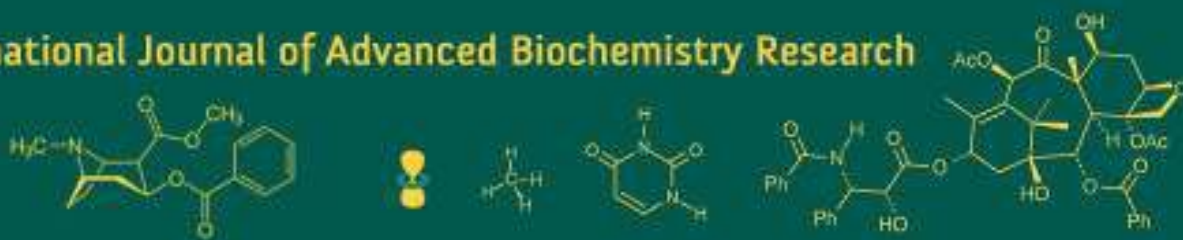


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Maha Diyaa Abdul Ameer
 Department of Horticulture
 and Landscape Architecture,
 College of Agriculture, Al-
 Qasim Green University,
 Babylon, Iraq

Ehsan jali Thabeeb
 Department of Horticulture
 and Landscape Architecture,
 College of Agriculture, Al-
 Qasim Green University,
 Babylon, Iraq

Corresponding Author:
Maha Diyaa Abdul Ameer
 Department of Horticulture
 and Landscape Architecture,
 College of Agriculture, Al-
 Qasim Green University,
 Babylon, Iraq

The impact of irrigation water salinity levels and alpha-tocopherol on some vegetative and chemical characteristics of 'Wonderful' pomegranate seedlings

Maha Diyaa Abdul Ameer and Ehsan jali Thabeeb

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Abstract

This study was conducted in the fields of the Horticulture and Landscape Engineering Department, College of Agriculture, Al-Qasim Green University, during the 2025 growing season, at the University of Babylon site. The experiment began on March 16, 2025, and was designed as a factorial experiment using a randomized complete block design (RCBD). It included two factors: the first factor was the salinity levels of the irrigation water (1.5, 3, and 6 dS•m•K), and the second factor was the addition of α -Tocopherol at levels of 0, 150, and 300 mg/L•K, produced by the Indian company HIMEDIA, with three replicates. The most important findings of the research are:

1. Irrigation water salinity levels led to a significant decrease in most of the studied traits, especially the level of 6 dS/m², which resulted in the lowest values for traits such as plant height, stem diameter, and leaf area, with measurements of 67.49 cm in height, 7.18 mm in diameter, and 1460.49 cm² in leaf area, respectively. Meanwhile, high salinity levels, particularly 6 dS/m², led to a significant decrease in the following chemical traits: nitrogen, phosphorus, potassium, carbohydrates, and proline, with measurements of 2.031%, 0.295%, and 0.786%, respectively.
2. The application of α -Tocopherol as a foliar spray showed a significant positive effect, with the treatment (300 mg/L) yielding the highest measurements for traits such as plant height, stem diameter, and leaf area, reaching (77.15%), (7.66%), and (1691.93%), respectively. However, the application of α -Tocopherol did not have a significant effect on the following traits: nitrogen, phosphorus, and potassium.
3. The results indicated significant interactions, with the interaction consisting of normal river water (1.5 dS/m) with a concentration of (300 mg/L) of α -Tocopherol exhibiting the highest values for the following traits: average plant height, average stem diameter, and average leaf area, reaching (82.27 cm, 7.92 mm, and 1952.51 cm²), respectively

Keywords: Irrigation salinity, α -tocopherol, *Punica granatum*, vegetative growth

Introduction

The pomegranate is one of the oldest fruits known to humankind. Its name derives from the Old French words "pome," meaning apple, and "granate," referring to numerous seeds, thus meaning "apple with many seeds" (Abdul Hamid *et al.*, 2017) [7]. The region extending from Iran to the Himalayas in northern India is considered the pomegranate's original habitat. From Iran, it spread to Syria, Jordan, Palestine, and Lebanon, and then to North Africa, Egypt, and the Mediterranean basin (Abdul Hamid *et al.*, 2008). Syria holds a prominent position in pomegranate cultivation, with an area of 6,845 hectares in 2020, and a domestic production of 106,506 tons, according to the Statistical Abstract of Agriculture (Ministry of Agriculture, 2020). Pomegranates have been used in traditional medicine in many cultures and are revered in the Abrahamic religions, being mentioned in the Holy Quran.

