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Article

Response Productivity of Strawberry Plants Grown Under Water Stress Conditions to Spraying with Cerium Oxide, Selenium and Salicylic Acid

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Abstract: Field experiments were carried out at the Horticulture Research Station, El-Kanater El-Khiria, Qalyubia Governorate, Agricultural Research Centre, Egypt during the 2023/2024 and 2024/2025 growing seasons. The study aimed to evaluate the impact of varying irrigation water levels (100%, 80%, and 60% of crop evapotranspiration, ETc) combined with foliar applications of stimulant substances, including 5 mg/L selenium, 100 mg/L Salicylic acid, and 3 mg/L cerium oxide on vegetative growth, chemical composition, fruit yield and its components, as well as fruit quality of strawberry plants cv. Festival. The results show that irrigation levels at 100% and 80% combined with spraying plants four times with selenium, salicylic acid and cerium oxide after 45 days from transplanting significantly increased all vegetative growth characters, N. P. K. and total carbohydrate in plant foliage, fruit yield and its components as well as physical and chemical fruit quality. While the percentage of proline increased significantly at the 60% irrigation level. Deficit irrigation at 60% Etc. when paired with selenium resulted in the highest water productivity (11.17 kg/m³ and 10.29 kg/m³ in the two seasons, respectively), followed by salicylic acid indicating that both selenium and salicylic acid significantly improve strawberry crop water productivity (water-use efficiency) under conditions of water stress compared with the control, with selenium demonstrating the most pronounced effect across both seasons.

Key words: Strawberry, Water stress, Selenium, Salicylic acid, Cerium oxide, Growth, Yield.

1. Introduction

Strawberry (*Fragaria* X *ananassa* Duch.), classified under the Rosaceae family, is a highly valued cash crop in Egypt, strawberry has gained its value for several reasons: for its direct consumption as fresh fruit in the domestic market, for its usage in industrial processes, and for its economic importance as exportable crop. The cultivated area of strawberry in Egypt has significantly expanded in recent years covering up to around 24 thousand hectares yielding more than 687,500 tons. In 2024, Egypt strawberry export volume, reached up to 54,000 tons of fresh strawberries and approximately 140,000 tons of frozen ones (**M.A.L.R., 2024**). Reports from UN World Trade Center indicated that Egypt has become world's top leading exporter of frozen strawberries with 140,000 tons (14,3 %) of accounting for 20% of the global export share valued at $165 million in 2022 (**M.A.L.R., 2024) FAO, 2023**). Strawberries are well-known for their nutritional benefits for humans. They contain high concentration of vitamin C, essential minerals such as potassium and iron, and various types of antioxidants, dietary fiber, natural sugar, and bioactive metabolites. **(Halvorsen *et al.,* 2002 and Mohamed *et al*., 2021)**. Despite the prevalent use of modern irrigation in strawberry cultivation, there remains ambiguity regarding the exact quantity of water required. Previous studies have reported a broad spectrum of consumptive water usage, ranging from 300 mm **(Trout and Gartung, 2004)** to 797 mm **(Strand, 2008).** A similar scenario exists with water application rates varying between 4071 and 15,214 m^3 ha^{-1} **(García Morillo *et al.,* 2015a)**. To enhance their irrigation methods, farmers require tools to accurately calculate the irrigation needs for strawberries. In this regard, the FAO has established a methodology based on crop coefficient (Kc) and reference evapotranspiration (ETo) **(Doorenbos and Pruitt, 1977).** This methodology has been implemented globally to ascertain crop water requirements. The FAO-56 Irrigation and Drainage Paper **(Allen *et al.,* 1998)** manual provides some general Kc values for strawberry cultivation. Even in terms of water productivity, there exists a significant range of values from 4.0 kg. m^{-3} **(Kirschbaum *et al.,* 2003**) to 14.67 kg. m^{-3} **(Serrano *et al*., 1992).** Vulnerable to drought stress, strawberries growth, development and yield can be significantly inhibited due lack of water **(Gerhmann, 1985). Yang *et al*. (2025)** reported that increasing water stress levels in strawberry plants led to reduced fruit yield and single fruit weight, particularly under moderate and severe deficit conditions compared to full irrigation. Yield decreased significantly (by up to 35% in some cultivars under severe stress), alongside lower titratable acidity, while quality parameters like vitamin C, soluble sugars, and the sugar-acid ratio improved. The most pronounced negative effects on yield occurred during critical stages such as seedling growth and fruit color-turning (maturation), though water restriction during reproductive phases generally limited fruit size and overall production. Similarly**, Dal Magro *et al.* (2026)** found in soilless cultivation that strawberry plants under mild water deficit or standard irrigation maintained higher yields than those exposed to moderate or severe deficit, with severe stress notably reducing total number of fruits and productivity. Mild stress had limited impact on yield but influenced fruit quality traits like lower acidity.

These results align with **Raffaelli *et al.* (2025)**, who observed that while some cultivars of strawberry plants showed slight yield increases (e.g., up to 10% in one case) under moderate stress, overall water limitation during key reproductive periods tended to constrain fruit development, though it often enhanced sensorial and nutritional quality (e.g., higher soluble solids and citric acid).

Salicylic acid, a phenolic compound and a natural plant hormone, functions both as a signaling molecule and as an enhancer for treated plants in their response to biological stresses. **(Khan *et al.,* 2012).** It can be found in a diverse array of plants and is utilized as a systemic approach to address biotic challenges. SA plays a direct role in promoting plant growth, facilitating ion absorption, and aiding the movement of nutrients within the tissues of plants **(Meena *et al.,* 2001).** Furthermore, Salicylic acid (SA) is crucial for maintaining water balance, improving photosynthesis, and stimulating plant development **(Arfan *et al.,* 2007).** Previous studies on the external application of S.A. have indicated positive responses such as an increase in yield **(El-Tayeb, 2005; Khodary, 2004; Yildirim *et al.,* 2008; Larque-saavedra and Martin-Mex, 2007)**, more efficient photosynthesis (**Singh and Usha, 2003),** higher levels of total anthocyanin and suppression of ethylene production **(Hernandez and Vargas, 1997),** and more resistance to both biotic and abiotic stresses **(Doares *et al.,* 1995 and Karlidag *et al.,* 2009).**

Though it is a trace element in plants, selenium is well-known to be a crucial mineral nutrient for humans' nutrition **(Bybordi, 2016)**. Selenium has the potential to directly elevate the concentration of antioxidants in plants under stress, thereby improving their tolerance to the stress condition **(Sousa. *et al.,* 2023).** Selenium possesses a notable capacity to absorb excessive free radicals in plants, while also enhancing resistance to drought, metal contamination, and salinity. Furthermore, selenium contributes to the enhancement of nutritional quality and flavor in fruits **(Huang *et al.,* 2018 and Hasanuzzaman *et al.,* 2020).** In recent years, studies have underscored the importance of selenium as a natural fortification in strawberry, especially its role in tolerating environmental stressors (**Iqbal *et al.*, 2022 and Yuan *et al.*, 2024).** Yet, these studies on selenium as a quality improver in strawberries and stress tolerance enhancer are still insufficient.

CeO_2, which act as antioxidants, play a significant role in the field of plant biology **(Wang *et al.*, 2013).** Moreover, by reducing excessive ROS, they can also enhance the plants' resilience to environmental stresses as salinity. **(Wang *et al.*, 2013 and Rossi *et al.*, 2017),** excessive sunlight and severe climate changes **(Rossi *et al.*, 2017).** These nanoparticles, according to **Wu *et al.* (2017)** can improve plant's resistance against drought by modifying the functions of proteins associated with K^+ release which improve mesophyll K^+ storage and activate the transcription of the HKT1 gene to enhance shoot Na^+ exclusion. However, many researches have shown that the dosage of CeO_2 can either increase or reduce stress in plants (**Prakash *et al.*, 2021**). CeO_2 can also control oxidative stress **(Khan *et al.*, 2021).**

The present research was conducted to examine the response productivity of strawberry plants grown under water stress conditions when treated with Cerium oxide, Selenium and Salicylic acid.

