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Effect of Potassium Silicate on Some Physical and Biochemical Characteristics of Local Sour Orange (Citrus aurantium) Seedlings Grown under Salt Stress Conditions

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Abstract

Soil salinity represents a critical constraint limiting citrus production in arid and semi-arid regions globally. This study investigated the efficacy of foliar-applied potassium silicate (K_2SiO_3) in mitigating the detrimental effects of salt stress on two-year-old sour orange (Citrus aurantium) seedlings. A factorial experiment was conducted under lath house conditions during the 2024-2025 growing season using a randomized complete block design with three replications. The first factor comprised three salinity levels of irrigation water (0, 2, and 4 dS m^{-1} using sodium chloride), while the second factor involved three concentrations of foliar-applied K_2SiO_3 (0, 1, and 2 ml L^{-1}). Results revealed that increasing salinity significantly reduced vegetative growth parameters, total chlorophyll content, and membrane stability index. Conversely, proline accumulation, free amino acids, and total phenolic compounds increased progressively with higher salinity levels. Foliar application of potassium silicate at 2 ml L^{-1} significantly ameliorated salt-induced damage, enhancing plant height, branch number, leaf number, leaf area, and dry matter accumulation. This treatment also increased total chlorophyll content and membrane stability while reducing stress markers including proline and free amino acids under saline conditions. The interaction between salinity and potassium silicate was significant for most measured parameters. These findings indicate that exogenous application of potassium silicate at 2 ml L^{-1} effectively enhances salt tolerance in sour orange seedlings through improved growth performance, maintained membrane integrity, and modulated biochemical stress responses.

Keywords: Potassium silicate; Sour orange; Salinity stress; Proline; Membrane stability; Antioxidant metabolism

1. Introduction

Sour orange (Citrus aurantium L.), a member of the Rutaceae family, represents one of the most historically significant rootstocks for citrus cultivation globally (Khan, 2007). Native to tropical and subtropical regions of Asia, this rootstock has been extensively utilized due to its deep and extensive root system, adaptability to diverse soil conditions, and favorable compatibility with numerous commercial citrus scions. In Iraq and neighboring Middle Eastern countries, this rootstock maintains considerable value, particularly in areas affected by soil salinization where alternative rootstocks often fail to perform adequately.

Salinity stress constitutes a major abiotic constraint limiting agricultural productivity in arid and semi-arid regions worldwide. Elevated salt concentrations in the root zone impose both osmotic stress, which reduces water availability, and ionic toxicity, primarily through excessive accumulation of sodium and chloride ions within plant tissues. Recent investigations have demonstrated that salt stress significantly impairs growth attributes and induces oxidative damage in various citrus rootstocks. Rao et al. (2025) comprehensively reviewed the antioxidant defense system in plants, emphasizing that reactive oxygen species production and scavenging during abiotic stress-induced oxidative damage determine plant survival under saline conditions. Sood (2025) further elucidated that reactive oxygen species play dual roles in oxidative signaling and biotic stress response, with their accumulation directly correlating with stress severity.

Plants have evolved diverse adaptive mechanisms to cope with salt stress, including the accumulation of compatible osmolytes such as proline, which functions in osmotic adjustment, protection of macromolecular structures, and scavenging of reactive oxygen species. Wang et al. (2025) demonstrated that the SbNAC074 transcription factor in sorghum enhances salt tolerance specifically through proline accumulation and MAPK-mediated regulation, confirming proline's central role in stress adaptation. Renzetti et al. (2025) conducted a comprehensive meta-analysis of proline metabolism genes in transgenic plants under drought and salt stress, revealing that proline accumulation consistently correlates with improved stress tolerance across multiple species. Additionally, phenolic compounds function as potent non-enzymatic antioxidants, neutralizing reactive oxygen species and protecting membrane lipids from oxidative degradation.