The pomegranate is characterized by the presence of numerous bioactive compounds beneficial to the human body, concentrated in parts of the fruit such as the juice and peel. The importance of these compounds stems from their therapeutic properties, such as their ability to prevent oxidation and combat free radicals, which play a significant role in the development of many serious diseases, including cancer and atherosclerosis. These compounds include phenols, anthocyanins, tannins, and others, all of which contribute to antioxidant activity (Abdul-Barr & Sadiq, 2020) [6]. Furthermore, these bioactive compounds

provide the body with energy and immunity, as they contain a good proportion of simple sugars like glucose and fructose, making them a good source of nutrition and energy. They are also rich in potassium, ascorbic acid (vitamin C), niacin (vitamin B), and several lipid-active compounds such as sterols and plant steroids (Hassan, 2020). Pomegranates are also rich in minerals such as calcium, magnesium, potassium, and zinc, giving their fruit nutritional value (Gil M: Thomas, 2000).

These compounds are also rich in minerals such as calcium, magnesium, potassium, and zinc. The juice is extracted from pomegranate fruits, which is also used to produce pomegranate molasses, a method of preserving the fruit for consumption out of season by condensing the juice to remove moisture using techniques such as boiling or vacuum to preserve it for a long time.

The results of a study conducted by Abdel-Barr and Sadiq (2020) [6] on the Syrian pomegranate variety (Laffan) confirmed that the optimal temperature for preparing pomegranate molasses under vacuum was 60°C at a vacuum pressure of 30 mmHg.

In a study involving six varieties of the Molar group of pomegranates in Spain (Paul *et al.*, 2012) [26], the highest soluble solids content was found in the sixth, sweet variety (15.81%)

The results of studies conducted by Paul *et al.* (2012) [26] indicated that glucose is the main sugar in all pomegranate varieties, comprising 60-64% of the total sugars, followed by fructose, maltose, and sucrose. Citric acid was the predominant acid. Researchers (Anahita *et al.*, 2015) [8] studied the vitamin content of Spanish pomegranate varieties and found that the concentration of vitamin A in pomegranate juice was 22.8 µg/100 g, the concentration of vitamin C was 57.8 mg/100 g, and the amount of phenols in the juice was 2502 mg.

Soil salinity is a harmful environmental factor that hinders the growth and production of horticultural plants worldwide. It is estimated that approximately 20% of agricultural land and half of irrigated land are affected by salinity. Among the most prominent factors contributing to soil salinization are the excessive use of chemical fertilizers, the use of saline irrigation water, and rising groundwater levels (Mastrogiannidou *et al.*, 2016) [22]. This has led to significant degradation in pomegranate orchards, necessitating the adoption of methods to halt this decline and mitigate the damage caused by salt stress in lands irrigated with highly saline water. One such method is the use of certain types of

Nano-fertilizer treatments to enhance water and nutrient uptake by plants and reduce salt stress (El-khawaga, 2013) [14]

Alpha-tocopherol is an antioxidant chemical compound belonging to the vitamin E family and is generally produced in photosynthetic plants. It is considered a vitamin used to reduce the effects of salinity and is a fat-soluble isoprenoid from the tocopherol family, primarily synthesized in photosynthetic organisms (Fritsche *et al.*, 2017) [15]. Tocopherols are of great importance, working synergistically with tocotrienols, and are the only natural compounds exhibiting vitamin E activity. They are considered essential nutrients (Traber *et al.*, 1996) [30]. Plants treated with alpha-tocopherol exhibit stress tolerance and protect themselves from oxidative stress caused by various factors (Kumar *et al.*, 2012) [20].