2. Materials and Methods

Field experiments were conducted over two consecutive seasons, specifically 2023/2024 and 2024/2025, at the El-Kanater El-Khiria Horticulture Research Station located in the Qalyubia Governorate, (latitude 30°17′25.7″N 31°11′50.1″E) under the auspices of the Agricultural Research Center (ARC) in Egypt. This study focused on the application of various irrigation water levels and the foliar application of certain anti-water stress stimulants, assessing their effects on the vegetative growth, chemical composition, fruit yield, and quality of strawberry plants (*Fragaria* X *ananassa* Duch) cultivar Festival. Prior to transplanting, the transplants were immersed in a Vitavax solution at a concentration of 2.5 g/liter for a duration of 15 minutes to disinfect against pathogens. The soil type of the experiment site is characterized as clay loamy, with the physical analyses of the soil, bulk density and water-soil characteristics, described in Table (1). Furthermore, the meteorological data pertinent to the experimental site is presented in Table (2)

Table (1). The physical characteristics and soil-water parameters of the experimental soil

Particle size distribution (%)							**Value**
Clay %							32.4
Silt %							35.3
Fine sand %							31.1
Coarse sand %							1.2
Texture class							Clay loam
Some soil - water parameters and bulk density							
Depth	**Field capacity (FC)**		**Wilting Point (WP)**		**Available water (AW)**		**Bulk density (BD) g/cm^3**
	% by weight	**Mm**	**% by weight**	**Mm**	**% by weight**	**Mm**	
0-15	38.2	67.6	18.3	32.4	19.9	35.2	1.18
15-30	37.1	67.3	17.7	32.1	19.4	35.2	1.21
30-45	34.6	63.8	17.4	32.1	17.2	31.7	1.23
45-60	32.3	64.0	16.6	32.9	15.7	31.1	1.32
Total		**262.7**		**129.5**		**133.2**	

Table (2). Meteorological data for the experimental location for 2023/2024 and 2024/2025 seasons

Month	2023/2024						
	T max	T min	WS	RH	SS	SR	RF
October	32.0	19.4	2.6	58.1	8.6	17.4	53.0
November	26.7	14.9	2.4	65.1	7.8	13.8	5.3
December	22.5	11.5	2.4	71.7	6.5	11.3	26.0
January	20.4	8.3	2.2	59.2	6.7	12.1	4.4
February	21.3	8.2	2.4	61.3	7.3	15.0	7.6
March	25.6	10.3	2.5	51.6	9.1	19.9	3.0
April	31.9	14.9	3.2	46.4	9.8	23.4	1.3
May	34.2	17.6	3.2	39.9	11.5	27.0	1.2
2024/2025							
October	31.5	17.4	3.1	54.0	9.8	18.9	0
November	25.5	13.4	2.5	60.3	7.6	13.6	0.0
December	21.4	9.0	2.5	63.7	7.2	12.0	1.6
January	21.9	9.3	2.2	61.9	7.3	12.8	0.0
February	19.9	6.9	2.7	59.4	7.2	14.9	0.0
March	26.8	11.0	2.6	52.6	9.3	20.2	1.0
April	29.6	13.7	3.1	44.6	9.6	23.1	32.3
May	34.4	17.5	3.3	37.8	11.3	26.7	1.0

T max, T min = maximum and minimum temperatures °C; WS = wind speed (m / sec^{-1}); RH = relative humidity (%); SS = actual sunshine duration (h/day^{-1}); SR = solar radiation (MJ/ m² / day^{-1}); RF = rainfall (mm / $month^{-1}$).

The experimental plot covered an area of 16.8m², consisting of 2 beds, each measuring 7 m^2 in length and 1.20 m^2 in width. Each bed contained 2 rows, with transplants spaced 25 cm apart within the same row. Transplanting occurred on the 5nd and 3rd of October in the years 2023/2024 and 2024/2025, respectively. Initially, sprinkler irrigation was implemented for the first month; then, the beds were covered with 40-micron black plastic mulch. Following this, drip irrigation was utilized until the conclusion of the growing season.

The experimental treatments were organized in a split-plot design, comprising three replicates that included two factors and a total of 12 treatments (3 irrigation treatments x 4 stimulants treatments).

The treatments were as follows:

A: Irrigation treatments (main plots)

3 different amount of irrigation water, calculated using the Penman-Monteith equation, were evaluated in this study. The irrigation treatments were as follows:

1. Irrigation with a water amount equivalent to 100% of the potential evapotranspiration (ETc).
2. Irrigation with a water amount equivalent to 80% of the potential evapotranspiration (ETc).
3. Irrigation with a water amount equivalent to 60% of the potential evapotranspiration (ETc).

Irrigation treatments were started six weeks after planting.

B: Stimulant substances (sub-plots)

1. Untreated (control) tab water.
2. Foliar spray with selenium at 5mg/L (Se).
3. Foliar spray with salicylic acid at 100 mg/L (SA).
4. Foliar spray with cerium oxide at 3 mg/L (CeO_2).

Selenium and salicylic acid which was produced by El-Gomhouria company in Egypt while cerium oxide sourced from Warchem company in Poland.

Foliar spray applications commenced 45 days post-transplantation and were administered every 15 days totaling 4 times during the growing season.

Crop-soil-water relations

Calculation of crop coefficient and evapotranspiration

Reference crop evapotranspiration (ET_o)

ETo values were derived from the local meteorological data of the experimental site (Table 3) and were computed in accordance with the Penman-Monteith equation (**FAO, 1998**). The calculations .(were executed utilizing the CROPWAT model (**FAO, 1992**)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$$

Where: ET_o: reference evapotranspiration (mm day^{-1}),
R_n: net radiation at the crop surface (MJ m^{-2} day^{-1}),
G: soil heat flux density (MJ m^{-2} day^{-1}),
T: mean daily air temperature at 2 m height (°C),
u_2:wind speed at 2 m height (m s^{-1}),
e_s: saturation vapor pressure (kPa),
e_a: actual vapor pressure (kP)
e_s-e_a: vapor pressure deficit (kPa),
Δ: slope of the vapor pressure-temperature curve (kPa $°C^{-1}$),
γ: psychrometric constant (kPa $°C^{-1}$).

Crop evapotranspiration (ETc)

The ETc values were determined using the equation provided by **(FAO 1977)**

$$\mathbf{ETc = ETo \times Kc}$$

Where:

ETc: crop evapotranspiration (mm day^{-1})

ET_o: reference crop evapotranspiration (mm day^{-1})

Kc: crop coefficient.

Amount of applied irrigation water (AIW)

The quantities of irrigation water utilized were determined using the formula provided by **Vermeiren and Jopling (1984)** as follows:

$$\mathbf{AIW} = \frac{\mathbf{ETc} \times \mathbf{Kr} \times \mathbf{I}}{\mathbf{E}\boldsymbol{a}\,(\mathbf{1} - \boldsymbol{LR})}$$

Where:

AIW: depth of applied irrigation water (mm).

Etc : crop evapotranspiration (mm day^{-1}).

Kr: reduction factor that depends on ground cover.

I: irrigation interval (days).

Ea: irrigation application efficiency for the drip irrigation system (≈ 90% at the site location).

LR: leaching requirements.

The farm's drip irrigation system incorporated a 2 hp water pump linked to both sand and screen filters, along with a fertilizer injector tank. The pipeline system for conveying water features a PVC main line with a diameter of 63 mm, which connects to a sub-main line measuring 38.1 mm. Each of these lines is supported by two lateral lines positioned approximately 30 cm apart. The lateral lines are connected to the manifold line and are fitted with built-in emitters that have a discharge rate of 4 L/h, spaced 0.30 m apart.

Table (3). Penman Monteith equation in 2023/2024 and 2024/2025 seasons

Season / Month		Penman Monteith ETo			
		2023/2024		2024/2025	
	Kc	mm/day	mm/month	mm/day	mm/month
October	0.5	4.11	127.4	4.64	143.8
November	0.7	3.65	109.5	3.72	111.6
December	0.9	3.29	102.0	3.49	108.2
January	1.0	3.72	115.3	3.87	120.0
February	1.09	4.01	112.3	3.98	111.4
March	0.9	5.15	159.7	5.37	166.5
April	0.8	6.85	205.5	6.43	192.9
May (15 days)	0.7	7.67	115.1	7.81	117.2
Seasonal (mm)	-	-	**1046.7**	-	**1071.6**

Data recorded

Vegetative growth characteristics

After 130 days post-planting, five plants were sampled from each experimental unit in the field trials. Measurements taken included plant height (cm), fresh and dry weight per plant (g), number of leaves per plant, number of crowns, crown diameter (cm) and leaf area (cm^2).

Additionally, the chemical composition of the plant foliage was analyzed, focusing on total carbohydrates, nitrogen, phosphorus, and potassium content. These analyses were conducted following methodologies outlined by **A.O.A.C. (1990), Pregl (1945), John (1970),** and **Brown and Lilleland (1946).** Proline was determined colorimetrically as (µg /g F.W) according to **Bates *et al.*, (1973).**

Fruit yield and its components

Early fruit yield was measured by the total weight of all fruits harvested at the ripe stage during December and January. Exportable yield was evaluated based on the weight of fruits harvested at the 3/4 color stage during December and January excluding any misshapen fruits. Additionally, the total fruit yield was recorded per plant and per feddan. Marketable yield was determined after removing all infected fruits. Unmarketable yield represented the total weight of infected fruits collected throughout the harvesting season.

