.3B	35.0B	43.4A	

The values that take lowercase letters and similar have no significant difference between them.
The general average values that are capitalized and similar have no significant difference between them..

Deficit irrigation negatively affected cucumber vegetative growth and yield. The 100% and 80% irrigation levels produced significantly higher yields than 60%, likely due to improved vegetative development and dry matter accumulation. Yield and its components declined with increasing water deficit, consistent with findings by Azevedo *et al.* (2016), Elvis *et al.* (2017), Arshad *et al.* (2017), Nada and Abd El-Hady (2019), Shehata *et al.* (2019), Masria *et al.* (2021), Parkash *et al.* (2021), Bello *et al.* (2023), and Khalifa *et al.* (2022).

The yield improvement with potassium silicate application is attributed to its key components potassium and silicon both essential for plant growth and productivity. Potassium enhances fruit yield and quality by facilitating carbohydrate translocation, while silicon, though quasi-essential, supports vegetative growth and stress tolerance. Applied as potassium silicate, this compound significantly boosts growth and yield (Fayed *et al.*, 2021; Meunier *et al.*, 2022; Ghanaym *et al.*, 2022). The superiority of calcium boron over the control is likely due to calcium's vital roles in plant physiology. As a key structural component of cell walls, it maintains integrity, supports membrane function, and facilitates nutrient and water transport. Calcium also acts as an enzyme cofactor, enhancing growth and fruit quality while reducing postharvest disorders like bitter pit and internal breakdown (Siddique *et al.*, 2017). Calcium preserves fruit texture and flavor by maintaining cell structure, while boron reinforces cell walls, regulates sugar transport, and supports hormone activity, flowering, and fruit set (Bommesh *et al.*, 2017). Their combined application enhances cucumber growth, yield, and quality by strengthening tissues, improving stress tolerance, and supporting reproductive development. This synergy also extends shelf life, reduces postharvest losses, and enhances marketability under environmental stresses (Elsisi *et al.*, 2025).

Conclusions

The results highlight that moderate irrigation (80%) yielded comparable or superior outcomes to full irrigation (100%) and outperformed deficit irrigation (60%) in fruit number, total yield, and water productivity. Anti-stress compounds particularly potassium silicate and salicylic acid significantly enhanced these traits, especially under 80% irrigation. The greatest improvements were observed when these compounds were combined with moderate irrigation, confirming their synergistic effect in mitigating water stress and optimizing cucumber yield.

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