Objectives of the study

1. To investigate the effect of spraying alpha-tocopherol on pomegranate seedlings irrigated with saline water.
2. Studying the response of pomegranate seedlings to irrigation with saline water.
3. Studying the interaction effect of experimental factors on pomegranate seedlings.

Materials and Methods

Study Location

The study was conducted in the fields belonging to the Department of Horticulture and Landscape Engineering at the College of Agriculture, Al-Qasim Green University, during the 2025 growing season, at the University of Babylon site.

Seedling Preparation

The research was conducted on one-year-old pomegranate seedlings of the Wonderful variety, as uniform in size as possible. The seedlings were obtained from the General Company for Horticulture and Forestry/Horticulture Station in Al-Hindiya, Karbala Governorate, totaling 150 seedlings planted in 2 kg plastic bags. The seedlings were then transferred to 10 kg black plastic (polyethylene) pots, which were filled with soil taken from the ground adjacent to the wooden shade structure at the College of Agriculture after being cleaned of impurities and debris. From the available seedlings, 135 seedlings were selected and distributed equally among the three replicates.

Thus, the number of treatments is 9 with three replicates, making the total number of treatments 27. Each treatment is randomly applied to an experimental unit containing five seedlings, for a total of 135 seedlings, with each replicate containing 45 seedlings.

Soil Analysis

Random samples were taken from different areas of the pots' soil before the experiment. This procedure was carried out prior to the seedling treatment to study some chemical and physical properties. The soil analysis was performed at the Ghaya Al-Maarefa Private Laboratory.

Experimental Design

The experiment was designed as a factorial experiment according to the design of the completely randomized block (R.C.B.D), where the experiment includes two factors: the first factor is the salinity levels of irrigation water (river water comparison, 6.3 dS/L), and the second factor is the concentration of alpha-tocopherol (0, 150, 300 mg per liter) produced by the Indian company HIMEDIA, with three replicates (Al-Rawi and Khalaf Allah, 2000) [2]

Date and Number of Sprays

The treatments were sprayed four times, 15 days apart, on the following dates:

- **First spray:** April 15, 2025
- **Second spray:** April 30, 2025
- **Third spray:** May 15, 2025
- **Fourth spray:** June 1, 2025

Preparation of Study Factors

1. Preparation of Irrigation Water Concentrations

A 2000-liter tank filled with drainage water from the Ibrahimia area was used as the base solution. 500 liters were

prepared, and the salinity was fixed at 3 decimeters. Another 500 liters were prepared, and the salinity was fixed at 6 decimeters after adding sodium chloride to the water. This was done using the equation for converting salinity measurements from decimeters to grams. The amount of irrigation water was estimated at one liter per seedling.

2. Preparation of alpha-tocopherol concentrations

Dissolve each concentration of alpha-tocopherol separately in 100 ml of water in a 1-liter volumetric flask, then complete the volume to 1 liter according to the required concentration.

Studied Characteristics

Vegetative Growth Characteristics

(Average Seedling Height (cm))

The seedling height was measured using a tape measure from the soil surface to the top of the main stem. Five seedlings were used per experimental unit, with three replicates.

(g Average Seedling Diameter (m))

The diameter of the main stem of the seedlings growing above the point where the main stem meets the soil was measured using a caliper. Five seedlings were used per experimental unit, with three replicates.

(Average Leaf Area (cm²))

The leaf area was measured by taking one leaf from each plant in each experimental unit and using a scanner and the Images software. The average was then multiplied by the number of leaves per plant to calculate the area, according to the method used by Al-Zaidy (2016) [3].

Estimation of NPK content in leaves

Digestion of samples

A sample of mature leaves and flower heads was taken, then cut and air-dried in a well-ventilated room. The sample was placed in perforated paper bags inside an electric oven at 68°C until weight stabilized. Afterward

The sample was transferred to airtight plastic containers and stored in a dry place until its constituent elements could be determined and analyzed (Al-Sahaf, 1989) [4].