Physical and chemical fruit quality

A random sample of 10 fruits at the marketable stage was collected from each experimental plot to evaluate the following properties: average fruit weight, fruit length, fruit diameter, and firmness. Additionally, total soluble solids (T.S.S.), total titratable acidity, ascorbic acid, and anthocyanin levels were analyzed following the method described in **A.O.A.C. (1990).** Total sugars were assessed using the procedure outlined by **Nelson (1974).**

Soil Physical Analysis

The particle size distribution was assessed utilizing the pipette method as outlined by **Piper (1950).** The soil moisture constant was measured with the pressure membrane apparatus, taking into account the saturation percent "SP" at 0 kPa tension, field capacity "FC" at 33 kPa (0.33 bar) tension, and wilting point "WP" at 1.5 MPa (15-bar) tension. The available water was defined as the difference between FC and WP **(Stackman, 1966).**

Crop water productivity (CWP)

(CWP) represents the crop yield achieved per unit of irrigation water applied, focusing on the efficient utilization of this water resource **(Zhang, 2003)**. It is defined as follows:

$$WP = \frac{\text{Yield kg fed.}^{-1}}{\text{Applied irrigation water m}^{3}\text{ fed.}^{-1}}$$

Statistical analysis

All gathered data underwent statistical analysis as per **Sndecor and Cochran (1991)**, where the least significant difference was taken into account whenever feasible.

3. Results and Discussion

Water relations

Water requirements for strawberry

The impact of the evaluated irrigation treatments on the volume of irrigation water utilized, quantified in liters per day, cubic meters per fed. per month, and cubic meters per fed. per year for the growing seasons of 2023/2024 and 2024/2025, is detailed in Table (4). The findings indicate that the volumes of irrigation water applied were 2671, 2110, and 1629 m^3/fed./year during the first season, and 2722, 2151, and 1661 m^3/fed./year in the second season for the (100% ETc), (80% ETc), and (60% ETc) irrigation treatments, respectively. The data reveal that the total seasonal water applied is greater in the second season compared to the first. These results can primarily be attributed to variations in climatic conditions

In Egyptian conditions, strawberry is a relatively high water-demand crop (≈ 650 mm/season), with peak requirements in spring. Using 80% ETc is generally a S.A.fe and sustainable deficit-irrigation strategy that can reduce water use by 20–21% while maintaining commercially acceptable yield and often improving fruit sweetness and shelf life. Severe deficit (60% ETc) should be avoided unless water availability is critically limited. Precise drip irrigation and regular monitoring of soil moisture or plant water status are strongly recommended, especially during March and April.

Table (4). Monthly and seasonal applied irrigation water to strawberry plants by drip irrigation system in 2023/2024 and 2024/2025 growing seasons

Month	Irrigation treatments					
	100% ETc		80% ETc		60% ETc	
	m^3/fed. /day	m^3/fed. /month	m^3/fed. /day	m^3/fed. /month	m^3/fed. /day	m^3/fed. /month
2023/2024						
October	6.39	198.2	5.05	156.6	3.90	120.9
November	7.95	238.5	6.28	188.4	4.85	145.5
December	9.21	285.6	7.28	225.6	5.62	174.2
January	11.57	358.8	9.14	283.4	7.06	218.9
February	13.60	380.8	10.74	300.8	8.29	232.3
March	14.42	447.0	11.39	353.1	8.80	272.7
April	17.05	511.5	13.47	404.1	10.40	312.0
May	16.70	250.6	13.20	197.9	10.19	152.8
Seasonal (m^3/fed..)		**2671**		**2110**		**1629**
2024/2025						
October	7.22	223.8	5.70	176.8	4.40	136.5
November	8.10	243.0	6.40	192.0	4.94	148.3
December	9.77	302.9	7.72	239.3	5.96	184.8
January	12.04	373.2	9.51	294.9	7.34	227.7
February	13.50	377.9	10.66	298.5	8.23	230.5
March	15.04	466.1	11.88	368.2	9.17	284.3
April	16.00	480.1	12.64	379.3	9.76	292.9
May	17.01	255.1	13.44	201.6	10.38	155.6
Seasonal (m^3/fed..)		**2722**		**2151**		**1661**

Monthly water requirements for strawberry crop

Data in Table (4) and Fig (1) indicate that water requirements of strawberry increase gradually from the beginning of the season in October, reach their peak during spring, and then drop sharply toward the end of the season in May.

In October, water needs are relatively low because the plants are still in the establishment and early flowering stage. At full irrigation (100% ETc), the requirements range between 198–224 m^3/feddan, and can be reduced to 120–137 m^3/fed.dan under the 60% ETc treatment. During November, water demand rises slightly as vegetative growth accelerates, reaching 238–243 m^3/feddan at 100% ETc and 145–148 m^3/feddan at 60% ETc. From December through February, water requirements continue to increase noticeably due to cooler winter weather, larger plant canopy, and intensive flowering. Monthly needs range from 286 to 380 m^3/feddan at full irrigation, and can be lowered to 174-232 m^3/feddan at the 60% level. There was positive correlation between monthly water requirements of strawberry (Table 4 and Fig 1) and meteorological data (temperatures, wind speed, relative humidity, actual sunshine duration, solar radiation and rainfall) during growing season as shown in Table 2.

The true peak in water demand occurs in March and April, which are by far the most critical months. These periods coincide with fruit set, berry enlargement, and ripening. Water requirements reach their highest levels of the entire season (447–511 m^3/feddan per month at 100% ETc). A lack of water over these two months directly leads to a notable reduction in both fruit size and overall yield. In May, as harvesting nears completion and the plants begin to senesce, water requirements drop sharply to only 250–255 m^3/feddan at full irrigation and 155–202 m^3/feddan at the lowest treatment.

Overall, one feddan of strawberry in Egypt requires approximately 2,670–2,720 m³ of water throughout the entire season (October to May) when irrigated at 100% ETc. Applying only 80% ETc saves about 560–570 m³/feddan (20–21%) with usually minimal impact on yield in most modern cultivars, and often improves fruit sweetness and shelf life. The 60% ETc treatment saves nearly 39–40% of the water but typically results in noticeable reduction in both yield and fruit quality. Therefore, the majority of strawberry growers are advised to adopt the 80% ETc strategy as an ideal balance between water conservation and maintaining high productivity and excellent fruit quality, while ensuring that no water deficit occurs especially during March and April. **Klar *et al.* (1990)** studied the influence of drought on strawberry through three phases. They found out that water stress through the vegetation stage had no significant influence on fruit yield. Conversely, the absence of water during both the flowering and fruit formation stages adversely impacted the ultimate yield and the water content within the fruit; however, the levels of vitamin C remained stable.

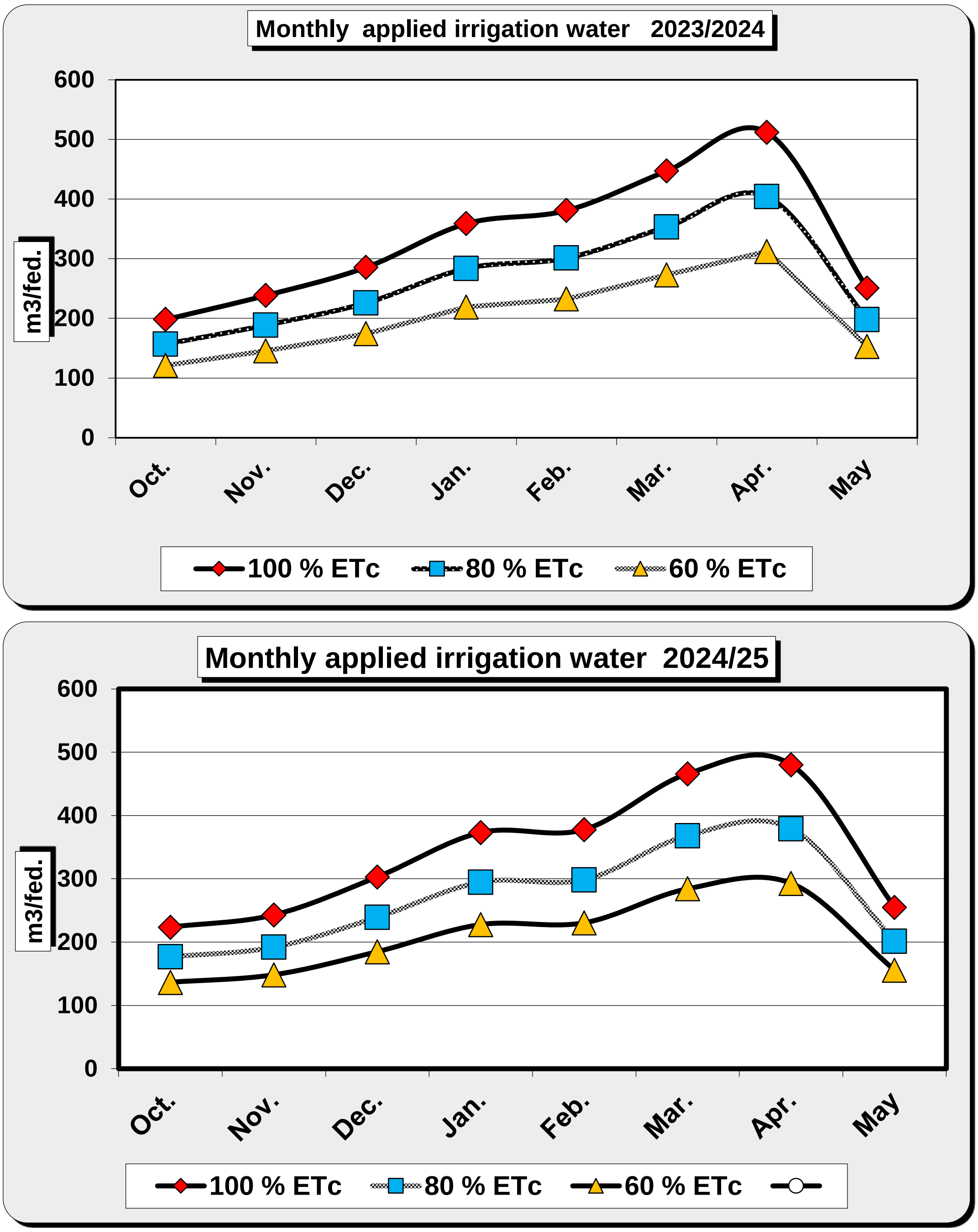

Fig (1). Monthly applied irrigation water under irrigation treatments in 2023/2024 and 2024/2025 seasons