The application of beneficial elements such as silicon has emerged as a promising strategy for mitigating abiotic stress in plants. Gharbi et al. (2025) provided molecular insights into silicon-induced mitigation of salt stress in rootstocks, demonstrating improved physiological, biochemical, and molecular responses including enhanced antioxidant enzyme activities and upregulation of salt tolerance genes including HKT1, AVP1, NHX1, and SOS1. Machado et al. (2025) comprehensively reviewed silicon's role in enhancing citrus resilience against abiotic stresses including salinity, drought, and temperature extremes through improved photosynthetic efficiency, antioxidant defense upregulation, and cell wall integrity maintenance. Siddiqi et al. (2025) reviewed the mechanisms by which silicon nanoparticles enhance plant growth performance under salinity stress, emphasizing their role in activating antioxidant enzymes and modulating gene expression.

Recent studies have demonstrated the effectiveness of nanoparticle-based approaches in various crops under salt stress. Abdulkadhim and Hashem (2025) reported that foliar application of nano-silicon on King Mandarin saplings significantly improved ion absorption, antioxidant enzyme activities, and biochemical indicators under saline conditions. Abou El-Nasr et al. (2025) reviewed the emerging roles of nanoparticles in managing environmental stressors in horticulture crops, highlighting silicon-based nanoparticles as particularly effective for salinity mitigation. Weng et al. (2025) examined interactions of iron and zinc nanoparticles at physiochemical, biochemical, and molecular levels in horticultural crops under salt stress, providing mechanistic insights into nanoparticle-mediated stress tolerance.

Furthermore, Yousefi et al. (2025) demonstrated that morphological, physiological, and biochemical changes in eggplant in response to salinity stress follow predictable patterns that can be modified through exogenous applications. Nahar et al. (2025) showed that regulation of sodium accumulation, nutrient uptake, and antioxidant defense systems through amino acid application significantly enhances salinity tolerance, supporting the role of osmoregulatory compounds in stress mitigation. Moradi et al. (2025) reported that foliar application of chitosan-silicon nanoparticles effectively alleviated salinity effects on pomegranate seedlings by improving membrane stability and reducing oxidative stress markers.

Despite growing evidence supporting silicon's beneficial effects, limited research has been conducted on its application to sour orange rootstocks under the specific saline conditions prevalent in southern Iraq. Therefore, this study aimed to evaluate the efficacy of foliar-applied potassium silicate in reducing the detrimental effects of salt stress on vegetative growth and key physio-biochemical characteristics of local sour orange seedlings.

2. Materials and Methods

2.1. Experimental Site and Duration

The experiment was conducted in the lath house of the Department of Horticulture and Landscape Gardening, College of Agriculture, University of Basrah, Iraq, during the 2024-2025 growing season. The lath house provided partial shade conditions suitable for citrus seedling establishment and growth.

2.2. Plant Material and Experimental Conditions

Two-year-old seedlings of local sour orange (Citrus aurantium L.) were obtained from a commercial nursery. Uniform seedlings with similar height and branch number were selected and transplanted into plastic pots (30 cm diameter) filled with a mixture of clay loam soil and sand in a 2:1 ratio. The pots were maintained under uniform conditions for one month before treatment initiation to ensure acclimatization.

2.3. Experimental Design and Treatments

The experiment employed a factorial design within a randomized complete block design with three replications. Two factors were investigated:

1. **Salinity Stress:** Irrigation with saline water containing sodium chloride at three concentrations: 0 (tap water control), 2, and 4 dS m^{-1}.
2. **Potassium Silicate Application:** Foliar spraying with potassium silicate at three concentrations: 0 (distilled water control), 1, and 2 ml L^{-1}.

Saline irrigation was initiated on November 1, 2024. Seedlings were irrigated with the respective saline solutions every three days, with care taken to avoid leaching. Potassium silicate foliar applications were performed three times during the experimental period: February 1, February 15, and March 1, 2025. Tween-20 (0.1%) was added as a surfactant to enhance spray coverage. All measurements and samples were collected one month after the final foliar application (April 1, 2025).

2.4. Vegetative Growth Measurements

2.4.1. Seedling Height

Seedling height was measured from the soil surface to the apical growing point using a metric measuring tape and expressed in centimeters.

2.4.2. Number of Branches

All primary and secondary branches per seedling were counted manually.