A 0.2 g sample of the ground sample was then dissolved by adding 4 mL of concentrated sulfuric acid and 1.75 mL of concentrated perchloric acid. This was then placed in digestion flasks on a heated plate. Upon completion of digestion, a colorless solution was obtained. The liquid was then transferred to 100 mL plastic containers, and the solution was topped up with distilled water to the mark. It was then transferred to plastic containers according to the method described (Jones and Steyr, 1973) [16], and the constituent elements were determined as follows:

Nitrogen Percentage (%)

The percentage of total nitrogen was determined using a Kjeldahl micrometer according to the method described by Page *et al.* (1982) [24] at the Plant Analysis Laboratory, Faculty of Agriculture, Al-Qasim Green University. Five milliliters of the digested sample were taken, and then five milliliters of 2% boric acid and an indicator of Methyl Red Bromocresol Green were added, along with 10 milliliters of 40% sodium hydroxide (NaOH). The mixture was then distilled, and the released ammonia was collected in a glass flask. The collected ammonia was then rectified using 0.005 M hydrochloric acid (HCl).

Percentage of Phosphorus. (%):6-2-4

The percentage of phosphorus in the plant was estimated using the ammonium molybdate-phenolate method (Al-Sahaf, 1989) [4]. 22.5 g of ammonium molybdate was dissolved in 400 mL of distilled water (Solution 8), and then 1.25 g of ammonium phenolate was dissolved in 300 mL of hot distilled water (Solution 8). Next, solution 8 was added to the other solution, and the mixture was allowed to cool. Then, 250 mL of concentrated nitric acid (3HNO₃) was carefully added and allowed to cool to room temperature. The volume was then brought up to 1 liter of distilled water. Five mL of the digested sample was then taken, and 5 mL of ammonium molybdate and phenolate solution were added. The volume was then brought up to 50 mL with water.

The distillate was left to stand for 30 minutes. Afterward, the optical absorption reading was taken using a spectrophotometer at a wavelength of 410 nm. The control sample (Bank) was prepared in the same way, except that the standard curve was prepared using potassium dihydrogen phosphate (4KH₂PO₄).

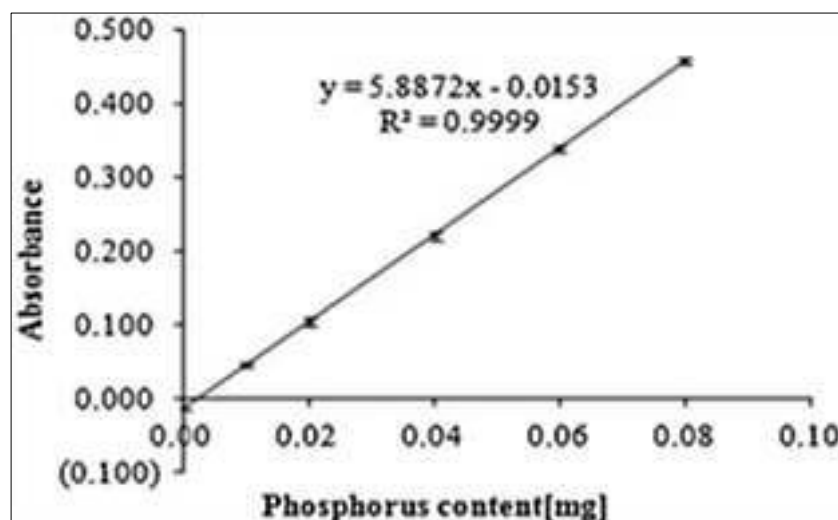


Fig 1: Standard curve of phosphorus

Potassium Concentration (%)

Measured using a Flame Photometer according to Page's method (1982) [24]

Results and Discussion

Vegetative Growth Characteristics

Seedling Height cm

The results in Table (1) indicate significant differences in seedling height (cm) based on irrigation water salinity levels. Normal river water (1.5 dS/m) significantly outperformed other levels, achieving the highest seedling height of 76.37 cm, compared to the lowest (6 dS/m) level (67.49 cm). The same table also shows significant differences in alpha-tocopherol treatment for pomegranate seedling height. The concentration (300 mg/L) significantly

resulted in the highest seedling height of 77.15 cm, compared to the untreated seedlings, which recorded the lowest height of 67.31 cm.