Vegetative growth characteristics

According to the data presented in Tables 5 and 6 irrigation rates across the two seasons significantly influenced the vegetative growth traits. This impact was evident in parameters such as plant height, fresh weight and dry weight per plant, leaves number, crowns number, diameter of crown and leaf area. These findings indicated that, irrigation at 100% and 80% ETc were the most effective methods. However, utilizing 60% ETc in the two seasons resulted in lowest value of all plant development attributes under water stress. Increasing amounts of applied water to strawberry plants increased the soil moisture content, which may had positive effect on plant metabolism, improving plant development traits and increasing dry matter. Conversely, water stress had led to reduction in the uptake of nutrient components, which may disrupt the physiological functions necessary for plant development **(Salter and Goode, 1967).** Additionally, water stress impacts protein synthesis, glucose metabolism, and the activity of numerous enzymes, which may indicate a shift in the equilibrium between Anabolism and catabolism rates, resulting in reducing plant growth and the buildup of dry matter **(Suruchi, 2024)**. However, **Marschner (1995)** discovered that, in the presence of adequate water, gibberellins (GA_s), (CYT) and (IAA) increased while (ABA) decreased, indicating healthy development and increasing dry matter content. Moreover, these outcomes concur with those published by **Ismail and Mubarak (2016), Ahmed and Gad (2022), Bhagwat *et al*., (2023)** on strawberry where they found that as water quantity levels rise, plant growth characteristics also increased by providing sufficient water to plants leads to improved root absorption, increased metabolic efficiency and easier movement of nutrients inside plants therefore, fruit production and quality increase with moderate irrigation rates. Also**, Elzopy *et al*. (2023)** on strawberry reported that the highest mean values of plant height, leaves number /plant, fresh weight and dry weight per plant recorded with irrigation levels at 100% ETo followed by 75% as compared with 50% during both seasons.

Tables 5 and 6 highlight the significant effects of foliar spray treatments on various vegetative growth characteristics. Spraying plants with Se at 5 mg/L, SA at 100 mg/L and CeO_2 at 3 mg/L notably influenced all observed growth parameters, including plant height, leaves number, secondary crowns per plant, diameter of crown, fresh weight, dry weight and leaf area per plant across two growing seasons compared to the control treatment. These findings can be attributed to selenium's role in enhancing drought tolerance in plants. Se in reducing drought stress by activating antioxidant defenses against oxidative damage, regulating water balance within the plant, boosting antioxidant enzyme activity, and encouraging the production of protective compounds like proline. The application of Se through either seed priming or foliar sprays has been demonstrated to substantially improve crop resilience and productivity in water-limited conditions (**Ahmad *et al.*, 2016 and Dar *et al.*, 2021**).

Concerning salicylic acid (SA) effect, SA is an essential factor for increasing crop resistance to various abiotic stresses. Numerous physiological functions, including enhancing water retention, boosting antioxidant activity, and fortifying cell walls, are triggered by SA. These interactions support growth, preserve metabolic balance, and shield plants from stress-induced damage **(Xu *et al.*, 2015)**. Also**,** foliar application of cerium oxide (CeO_2) under salt or water stress enhanced growth, increased chlorophyll and carotenoid levels, and boosted photosynthesis and fruit weight. However, this treatment can negatively affect fruit quality at high concentrations, resulting in lighter flesh color and decreased anthocyanin due to altered fruit metabolism and potentially inhibited anthocyanin synthesis **(Hassanpouraghdam, *et al*., 2022),** (**Haghmadad Milani *et al*., 2024)**. Comparable outcomes were reported by **Mohamed *et al*. (2017)** on Strawberry indicated that foliar spray with SA at 3 mM level significantly increased vegetative growth (crowns no/plant, leaves no/plant and leaf area/plant). Moreover, **Khalil and Al-Aareji (2022)** reported that spraying strawberry plants with Se at 6 mg L^{-1} increased plant height and leave area. Also, **Zhao *et al*. (2022)** found that use of 30 μmol/L cerium nitrate improved strawberry plant height and plant biomass. Also, **Masoud *et al.* (2024)** reported that SA spraying resulted in significant increase in plant height, leaves number, runners number and leaf area, comparing to the control. Also, **Mohamed and Ahmed (2024)**, found that foliar application with 50 mg/L SA and 5 mg/L Se on squash plants increased plant height, leaves number and leaf area comparing to the control.

As for effect of interaction between irrigation levels and foliar spray treatments data in Tables (5 and 6) indicate that plant height, leaves number, secondary crowns per plant as well as diameter of crown, fresh weight, dry weight and leaf area per plant were significantly increased as a result of interaction treatments. In this connection, the highest values were reported as a result of water irrigation 100% (ETc) combined with spray with Se at 5 mg/L during both seasons of the study.

Table (5). Impact of irrigation and foliar spray application with selenium, salicylic acid and cerium oxide and their interaction on vegetative growth characteristics of strawberry at 130 days after planting during 2023/2024 season.

Treatments		season 2023/2024						
Irrigation levels	**Stimulant substances**	**Plant height (cm)**	**FW/ Plant (g)**	**DW/ Plant (g)**	**No of leaves/ Plant**	**No of crowns/ Plant**	**Crown diameter (cm)**	**Leaf area (cm^2)**
100% ETc		19.54	82.45	26.28	25.04	3.458	2.28	643.17
80% ETc		18.79	80.33	23.24	24.75	3.175	2.00	642.03
60% ETc		17.83	72.51	16.71	21.04	2.458	1.57	634.05
L.S.D at 0.05%		**1.195**	**3.38**	**1.89**	**1.03**	**0.66**	**0.35**	**2.57**
	CO	17.72	73.08	17.74	19.83	2.61	1.66	635.60
	Se	19.47	80.61	24.06	24.78	3.33	2.06	643.46
	SA	18.89	80.49	23.87	25.28	3.23	2.04	640.11
	CeO_2	18.81	79.53	22.62	24.56	2.94	2.03	639.83
L.S.D at 0.05%		**0.87**	**3.22**	**1.96**	**0.88**	**0.48**	**0.35**	**5.58**
100% ETc	**CO**	19.17	80.69	22.14	24.67	3.00	1.90	642.40
	Se	20.01	84.57	29.67	27.33	3.83	2.53	651.01
	SA	20.00	84.29	28.61	28.00	3.70	2.40	645.20
	CeO_2	19.50	83.19	28.19	27.00	3.67	2.37	643.32
80% ETc	**CO**	18.67	72.95	18.25	21.50	2.67	1.60	636.26
	Se	20.00	81.60	24.95	26.67	3.67	2.33	641.74
	SA	19.42	81.55	24.69	25.66	3.33	2.23	640.45
	CeO_2	19.25	81.33	23.63	24.00	3.00	2.13	640.41
60% ETc	**CO**	15.17	64.77	14.88	19.00	2.17	1.23	628.80
	Se	18.50	76.62	16.19	20.50	2.6	1.87	636.67
	SA	18.00	75.69	15.39	19.00	2.33	1.53	636.06
	CeO_2	17.00	73.79	18.33	20.00	2.33	1.23	634.69
L.S.D at 0.05%		**1.50**	**5.57**	**3.39**	**1.52**	**0.84**	**0.60**	**9.67**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide, F.W. = fresh weight, D.W. = dry weight.

Table (6). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on vegetative growth characteristics of strawberry at 130 days after planting during 2024/2025 season.