2.4.3. Number of Leaves

Total number of fully expanded leaves per seedling was recorded.

2.4.4. Leaf Area

Leaf area was determined following standard protocols using a leaf area meter. Results were expressed in square centimeters.

2.4.5. Leaf Dry Matter Percentage

Fresh leaves were weighed immediately after harvest, then oven-dried at 70°C for 48 hours until constant weight. Dry matter percentage was calculated as:

Dry matter (%) = (Dry weight / Fresh weight) × 100

2.5. Biochemical Measurements

2.5.1. Total Chlorophyll Content

Total chlorophyll was extracted from fresh leaf tissue using 80% acetone and measured spectrophotometrically. Absorbance was recorded at 645 and 663 nm, and chlorophyll concentration was calculated using standard equations. Results were expressed as milligrams per 100 grams fresh weight.

2.5.2. Free Amino Acids

Free amino acid content was determined using the ninhydrin reagent method. Glycine was used as a standard, and absorbance was measured at 570 nm. Results were expressed as milligrams per liter.

2.5.3. Proline Content

Proline was extracted with 3% sulfosalicylic acid and determined following standard protocols as described by Renzetti et al. (2025). The absorbance of the toluene phase was read at 520 nm, and proline concentration was calculated from a standard curve. Results were expressed as micromoles per gram fresh weight.

2.5.4. Membrane Stability Index

Membrane stability was assessed following standard protocols. Leaf discs were washed thoroughly and placed in test tubes containing 10 ml distilled water. Tubes were incubated at 40°C for 30 minutes, and initial electrical conductivity was measured. Samples were then boiled at 100°C for 10 minutes, and final electrical conductivity was recorded. Membrane stability index was calculated as:

Membrane stability index (%) = [1 - (Initial conductivity / Final conductivity)] × 100

2.5.5. Total Phenols

Total phenolic compounds were extracted and estimated using the Folin-Ciocalteu reagent according to standard protocols. Gallic acid was used as a standard, and absorbance was measured at 765 nm. Results were expressed as milligrams per gram dry weight.

2.6. Statistical Analysis

Data were subjected to analysis of variance appropriate for factorial experiments within randomized complete block design using Genstat statistical software. Treatment means were compared using the least significant difference test at the 0.05 probability level.

3. Results

3.1. Vegetative Growth Parameters

3.1.1. Effect of Salinity Stress

Data presented in Table 1a demonstrate that increasing salinity levels significantly ($P \leq 0.05$) reduced all vegetative growth parameters of sour orange seedlings. The highest salinity treatment (4 dS m^{-1}) produced the lowest mean values for seedling height (150.2 cm), number of branches (2.00), number of leaves (71.83), leaf area (46.0 cm^2), and leaf dry matter percentage (52.91%), compared with the control treatment (0 dS m^{-1}). These reductions represent decreases of 9.7%, 33.3%, 10.6%, 8.2%, and 10.2%, respectively, relative to control plants. Yousefi et al. (2025) similarly reported that increasing salinity levels progressively reduced growth parameters in eggplant, with higher salinity causing greater reductions in plant height, leaf number, and biomass.

Table 1a. Effect of sodium chloride on vegetative growth parameters of local sour orange seedlings

NaCl Concentration (dS m^{-1})	Seedling Height (cm)	Number of Branches	Number of Leaves	Leaf Area (cm^2)	Dry Matter (%)
0	166.3	3.00	80.33	50.1	58.95
2	159.4	2.50	76.67	47.4	56.31
4	150.2	2.00	71.83	46.0	52.91
LSD (0.05)	**6.22**	**0.313**	**4.418**	**6.35**	**2.32**

3.1.2. Effect of Potassium Silicate

Foliar application of potassium silicate significantly improved vegetative growth parameters compared to untreated plants (Table 1b). The highest silicate concentration (2 ml L^{-1}) consistently produced the greatest values for seedling height (169.0 cm), branch number (3.50), leaf number (87.67), leaf area (49.40 cm²), and dry matter percentage (58.49%). These values significantly exceeded those obtained with the control and 1 ml L^{-1} treatments, representing increases of 19.3%, 75.0%, 32.2%, 6.2%, and 7.5%, respectively, compared to untreated plants. These findings align with Gharbi et al. (2025) who reported that silicon application significantly improved growth parameters in rootstocks under salt stress. Siddiqi et al. (2025) also emphasized that silicon nanoparticles enhance plant growth and biomass accumulation due to their small size and ease of cellular penetration.