As for the interaction between the two experimental factors, it was observed from the data in the same table that there were significant differences for most of the interactions with the comparison treatment, as the interaction treatment of irrigating the seedlings with ordinary river water (1.5 dS/m-1) with spraying with alpha-tocopherol at a concentration of (300 mg/L-1) achieved the highest rate of seedling height, which reached (82.27 cm), compared to the seedlings that were sprayed with water with a salinity level of (6 dS/m-1) with spraying with alpha-tocopherol at a concentration of (0 mg/L-1), as the rate of seedling height reached the lowest level, which reached (62.33 cm)

Table 1: Effect of salinity levels of irrigation water and spraying with alpha-tocopherol and their interactions on the average height of the seedling (cm)

Factor A	Factor B Alph at ocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
76.37	82.27	77.42	69.44	Normal river water (1.5 dS/m-1)
69.65	75.87	62.91	70.18	3
67.49	73.33	66.82	62.33	6
	77.15	69.05	67.31	Factor B
A*B= 5.807	B=3.353	A=3.353		

Average Main Stem Diameter of Pomegranate Seedlings mm

The results in Table (2) indicate significant differences in the average stem diameter of the seedlings based on irrigation water salinity levels. Normal river water (1.5 dS·m⁻¹) significantly outperformed all other levels, achieving the highest average stem diameter of 7.26 mm, compared to the lowest average diameter of 7.18 mm at the 6 dS·m⁻¹ level.

The same table also shows significant differences in the average stem diameter of pomegranate seedlings based on alpha-tocopherol treatment. A concentration of 300 mg L⁻¹ significantly resulted in the highest average stem diameter

of 7.66 mm, compared to seedlings that were not sprayed, which recorded the lowest average stem diameter of 6.91 mm.

Regarding the interaction of experimental factors, the data showed that irrigating seedlings with water at a salinity level of (6 dS/m-1) while spraying with alpha-tocopherol at a concentration of (300 mg/L-1) resulted in a significant increase in the average stem diameter of pomegranate seedlings, reaching (7.92 mm plant-1). Conversely, the lowest average stem diameter was recorded at a salinity level of (3 dS/m-1) while spraying with alpha-tocopherol at a concentration of (0 mg/L-1), reaching (6.49 mm)).

Table 2: Effect of salinity levels of irrigation water and spraying with alpha-tocopherol and their interactions on the average stem diameter of pomegranate seedlings (mm)

Factor A	Factor B Alph at ocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
7.26	7.28	7.22	7.52	Normal river water (1.5 dS/m-1)
7.34	7.79	7.52	6.49	3
7.18	7.92	6.89	6.73	6
	7.66	7.21	6.91	Factor B
A*B=1.022	B=0.081	A=0.081	L.S.D= 0.05	

Average total leaf area of the seedling cm

Table (3) shows significant differences in the leaf area (cm²) of seedlings based on irrigation water salinity levels. Normal river water (1.5 dS·m⁻¹) resulted in the highest leaf area (1685.66 cm²), compared to the lowest (1460.49 cm²) at a salinity level of 6 dS·m⁻¹.

The same table also shows significant differences in the leaf area of pomegranate seedlings when sprayed with alpha-tocopherol. Spraying with 300 mg L⁻¹ resulted in the highest leaf area (1691.93 cm²), while spraying with 150 mg L⁻¹ resulted in the lowest leaf area (1561.25 cm²), which was

not significantly different from the control treatment.

Regarding the interaction between the two experimental factors, the same table shows that irrigating seedlings with water at a salinity level of 3 dS·m⁻¹ and spraying with alpha-tocopherol at a concentration of 300 mg/L⁻¹ significantly affected this indicator. This resulted in the highest leaf area (1952.51 cm²) compared to seedlings sprayed with alpha-tocopherol (300 mg/L⁻¹) at a salinity level of 6 dS·m⁻¹, which yielded the lowest leaf area (1338.74 cm²) for pomegranate seedlings.