Treatments		season 2024/2025						
Irrigation levels	Stimulant substances	Plant height (cm)	FW/ Plant (g)	DW/ Plant (g)	No of leaves/ Plant	No of crowns/ Plant	Crown diameter (cm)	Leaf area (cm^2)
100% ETc		18.33	78.35	24.79	24.21	3.49	2.54	538.21
80% ETc		17.17	75.42	23.03	23.58	3.32	2.33	533.44
60% ETc		16.50	69.10	20.37	17.25	2.63	1.65	525.57
L.S.D. at 0.05%		**1.24**	**3.76**	**1.45**	**1.05**	**0.34**	**0.39**	**6.08**
	CO	15.86	61.82	18.47	17.06	2.52	1.940	526.34
	Se	18.2	79.62	24.34	23.44	3.39	2.31	536.55
	SA	17.86	77.91	24.07	23.33	3.37	2.33	533.56
	CeO_2	17.33	77.81	24.03	22.89	3.30	2.11	533.18
L.S.D. at 0.05%		**1.09**	**2.95**	**1.44**	**0.96**	**0.47**	**0.29**	**3.92**
100% ETc	**CO**	16.75	67.54	24.21	17.00	3.43	2.47	534.92
	Se	19.35	85.27	29.41	28.50	3.67	2.53	543.02
	SA	19.33	84.01	27.08	26.67	3.73	2.70	538.26
	CeO_2	19.00	76.57	19.62	24.67	3.67	2.47	536.62
80% ETc	**CO**	16.58	61.45	18.45	18.00	2.83	1.90	532.33
	Se	19.00	78.37	26.84	25.33	3.67	2.63	534.97
	SA	17.50	85.24	24.33	26.00	2.93	2.70	533.52
	CeO_2	16.83	76.63	21.32	25.00	3.70	2.10	532.95
60% ETc	**CO**	15.00	56.48	16.77	16.17	2.20	1.45	511.15
	Se	16.17	76.98	17.34	16.50	2.90	1.90	538.07
	SA	16.50	71.04	26.55	17.33	2.53	1.70	527.75
	CeO_2	16.00	71.91	20.81	19.00	2.47	1.53	525.33
L.S.D. at 0.05%		**1.89**	**5.11**	**2.49**	**1.66**	**0.82**	**0.51**	**6.80**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide, F.W. = fresh weight, D.W. = dry weight.

Chemical composition of plant foliage

Regarding irrigation levels, Tables 7 and 8 illustrates irrigation rates effect on the concentrations of total nitrogen, phosphate, potassium, carbohydrates and proline in strawberry plant foliage over the course of the two study seasons. The results showed that, irrigation at 100% and 80% ETc show significant effects on minerals content compared with water stress (60% ETc) which led to lowest value excepting proline content in leaves, which increased as water stress increased. That was true in two seasons of study. As previously said, adding more the increased water availability enhanced soil moisture, which in turn improved the accessibility of minerals for plant uptake, thereby increasing their concentration. These results align with observations by **Ahmed and Gad (2022)** on strawberries, **Rizk and Deshesh (2021), and Sapt *et al*. (2019) as well as Youssef (2007).** All reported a gradual rise in NPK concentrations in plants as water supply to the soil increased. Similarly, **Elzopy *et al*. (2023)** noted that irrigation at 100% resulted in the highest N, P, and K percentages in strawberry leaves, followed by 75%, compared to the 50% level during both seasons.

Data shown in Tables 7 and 8 demonstrates that spraying with Se at 5 mg/L, SA at 100 mg/L, and

CeO_2 at 3 mg/L significantly enhanced the total nitrogen, phosphorus, potassium, carbohydrate and proline content in plant foliage compared to the control treatment. Notably, the highest levels of all measured chemical components were observed with the application of SA at 100 mg/L. This result was consistent across both study seasons. The observed increases in N, P, K, and carbohydrate content resulting from the tested growth stimulants, may be attributed to their crucial role in influencing enzymes responsible for facilitating active nutrient and water absorption from the soil. These findings align with those reported by **Abo-Sedera *et al*. (2014)** on strawberries, where foliar application of salicylic acid at 1 g/L yielded the highest NPK and carbohydrate values. Similarly, **Ahmed (2024)** noted that selenium application significantly boosted leaf potassium concentration by 22% in untreated tomato plants.

The interaction effects on nitrogen, phosphorus, potassium, carbohydrate and proline contents revealed significant differences, as demonstrated in Table 7. Foliar application of SA at a concentration of 100 mg/L under the first irrigation level (100%) markedly enhanced nitrogen, phosphorus, potassium, carbohydrate and proline contents compared to other treatments during both the 2023/2024 and 2024/2025 seasons.

Table (7). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on chemical composition of plant foliage strawberry at 130 days after planting during 2023/2024 season.

Treatments		season 2023/2024				
Irrigation levels	**Stimulant substances**	**N (%)**	**P (%)**	**K (%)**	**Carbohydrates (gm/100 gm DW)**	**Proline (µg/ g.F.W)**
100% ETc		2.63	0.627	1.58	15.48	27.53
80% ETc		2.56	0.535	1.55	15.45	31.74
60% ETc		2.48	0.428	1.24	14.17	36.15
L.S.D. at 0.05%		**0.04**	**0.013**	**0.05**	**0.39**	**1.49**
	CO	2.53	0.378	1.41	14.70	21.98
	Se	2.57	0.578	1.47	15.25	35.54
	SA	2.58	0.586	1.48	15.28	34.93
	CeO_2	2.55	0.579	1.46	14.90	34.77
L.S.D. at 0.05%		**NS**	**0.025**	**0.05**	**0.41**	**1.57**
100% ETc	**CO**	2.59	0.410	1.54	15.09	18.98
	Se	2.64	0.680	1.60	15.55	28.46
	SA	2.66	0.713	1.61	16.03	23.49
	CeO_2	2.62	0.703	1.59	15.26	23.46
80% ETc	**CO**	2.53	0.370	1.50	15.14	30.92
	Se	2.61	0.580	1.58	15.47	34.83
	SA	2.55	0.600	1.57	15.88	32.75
	CeO_2	2.55	0.590	1.53	15.31	31.73
60% ETc	**CO**	2.45	0.353	1.17	13.54	35.91
	Se	2.51	0.463	1.27	14.41	40.86
	SA	2.49	0.457	1.27	14.47	40.41
	CeO_2	2.48	0.440	1.24	14.25	39.83
L.S.D. at 0.05%		**0.14**	**0.04**	**0.09**	**0.72**	**2.71**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide F.W. = fresh weight, D.W. = dry weight.

Table (8). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on chemical composition of plant foliage strawberry at 130 days after planting during 2024/2025 season.

Treatments		season 2024/2025				
Irrigation levels	Stimulant substances	N (%)	P (%)	K (%)	Carbohydrates (gm/100 gm DW)	Proline (µg/ g.F.W)
100% ETc		2.63	0.613	1.56	15.38	28.16
80% ETc		2.53	0.528	1.49	15.29	34.40
60% ETc		2.48	0.445	1.24	13.97	36.88
L.S.D. at 0.05%		**0.04**	**0.015**	**0.09**	**0.16**	**1.26**
	CO	2.51	0.372	1.36	14.47	20.80
	Se	2.56	0.572	1.43	14.98	38.08
	SA	2.56	0.592	1.49	15.11	37.25
	CeO_2	2.55	0.578	1.43	14.96	36.47
L.S.D. at 0.05%		**0.03**	**0.021**	**0.05**	**0.51**	**1.27**
100% ETc	**CO**	2.60	0.400	1.52	14.98	17.70
	Se	2.65	0.663	1.59	15.53	32.38
	SA	2.65	0.700	1.62	15.75	31.66
	CeO_2	2.60	0.690	1.52	15.25	30.89
80% ETc	**CO**	2.49	0.343	1.34	14.98	22.95
	Se	2.55	0.593	1.56	15.25	40.89
	SA	2.55	0.590	1.56	15.75	38.82
	CeO_2	2.52	0.583	1.48	15.20	34.94
60% ETc	**CO**	2.45	0.373	1.11	13.46	21.73
	Se	2.52	0.486	1.34	14.59	42.45
	SA	2.48	0.470	1.29	14.39	42.08
	CeO_2	2.49	0.450	1.19	13.46	41.28
L.S.D. at 0.05%		**0.05**	**0.037**	**0.09**	**0.88**	**2.19**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide, F.W. = fresh weight, D.W. = dry weight.

Fruit yield and its components

The data recorded in Tables 9 and 10 illustrate of varying irrigation rates on early yield, exportable and marketable yield, total yield expressed as either (g/plant) and (t/fed.) as well as Unmarketable yield (kg/fed.) across both seasons. The results showed that irrigation levels of 100% and 80% ETc had a significant impact on total produced yield and its components when compared to the 60% level which exhibited the lowest mean values for these traits across both seasons. Moreover, the height infected yield (unmarketable) was recorded in case of ETc 60%. No significant differences in either early and exportable yield weight were observed between the 100% and 80% ETc treatments in either season. In terms of marketable yield, total yield (g/plant), and total yield (t/fed.), the data indicate that the first level of 100% ETc exhibited significant differences during the second season. There is no morale in the first season such increments in total produced yield and its components were connected with the increase in vegetative growth rate (Tables 5 and 6) and fruit physical parameters (Table 11) which subsequently influence the overall fruit yield. The observed increases in yield parameters may be attributed to the availability of adequate water, which facilitates plant growth and enhances the efficiency of the photosynthesis process. Nutrient elements are more effectively transferred and absorbed when water availability is sufficient. Similar findings were reported by **El-Sawy *et al.*, (2022)** in their study on potatoes, where they discovered that increased irrigation water resulted in a significant rise in potato tuber yield, with the highest significant values for the number of tubers per plant and total yield achieved under the 100% irrigation treatment. The maximum significant values for tuber yield per plant were also recorded with the 100% and 80% ETo irrigation treatments across the two growing seasons.