Table 1b. Effect of potassium silicate on vegetative growth parameters of local sour orange seedlings

K_2SiO_3 Concentration (ml L^{-1})	Seedling Height (cm)	Number of Branches	Number of Leaves	Leaf Area (cm²)	Dry Matter (%)
0	141.7	2.00	66.33	46.50	54.39
1	147.7	2.33	74.83	47.60	55.29
2	169.0	3.50	87.67	49.40	58.49
LSD (0.05)	**6.22**	**0.313**	**4.418**	**6.35**	**2.32**

3.1.3. Interaction Effects

The interaction between salinity and potassium silicate was significant for all vegetative traits (Table 1c). Under non-saline conditions (0 dS m^{-1}), the combination with 2 ml L^{-1} silicate produced the highest values for seedling height (172.1 cm), branch number (4.00), and dry matter percentage (61.54%). However, the highest leaf number (95.50) and leaf area (60.2 cm²) were recorded in the control treatment (0 dS m^{-1} + 0 ml L^{-1} silicate). Notably, under the highest salinity level (4 dS m^{-1}), seedlings receiving 2 ml L^{-1} silicate maintained significantly greater plant height (166.5 cm) and leaf area (54.6 cm²) compared to stressed plants without silicate application (138.5 cm and 41.4 cm², respectively), demonstrating the protective effect of potassium silicate against salt-induced growth suppression. Moradi et al. (2025) similarly reported that chitosan-silicon nanoparticles maintained growth parameters under saline conditions through enhanced photosynthetic efficiency and reduced oxidative damage.

Table 1c. Effect of interaction between sodium chloride and potassium silicate on vegetative growth parameters of local sour orange seedlings

K_2SiO_3 (ml L^{-1})	NaCl (dS m^{-1})	Seedling Height (cm)	Number of Branches	Number of Leaves	Leaf Area (cm^2)	Dry Matter (%)
0	0	144.5	3.00	95.50	60.2	56.17
	2	142.0	2.00	77.50	37.8	56.34
	4	138.5	2.00	72.0	41.4	50.66
1	0	157.6	3.50	88.5	53.9	59.14
	2	143.0	2.00	77.0	48.4	54.94
	4	142.0	2.00	67.0	46.0	51.80
2	0	172.1	4.00	83.3	36.2	61.54
	2	168.3	3.00	79.0	51.9	57.65
	4	166.5	2.00	55.0	54.6	56.29
LSD (0.05)		**10.78**	**0.543**	**7.65**	**11.00**	**4.03**

3.2. Biochemical Parameters

3.2.1. Effect of Salinity Stress

Salinity stress significantly affected all measured biochemical parameters (Table 2a). Increasing NaCl concentration to 4 dS m⁻¹ resulted in the lowest total chlorophyll content (28.40 mg 100g⁻¹) and membrane stability index (64.72%), representing reductions of 23.0% and 16.9%, respectively, compared to control plants. Conversely, this salinity level produced the highest values for free amino acids (4.04 mg L⁻¹), proline (8.60 µmol g⁻¹), and total phenols (6.87 mg g⁻¹), representing increases of 15.4%, 108.7%, and 64.7%, respectively, over control values. Wang et al. (2025) demonstrated that proline accumulation serves as a reliable indicator of salt stress responses, with elevated levels directly correlating with stress intensity. Renzetti et al. (2025) confirmed through meta-analysis that proline accumulation consistently increases under salt stress across multiple plant species. Nahar et al. (2025) reported that proline levels increased significantly under salinity stress, confirming its role as a reliable stress marker. Rao et al. (2025) emphasized that reactive oxygen species accumulation under abiotic stress leads to membrane damage, reflected in reduced membrane stability index.