Table 3: Effect of Irrigation Water Salinity Levels and Alpha-Tocopherol Spraying and Their Interactions on Leaf Area Total of Seedling (cm²)

Factor A	Factor B Alph at ocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
1685.66	1784.54	1684.22	1588.23	Normal river water (1.5 dS/m-1)
1670.25	1952.51	1641.87	1416.37	3
1460.49	1338.74	1357.66	1685.09	6
	1691.93	1561.25	1563.23	Factor B
268.02=A*B	A=112.834	A=112.834		

3-1-4 Nitrogen Percentage (%)

The results in Table (4) indicate significant differences in the effect of irrigation water salinity levels on the nitrogen percentage (%). Normal river water significantly outperformed other sources, achieving the highest nitrogen percentage at (2.707%), while the (6 dS·m⁻¹) level recorded the lowest percentage at (2.031%).

The same results also showed significant differences in the percentage of nitrogen achieved when spraying alpha-tocopherol (mg/L), with the concentration (150 mg/L) achieving the highest percentage (2.260%). Regarding the

interaction between the two experimental factors, the data in the same table showed significant differences for most interactions compared to the control treatment. The interaction treatment of irrigating seedlings with normal river water (1.5 dS/m) combined with spraying alpha-tocopherol at a concentration of (300 mg/L) achieved the highest percentage of nitrogen (3.064%), compared to seedlings sprayed with water at a salinity level of (6 dS/m) combined with spraying alpha-tocopherol at a concentration of (0 mg/L), where the average seedling height reached the lowest level (1.416%).

Table 4: Effect of salinity levels of irrigation and spray water with alpha-tocopherol and their interactions on the percentage of nitrogen (%)

Factor A	Factor B Alph at ocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
2.707	3.064	2.751	2.306	Normal river water (1.5 dS/m-1)
2.067	1.723	1.989	2.490	3
2.031	2.637	2.039	1.416	6
	2.475	2.260	2.070	Factor B
0.598 =A*B	0.345=A	0.345=A		

Average Phosphorus Percentage (%)

The results in Table (5) indicate significant differences in the effect of irrigation water salinity levels on the average phosphorus percentage (%). Normal river water level (1.5 dS/m⁻¹) showed the highest phosphorus percentage

(0.410%), while level (6 dS/m⁻¹) recorded the lowest (0.295%).

The same results showed no significant differences in the average phosphorus percentage (%) when alpha-tocopherol (mg/L⁻¹) was sprayed.

Table 5: The effect of salinity levels of irrigation and spray water with alpha-tocopherol and their interactions on the percentage of phosphorus. (%)

Factor A	Factor BAlphatocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
0.410	0.468	0.339	0.424	Normal river water (1.5 dS/m-1)
0.396	0.391	0.409	0.388	3
0.295	0.285	0.334	0.267	6
	0.381	0.361	0.359	Factor B
=0.210 A*B	0.104=B	0.104=A		

Regarding the interaction of experimental factors, the data in the table indicated no significant differences in the average phosphorus percentage (%). The treatment of irrigating the seedlings with ordinary river water (1.5 dS/m⁻¹) with spraying with alpha-tocopherol at a concentration of (300 mg/L-1) gave the highest percentage of (0.468%), compared to the seedlings treated with water with a salinity of (6 dS/m⁻¹) with spraying with alpha-tocopherol at a concentration of (0 mg/L-1), which achieved the lowest

percentage of (0.267%)

Average percentage of potassium (%)

Table (6) results showed no significant differences between irrigation water salinity levels in the average percentage of potassium (%), as the normal river water level (1.5 dS.m-1) significantly outperformed, achieving the highest percentage of potassium at 1.091% compared to the level (6 dS.m-1) The same table also showed no significant differences in the percentage of potassium when alpha-tocopherol was used.

Table 6: The effect of salinity levels of irrigation and spray water with alpha-tocopherol and their interactions on the percentage of potassium %.