Furthermore, **Ahmed and Gad (2022)** noted that the irrigation level at 100% ETo yielded the highest early and total strawberry yields compared to the 60% ETo irrigation level. Likewise, **Marcellini *et al.*, (2023)** reported that reducing irrigation by up to 20% of the standard regime did not result in significant losses in strawberry yield or reductions in fruit sensory quality or antioxidant activity. Additionally, **Niu *et al.*, (2025)** found that supplemental irrigation led to a 55% increase in potato yield compared to the control group that received no irrigation. Conversely, deficit irrigation, on average, significantly decreased yield.

The data presented in Tables 9 and 10 indicate that spraying plants with 100 mg/L SA resulted in the highest values across all measured yield parameters compared to other spray treatments during both seasons of the experiment. However, no significant differences were observed among the applied levels of Se, SA and CeO_2 in any of the yield parameters measured during both seasons. Also, using Se, SA and CaO_2 decreased the infected fruits compared with control treatment. The observed improvements in total yield and its components due to the use of SA, Se and CeO_2 were attributed to enhancements in vegetative growth parameters as shown in Tables (5 and 6). Additionally, these treatments positively influenced the plant's nutrient content (Tables 7 and 8), which contributed to better growth and consequently increased productivity. Furthermore, these growth stimulants reduced the percentage of infected fruits and shortened the time to flower an thesis, thereby boosting early and marketable yields. The findings align with those reported by **Khalil and Al-Aareji (2022) and Masoud *et al.*, (2024)** regarding strawberries, as well as **Mohamed and Ahmed (2024)** concerning squash.

Table (9). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on total fruit yield and its components of strawberry during 2023/2024 season.

Treatments		**season 2023/2024**					
Irrigation levels	**Stimulant substances**	**Early yield (t/fed.)**	**Exportable yield (t/fed.)**	**Marketable yield (t/fed.)**	**Unmarketable yield (kg/fed.)**	**Total yield (kg/plant)**	**Total yield (t/fed)**
100% ETc		5.123	3.453	19.539	483.08	0.527	20.022
80% ETc		4.978	3.250	19.321	564.73	0.524	19.886
60% ETc		3.425	2.363	17.157	765.73	0.473	17.922
L.S.D. at 0.05%		**0.428**	**0.242**	**0.6027**	**20.39**	**0.018**	**0.598**
	CO	3.731	2.718	17.314	724.20	0.477	18.039
	Se	4.784	3.109	19.198	577.06	0.519	19.775
	SA	4.884	3.214	19.316	554.79	0.524	19.870
	CeO_2	4.633	3.048	18.861	562.01	0.511	19.423
L.S.D. at 0.05%		**0.333**	**0.322**	**0.520**	**18.45**	**0.015**	**0.522**
100% ETc	**CO**	4.697	3.227	16.690	615.60	0.455	17.306
	Se	5.157	3.527	20.623	448.20	0.555	21.072
	SA	5.540	3.650	20.917	429.80	0.562	21.346
	CeO_2	5.097	3.420	19.927	438.70	0.536	20.365
80% ETc	**CO**	3.753	2.783	18.593	684.00	0.507	19.277
	Se	5.400	3.427	19.570	537.80	0.526	20.108
	SA	5.530	3.493	19.573	521.43	0.535	20.095
	CeO_2	5.227	3.297	19.547	515.70	0.529	20.062
60% ETc	**CO**	2.743	2.143	16.660	873.00	0.468	17.533
	Se	3.667	2.500	17.400	802.01	0.478	18.202
	SA	3.713	2.427	17.483	662.00	0.476	18.145
	CeO_2	3.577	2.426	17.083	725.90	0.469	17.809
L.S.D. at 0.05%		**0.578**	**0.558**	**0.901**	**31.96**	**0.026**	**0.905**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide

Table (10). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on total fruit yield and its components of strawberry during 2024/2025 season.

Treatments		season 2024/2025					
Irrigation levels	Stimulant substances	Early yield (t/fed.)	Exportable yield (t/fed.)	Marketable yield (t/fed.)	Unmarketable yield (kg/fed.)	Total yield (kg/plant)	Total yield (t/fed)
100% ETc		5.396	3.617	19.415	483.21	0.525	19.898
80% ETc		4.933	3.364	18.200	707.87	0.503	18.908
60% ETc		3.599	2.546	16.303	711.21	0.449	17.015
L.S.D. at 0.05%		**0.548**	**0.383**	**0.199**	**42.64**	**0.010**	**0.221**
	CO	3.733	2.896	16.222	727.11	0.447	16.949
	Se	4.962	3.227	18.462	652.71	0.509	19.115
	SA	5.053	3.393	18.604	648.00	0.509	19.252
	CeO_2	4.822	3.188	18.602	508.57	0.503	19.111
L.S.D. at 0.05%		**0.395**	**0.215**	**0.378**	**28.28**	**0.016**	**0.369**
100% ETc	**CO**	4.690	3.420	16.863	625.83	0.456	17.489
	Se	5.663	3.646	20.077	446.57	0.547	20.523
	SA	5.697	3.847	20.737	442.50	0.557	21.179
	CeO_2	5.533	3.557	19.983	417.93	0.537	20.401
80% ETc	**CO**	3.503	2.743	15.783	695.47	0.434	16.479
	Se	5.520	3.657	19.260	535.97	0.523	19.796
	SA	5.670	3.843	19.013	835.73	0.531	19.849
	CeO_2	5.040	3.213	18.743	764.33	0.522	19.508
60% ETc	**CO**	3.007	2.350	16.020	860.03	0.446	16.880
	Se	3.763	2.820	16.470	625.83	0.451	17.094
	SA	3.943	2.523	16.390	681.00	0.451	17.071
	CeO_2	3.683	2.490	16.333	680.00	0.449	17.013
L.S.D. at 0.05%		**0.683**	**0.373**	**0.654**	**48.97**	**0.027**	**0.640**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide

Regarding the interaction between treatments, the findings reveal that applying the first irrigation level at 100% (ETc) and the second level at 80% (ETc), combined with spraying plants with SA at 100 mg/L, resulted in the highest yield and its components compared to other treatment combinations across both study seasons. SA plays a direct role in promoting plant growth, facilitating ion absorption, and aiding the movement of nutrients within the tissues of plants **(Meena *et al.*, 2001)**. Maybe these effects enable plants to overcome stress resulting from a 20% reduction in irrigation rate.

Physical Fruit quality

Regarding irrigation levels, Table 11 illustrates the impact of different irrigation rates on the fruit quality, measured through parameters such as average fruit weight, length, diameter, and firmness across the two study seasons. The results indicate that an irrigation rate of 100% ETc significantly enhanced average fruit length, diameter, and weight. Conversely, the highest fruit firmness was observed with an 80% ETc irrigation rate in both seasons. Meanwhile, the lowest values for fruit length, diameter, weight, and firmness were consistently recorded at a 60% ETc irrigation level during both study periods. The results are coincided with those of **Ahmed and Gad (2022)** they found that irrigation at rate of 100% (ETo) increased the average fruit weight compared to other irrigation rates. Also, **Elzopy *et al.* (2023)** conducted a study on strawberries and discovered that maintaining irrigation at 100% resulted in the highest average values for yield characteristics, such as fruit weight and fruit length.

The data presented in Table 11 regarding the effects of growth stimulants indicate that spraying plants with Se at 5 mg/L, SA at 100 mg/L, and CeO_2 at 3 mg/L significantly enhanced the average fruit weight, length, diameter, and firmness compared to the control treatment. Notably, the application of SA at 100 mg/L proved to be more effective than the other treatments and the control during both growth seasons. This improvement in fruit parameters attributed to SA could be linked to its role in enhancing the uptake of NPK (as shown in Table 7), which subsequently contributed to increased fruit size. These findings are consistent with those of **Abo-Sedera *et al.* (2014)** and **Masoud *et al.* (2024)** on strawberries, as well as **Mohamed and Ahmed (2024)** on squash. Their studies similarly reported significant enhancements in physical fruit attributes-such as weight, height, diameter, and firmness-following treatments with either SA or Se.

Regarding the interaction effect, the data presented in Table (11) reveal that the highest values for all measured fruit parameters (weight, length, and diameter) were achieved through the combination of 100% irrigation level with SA at 100 mg/L spraying across both two seasons. Moreover, the 80% irrigation level combined with SA at 100 mg/L exhibited the highest fruit firmness values throughout both study seasons.

Table (11). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on physical fruit quality of strawberry during 2023/2024 and 2024/2025 seasons.