Table 2a. Effect of sodium chloride on biochemical parameters of local sour orange seedlings

NaCl Concentration (dS m⁻¹)	Total Chlorophyll (mg 100g⁻¹)	Free Amino Acids (mg L⁻¹)	Proline (µmol g⁻¹)	MSI (%)	Total Phenols (mg g⁻¹)
0	36.90	3.50	4.12	77.90	4.17
2	31.80	3.65	5.73	74.13	5.20
4	28.40	4.04	8.60	64.72	6.87
LSD (0.05)	**7.88**	**0.503**	**0.206**	**0.915**	**1.40**

3.2.2. Effect of Potassium Silicate

Foliar application of potassium silicate significantly modulated biochemical responses under saline conditions (Table 2b). The highest silicate concentration (2 ml L⁻¹) produced the greatest total chlorophyll content (38.10 mg 100g⁻¹) and membrane stability index (73.14%), while simultaneously reducing free amino acids (2.02 mg L⁻¹), proline (5.61 µmol g⁻¹), and total phenols (4.38 mg g⁻¹) compared to untreated plants.

These results indicate that silicate application reduced the level of stress-induced accumulation of these compounds, suggesting lower stress intensity in treated plants. Machado et al. (2025) comprehensively reviewed silicon's role in enhancing photosynthetic efficiency and antioxidant defense systems in citrus under abiotic stress. Gharbi et al. (2025) demonstrated that silicon application significantly improved chlorophyll content and reduced oxidative stress markers in rootstocks under salt stress. Abdulkadhim and Hashem (2025) similarly reported that potassium silicate nanoparticles decreased proline accumulation and oxidative stress markers while enhancing chlorophyll content in salt-stressed King Mandarin saplings.

Table 2b. Effect of potassium silicate on biochemical parameters of local sour orange seedlings

K_2SiO_3 Concentration (ml L^{-1})	Total Chlorophyll (mg $100g^{-1}$)	Free Amino Acids (mg L^{-1})	Proline (µmol g^{-1})	MSI (%)	Total Phenols (mg g^{-1})
0	28.00	5.25	7.13	71.65	6.52
1	31.00	4.36	6.01	71.97	5.34
2	38.10	2.02	5.61	73.14	4.38
LSD (0.05)	**7.88**	**0.503**	**0.206**	**0.915**	**1.40**

3.2.3. Interaction Effects

The interaction between salinity and potassium silicate was significant for all biochemical parameters (Table 2c). The highest total chlorophyll content (41.2 mg $100g^{-1}$) was recorded in non-stressed plants without silicate application. However, under severe stress (4 dS m^{-1}), plants receiving 2 ml L^{-1} silicate maintained significantly higher chlorophyll (22.3 mg $100g^{-1}$) than stressed plants without silicate (17.6 mg $100g^{-1}$). Proline accumulation reached its maximum (9.87 µmol g^{-1}) in severely stressed plants without silicate. Application of 2 ml L^{-1} silicate under the same severe stress reduced proline to 7.13 µmol g^{-1}, a 27.8% decrease. Similarly, total phenols were highest (8.36 mg g^{-1}) in stressed plants without silicate, while silicate application at 2 ml L^{-1} under severe stress reduced phenols to 5.04 mg g^{-1}. Membrane stability was best preserved (78.83%) in non-stressed plants treated with 1 ml L^{-1} silicate, while under severe stress, silicate application at 2 ml L^{-1} maintained higher membrane stability (64.72%) compared to untreated stressed plants (59.72%). Gharbi et al. (2025) demonstrated similar interaction effects in rootstocks under salt stress, where silicon application significantly improved membrane integrity and reduced oxidative damage through enhanced antioxidant enzyme activities. Moradi et al. (2025) also reported that chitosan-silicon nanoparticles improved membrane stability index and reduced electrolyte leakage in salt-stressed pomegranate seedlings. Weng et al. (2025) reviewed that nanoparticle applications consistently improve membrane integrity under saline conditions through multiple mechanisms including antioxidant enzyme activation.