Factor A	Factor B Alph at ocopherol (mg.L-1)	Factor A Irrigation water salinity / decimeters		
300	150	0		
1.091	1.244	0.901	1.130	Normal river water (1.5 dS/m-1)
1.053	1.041	1.089	1.030	3
0.786	0.759	0.890	0.709	6
	1.015	0.960	0.956	Factor B
=0.573 A*B	0.278=B	0.278=A		

Discussion

The Effect of Salinity Levels on Vegetative Growth Characteristics

Tables (1, 2, 3) show seedling height, stem diameter, and leaf area. A significant decrease in vegetative growth indicators was observed at irrigation water salinity levels of 3 and 6 dS/m⁻¹. Salinity reduces the rate of vegetative growth because increased salt levels in irrigation water may be due to increased salt concentration in the soil solution. This can have direct negative effects, such as inhibiting enzyme activity in plant cells and disrupting nutrient balance, or through impaired cell membrane function. Salinity also affects photosynthesis, respiration, and electron transport pathways. This decrease may also be due to indirect effects of salinity on soil properties, which negatively impact seedling growth. The increased osmotic potential of the soil solution at high irrigation water salinity levels leads to a water absorption deficit, reducing cell swelling pressure. This, in turn, affects cell wall flexibility, cell dilation, and elongation, ultimately reducing plant height and vegetative branch growth (Orcutt and Nielsen, 2000) [23]. These results are consistent with those reported by Tozlu *et al.* (2000) [29] in their study of trifoliate oranges regarding plant height and stem diameter, as well as with those reported by Khalil (2004) [5] in his study of sour orange seedlings regarding the average number of branches, the average number of leaves, and the average leaf area. These findings also align with those reported by Ahmed (1984) [1].

Effect of alpha-tocopherol concentrations on vegetative characteristics

Tables 1, 2, and 3 illustrate the effect of alpha-tocopherol spraying. Spraying at a concentration of 300 mg/L improved the studied vegetative growth indicators. This is due to its effect on increasing cell division and the activity of a number of enzymes such as glucosidase, amylase, β -amylase, and phosphatase, in addition to its assistance in the synthesis of other enzymes such as protease, α -amylase, and Smirnov lipase. It also increased the uptake of macronutrients that accumulate within the plant, leading to increased plant cell division and differentiation processes, and the maintenance of chloroplasts and their effect on carbon synthesis and its products (Dowdle *et al.*, 2007) [12].

Effect of Salinity Levels on Chemical Properties

Tables (4, 5, 6) indicate a decrease in leaf NPK content. The significant decrease in leaf chlorophyll content at high salinity concentrations may be due to inhibition of chlorophyll biosynthesis or degradation (Kumar, 2021), or dysregulation of chloroplasts (Camejo *et al.*, 2006) [11]. Madan *et al.* (2004) [21] reported that salinity stress led to a decrease in the rate of photosynthesis and chlorophyll

content in salt-tolerant plants, while the decrease was greater in salt-tolerant plants.

Effect of Alpha-Tocopherol Concentrations on Chemical Properties

Tables (4, 5, 6) show a decrease in leaf NPK content. The chlorophyll content in leaves increases significantly when sprayed with alpha-tocopherol, and this increase is associated with an increase in the amount of spray applied. This can be attributed to the effect of alpha-tocopherol, an antioxidant that protects green membranes and chloroplasts from photo-oxidation, creating favorable environmental conditions for photosynthesis. It acts as an internal signal transmitter, increasing cell and electron transport in the PSII photocatalytic system. The results also indicate that spray treatment with a concentration of 300 mg/L of alpha-tocopherol is superior in increasing leaf content of nitrogen, phosphorus, and potassium (N, P, K). This is because vitamins enhance plant efficiency in terms of carbon content and growth, leading to increased synthesis and translocation of substances to the roots. This, in turn, promotes growth and nutrient uptake, contributing to nutrient accumulation, particularly of NPK. Furthermore, it improves membrane permeability and increases the activity of membrane-associated enzymes, protecting plants by maintaining the structural integrity of the plasma membrane and enhancing its role in mineral nutrient uptake. This aligns with the findings of Semida *et al.* (2014) [28] and Rady *et al.* (2015) [27].

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