Treatments		2023/2024				2024/2025			
Irrigation levels	**Stimulant substances**	**Fruit weight (g)**	**Fruit length (cm)**	**Fruit diameter (cm)**	**Fruit firmness (g/cm^2)**	**Fruit weight (g)**	**Fruit length (cm)**	**Fruit diameter (cm)**	**Fruit firmness (g/cm^2)**
100% ETc		30.56	5.33	3.69	194.83	31.18	5.12	3.64	187.42
80% ETc		29.35	5.18	3.49	206.08	26.79	4.89	3.60	193.92
60% ETc		24.53	4.56	3.31	192.58	22.13	4.76	3.40	181.92
L.S.D. at 0.05%		**1.71**	**0.23**	**0.15**	**8.73**	**1.67**	**0.28**	**0.09**	**4.58**
	CO	23.77	4.38	3.13	183.44	24.86	4.44	3.12	166.67
	Se	30.31	5.27	3.66	205.22	27.25	5.17	3.70	194.89
	SA	30.81	5.42	3.72	205.67	28.25	5.12	3.75	200.56
	CeO_2	27.69	5.03	3.52	197.00	26.42	4.91	3.62	188.89
L.S.D. at 0.05%		**1.68**	**0.27**	**0.12**	**6.39**	**1.93**	**0.22**	**0.16**	**9.17**
100% ETc	**CO**	25.78	4.73	3.05	202.00	29.82	4.30	3.05	155.00
	Se	32.68	5.43	3.80	207.33	30.35	5.47	3.90	187.67
	SA	35.75	5.97	4.20	210.00	34.64	5.53	3.95	205.00
	CeO_2	28.02	5.20	3.73	205.00	29.89	5.17	3.50	180.00
80% ETc	**CO**	27.15	4.37	3.10	175.00	25.19	4.77	3.15	195.00
	Se	30.85	5.67	3.65	205.00	27.23	4.80	3.95	181.67
	SA	31.75	5.77	3.65	211.67	28.39	5.23	3.85	217.33
	CeO_2	27.66	4.93	3.58	187.67	26.34	4.77	3.60	181.67
60% ETc	**CO**	18.37	4.03	3.17	173.33	17.54	4.27	3.15	163.33
	Se	29.02	4.73	3.59	207.00	23.77	4.80	3.60	201.67
	SA	26.48	4.83	3.27	196.67	24.19	5.17	3.50	197.33
	CeO_2	24.22	4.63	3.23	193.33	23.01	4.80	3.35	187.33
L.S.D. at 0.05%		**2.92**	**0.48**	**0.21**	**11.07**	**3.34**	**0.38**	**0.28**	**15.88**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide

Chemical fruit quality

Regarding the irrigation levels, the data presented in Tables 12 and 13 illustrate the impact on the chemical constituents of the produced fruits, quantified as TSS%, VC, total acidity, total sugars, and anthocyanin content in both seasons of study. The irrigation levels of 100% and 80% demonstrated a significant effect on chemical content when compared to the 60% level, which exhibited the lowest mean values for these traits across both seasons. These findings are consistent with the research conducted by **Ahmed and Gad (2022)** and **Elzopy *et al.* (2023).**

The data presented in Tables 12 and 13 indicate that treating plants with anti-stress agents like Se at 5 mg/L, SA at 100 mg/L, and CeO_2 at 3 mg/L had a significant impact on various organic constituents. During the first season, total soluble solids (TSS), vitamin C, total sugars, and anthocyanin content were notably influenced, whereas, in the second season, TSS, vitamin C, total acidity, total sugars, and anthocyanin pigments showed significant affected. However, total acidity was not significantly affected during the first season. Among the treatments, spraying plants with Se at 5 mg/l consistently resulted in the highest values for all evaluated organic components, including TSS, vitamin C, acidity, total sugars, and anthocyanin content. This may be attributed that selenium plays a vital role in neutralizing the harmful effects of abiotic stresses, which leads to improved metabolic efficiency and enhanced quality characteristics also increased pigments, total soluble solids, acidity and vitamins concentrations as the end products of metabolism within plant tissues. Additionally, **Hu *et al.* (2023)** reported that the incorporation of Se in tomatoes led to increased levels of soluble sugars, V.C and anthocyanin. Furthermore, **Mohamed and Ahmed (2024)** showed that plants foliar spraying with Se and S.A. increased fruit quality (TSS, ascorbic acid and total sugars) of squash fruits.

Table (12). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on chemical fruit quality of strawberry during 2023/2024 season.

Treatments		Season 2023/2024				
Irrigation levels	**Stimulant substances**	**TSS (%)**	**Vit.C (mg/100g F.W.)**	**Acidity (mg/100g F.W.)**	**Total sugars%**	**Anthocyanin (mg/100g F.W.)**
100% ETc		11.22	77.75	1.46	6.84	89.42
80% ETc		11.08	74.17	1.33	6.67	87.67
60% ETc		10.17	68.16	1.31	6.06	82.99
L.S.D. at 0.05%		**0.74**	**3.66**	**NS**	**0.70**	**4.02**
	CO	10.27	70.11	1.54	6.13	83.48
	Se	11.16	76.66	1.26	6.71	87.80
	SA	11.04	75.56	1.42	6.69	86.67
	CeO_2	10.8	71.11	1.54	6.55	88.82
L.S.D. at 0.05%		**0.79**	**2.960**	**NS**	**0.39**	**4.18**
100% ETc	**CO**	10.30	74.00	1.36	6.34	88.18
	Se	12.63	82.66	1.53	7.23	90.50
	SA	11.03	78.00	1.53	7.07	90.33
	CeO_2	10.90	76.33	1.40	6.70	88.68
80% ETc	**CO**	9.60	68.00	1.13	6.13	82.46
	Se	12.07	76.00	1.50	7.04	87.88
	SA	11.47	81.33	1.20	6.96	89.87
	CeO_2	11.17	71.33	1.50	6.53	90.45
60% ETc	**CO**	9.67	62.66	1.10	5.85	71.83
	Se	10.67	68.33	1.13	6.48	85.20
	SA	10.17	77.67	1.40	6.00	87.05
	CeO_2	10.17	64.00	1.60	5.91	87.90
L.S.D. at 0.05%		**1.36**	**5.13**	**NS**	**0.68**	**7.24**

CO = control, Se = selenium, SA= salicylic acid, CeO_2 = cerium oxide, F.W. = fresh weight

Table (13). Impact of irrigation and foliar spray application with Selenium, salicylic acid and Cerium Oxide and their interaction on chemical fruit quality of strawberry during 2024/2025 season.

Treatments		Season 2024/2025				
Irrigation levels	Stimulant substances	TSS (%)	Vit.C (mg/100g F.W.)	Acidity (mg/100g F.W.)	Total sugars%	Anthocyanin (mg/100g F.W.)
100% ETc		11.09	76.75	1.29	6.97	93.98
80% ETc		10.83	72.17	1.25	6.58	91.71
60% ETc		9.65	65.58	1.13	6.19	89.36
L.S.D. at 0.05%		**1.07**	**2.09**	**0.10**	**0.42**	**4.03**
	CO	9.78	68.33	1.14	6.26	89.57
	Se	11.09	74.22	1.30	6.76	93.72
	SA	10.84	73.78	1.28	6.66	90.90
	CeO_2	10.39	69.67	1.17	6.62	92.52
L.S.D. at 0.05%		**0.57**	**2.19**	**0.11**	**0.47**	**3.52**
100% ETc	**CO**	10.50	72.00	1.20	6.66	93.36
	Se	11.66	82.67	1.43	7.46	95.13
	SA	11.17	80.33	1.30	6.88	93.71
	CeO_2	11.03	72.00	1.23	6.87	93.71
80% ETc	**CO**	10.13	66.00	1.10	6.21	87.69
	Se	12.27	74.00	1.10	6.75	92.57
	SA	10.73	79.33	1.37	6.68	92.79
	CeO_2	10.20	69.33	1.43	6.65	93.78
60% ETc	**CO**	8.700	59.33	1.03	5.92	81.23
	Se	10.13	67.00	1.10	6.46	91.07
	SA	9.97	75.33	1.16	6.23	91.66
	CeO_2	9.80	60.67	1.20	6.13	93.46
L.S.D. at 0.05%		**0.99**	**3.80**	**0.19**	**0.81**	**6.09**

CO = control, Se = selenium, SA = salicylic acid, CeO_2 = cerium oxide, F.W. = fresh weight

The data presented in Tables 12 and 13 point that combining the maximum irrigation level of 100% with the application of Se at 5 mg/L led to an enhancement in all examined organic constituents (TSS, vitamin C, acidity, total sugars, and anthocyanin) when compared to other interaction treatments. These findings were consistent across both study seasons.

Crop water productivity (WP)

Crop Water Productivity (CWP) represents the relationship between fruit yield and the amount of water utilized during the growing season. The data illustrated in Figure (2) reveals the impact of different irrigation amounts on strawberry CWP values. Upon averaging the data from both seasons, a distinct and consistent trend regarding crop water productivity (CWP, measured in kg of yield m^3 of water applied) becomes evident. At full irrigation (100% ETc), the untreated control achieved an average CWP of only 6.52 kg/m^3. All chemical treatments significantly improved water productivity under these conditions: Salicylic acid at 100 mg/l gave the highest value of 7.96 kg/m^3 (22.1% over control), followed closely by selenium at 5 mg/l (7.79 kg/m^3, 19.5%), and cerium at 3 mg/l (7.63 kg/m^3, 17.0%). This demonstrates that, when water is not limiting, exogenous application of these compounds enables the crop to convert water into harvestable yield much more efficiently.

As irrigation was reduced, water productivity increased dramatically in all treatments. At 80% ETc, average WP rise to 8.40 kg/m^3 in the control and to 9.29–9.38 kg/m^3 in the treated plots. The greatest jump occurred at 60% ETC where the control reached 10.46 kg/m^3 and the treated treatments ranged between 10.59 and 10.73 kg/m^3. In other words, applying only 60% of full irrigation water increased WP by more than 60% compared to full irrigation in the control, and by 34–39% in the chemically treated plots.

Under severe deficit irrigation (60 % ETc), the relative advantage of the chemical treatments became very small. Although salicylic acid and selenium still recorded the highest absolute values (10.71 and 10.73 kg/m³, respectively), they exceeded the untreated control by only 2.4 –2.6%. That indicates when water stress is strong, the crop develops physiological adaptation to deficit and becomes the dominant factor governing water productivity, leaving a little additional room for improving by exogenous Se, SA, or CeO_2.

Overall, SA at 100 mg/L and Se at 5 mg/L performed almost identically across the two seasons, with SA showing a slight edge at 100% and 80% ETc and Se performing marginally better under the most severe deficit. Both were clearly superior to CeO_2 at 3 mg/L. If water is abundant (full or near-full irrigation is possible), applying SA (100 mg/L) or Se (5 mg/L) is highly recommended, as it can increase water productivity by approximately 20–22%. If water is scarce and deficit irrigation must be practiced, reducing irrigation to 60% ETc is by far the most effective strategy for maximizing water productivity. Under such conditions, adding chemical treatments provides only marginal additional benefit (2–3%). Thus, the combined two-season results confirm that regulated deficit irrigation, particularly at 60% ETc, is the most powerful tool for improving crop water productivity, while SA and Se application is valuable especially when full irrigation is applied. The data reveal that under non-limiting water supply (100% ETc), exogenous SA (100mg/L), Se (5mg/L) and CeO_2 (3mg/L) significantly elevate crop water productivity (WP) by 17-22% over the untreated control (6.52 kg m^{-3}), indicating these compounds enhance physiological water-to-yield conversion efficiency through improved stomatal regulation and metabolic efficiency when evapotranspiration demand is fully met. As irrigation is reduced to 80 % and especially 60% ETc, WP rises markedly (up to > 60% in control) across all treatments owing to the crop's inherent physiological adaptations to deficit stress, which become the dominant driver of productivity and largely diminish the marginal additive benefit of the chemicals (only 2-3% advantage), demonstrating that regulated deficit irrigation itself is the most potent lever for water-use optimization. These findings align with research by **Dal Magro *et al.* (2026)**, who observed a direct correlation between irrigation management and fruit productivity in soilless strawberry cultivation, noting that mild deficit irrigation maintained fruit yield and number comparable to standard irrigation while significantly improving water use efficiency (WUE), with values reaching approximately 18.6 kg m^{-3} under mild deficit compared to 14.9 kg m^{-3} under standard conditions-an increase of about 25%. Also, **Hutchinson *et al.* (2025)**, who compared substrate-based and various water-culture systems for controlled-environment strawberry production, finding that substrate systems generally outperformed water-culture methods in yield and resource use efficiencies (including water), due to better oxygen availability and moisture retention in the root zone, and by **Alavi *et al.* (2025)**, who demonstrated that partial root-zone drying (PRD) strategies in hydroponic setups preserved substrate health, reduced water/fertigation needs by up to 50%, and improved overall efficiency while sustaining or enhancing yield and berry quality.

Moreover, there exists significant variation in water productivity, with recent values ranging from around 8-13 kg m^{-3} under deficit conditions in some cultivars (**Raffaelli *et al.* 2025**) to higher levels such as ~18.6-34 kg m^{-3} under optimized mild deficit or soilless management (**Dal Magro *et al.*, 2026 and Raffaelli *et al.* 2025**).

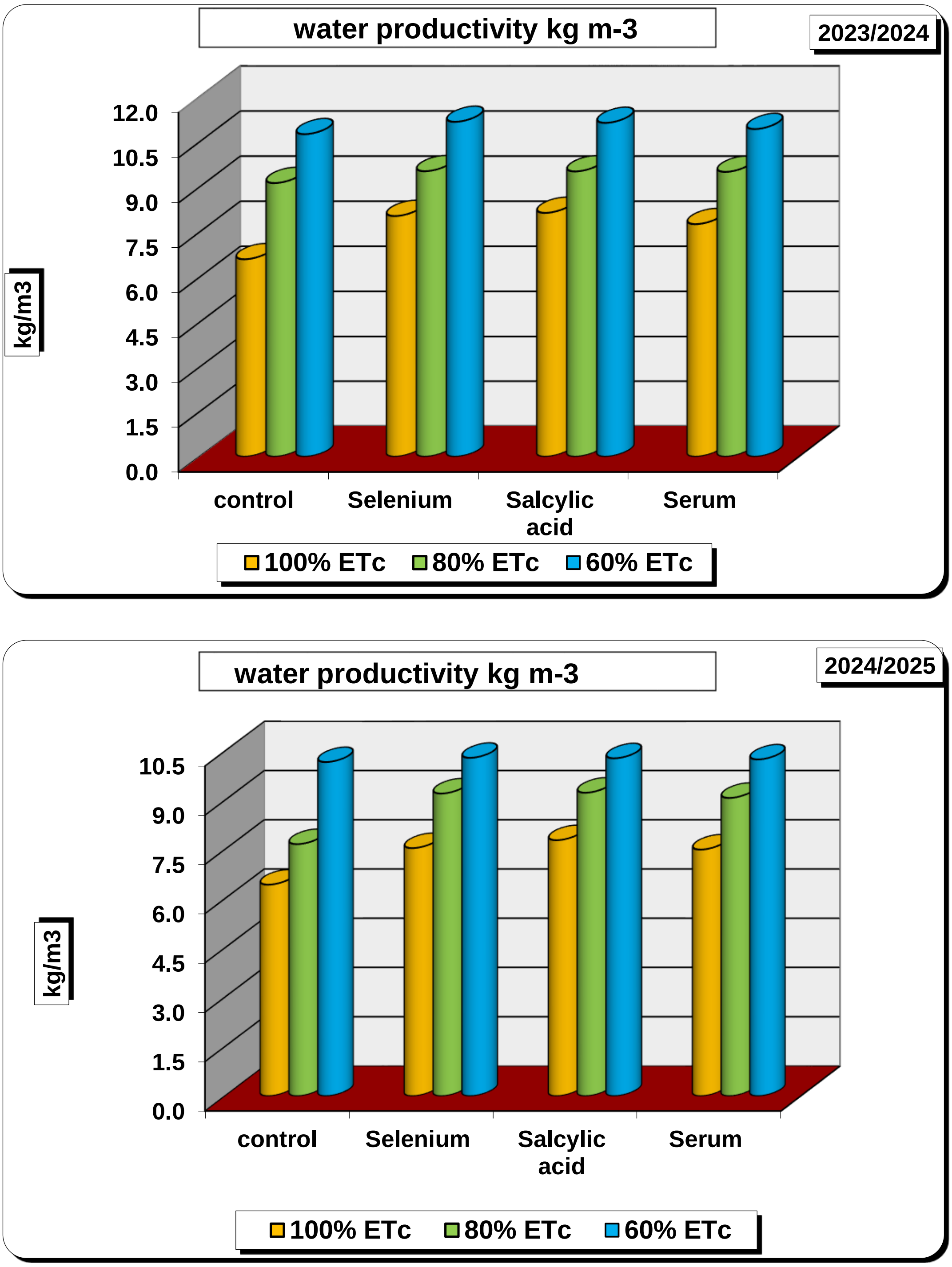

Fig (2). Crop-water productivity (kg m^{-3}) as affected by amounts of irrigation water and foliar spray treatments in 2023/2024 and 2024/2025 seasons

4. Conclusions

Under circumstances similar to those of the current research, it is recommended to grow the strawberry variety Festival for either local or export markets, employing an irrigation regimen that fulfills 80% of the water needs per feddan for the plants. Furthermore, the application of Se at a concentration of 5 mg/L or SA at 100 mg/L is suggested to attain optimal outcomes in vegetative growth traits, yield, water use efficiency, and fruit quality, while also conserving around 20% of irrigation water, especially in situations of water scarcity or drought.

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