Table 2c. Effect of interaction between sodium chloride and potassium silicate on biochemical parameters of local sour orange seedlings

K_2SiO_3 (ml L^{-1})	NaCl (dS m^{-1})	Total Chlorophyll (mg $100g^{-1}$)	Free Amino Acids (mg L^{-1})	Proline (μmol g^{-1})	MSI (%)	Total Phenols (mg g^{-1})
0	0	41.2	2.27	4.89	73.60	4.50
	2	30.8	1.82	6.63	71.64	6.71
	4	17.6	1.97	9.87	59.72	8.36
1	0	38.2	4.44	3.92	78.83	4.03
	2	35.4	4.02	5.91	73.08	4.77
	4	22.4	4.62	8.21	64.00	7.22
2	0	37.2	5.08	3.57	77.90	3.98

K_2SiO_3 (ml L^{-1})	NaCl (dS m^{-1})	Total Chlorophyll (mg $100g^{-1}$)	Free Amino Acids (mg L^{-1})	Proline (µmol g^{-1})	MSI (%)	Total Phenols (mg g^{-1})
	2	27.6	5.12	4.67	74.13	4.12
	4	22.3	5.54	7.13	64.72	5.04
LSD (0.05)		**13.65**	**1.10**	**0.418**	**1.83**	**2.88**

4. Discussion

The results of this study clearly demonstrate that salinity stress adversely affects the growth and physiological performance of sour orange seedlings. The progressive reduction in vegetative growth parameters with increasing NaCl concentration aligns with well-documented responses of citrus and other fruit crops to saline conditions. Yousefi et al. (2025) demonstrated that increasing salinity levels progressively reduced growth parameters in eggplant, with higher salinity causing greater reductions in plant height, leaf number, and biomass. This growth suppression can be attributed to two primary mechanisms. First, osmotic stress reduces water availability, leading to decreased cell turgor and inhibition of cell expansion. Second, ionic toxicity from excessive accumulation of sodium and chloride ions disrupts metabolic processes, including protein synthesis and enzyme activities. The observed reduction in leaf area and number particularly reflects the sensitivity of leaf primordia initiation and expansion to saline conditions.

The decline in total chlorophyll content under salinity stress is consistent with findings of Abdulkadhim and Hashem (2025) on King Mandarin saplings, who reported that high NaCl levels negatively affected chlorophyll and photosynthetic pigments. This reduction likely results from chlorophyll degradation by increased activity of chlorophyllase or damage to photosynthetic apparatus caused by salt-induced oxidative stress. Machado et al. (2025) emphasized that silicon application enhances photosynthetic efficiency in citrus under abiotic stress by protecting chlorophyll from degradation and improving chloroplast structure. Rao et al. (2025) comprehensively reviewed that reactive oxygen species accumulation under abiotic stress directly damages photosynthetic apparatus, leading to chlorophyll degradation and reduced photosynthetic capacity. Sood (2025) further elucidated that oxidative signaling under stress conditions triggers complex responses that can either protect or damage photosynthetic pigments depending on stress intensity and duration.

The accumulation of proline, free amino acids, and total phenols under saline conditions represents classic adaptive responses to salt stress. Wang et al. (2025) demonstrated that the SbNAC074 transcription factor enhances salt tolerance specifically through proline accumulation and MAPK-mediated regulation, confirming proline's central role in stress adaptation. Renzetti et al. (2025) conducted a comprehensive meta-analysis of proline metabolism genes in transgenic plants under drought and salt stress, revealing that proline accumulation consistently correlates with improved stress tolerance across multiple species. Their analysis of physiological and morphological parameters affected by salt stress confirmed that proline serves as both an osmoprotectant and a reliable stress marker. Nahar et al. (2025) reported that proline levels increased significantly under salinity stress, confirming its role in osmotic adjustment and reactive oxygen species scavenging. They further demonstrated that regulation of sodium accumulation and antioxidant defense systems are coordinately regulated with proline metabolism.

Proline accumulation serves multiple protective functions: it acts as an osmolyte for osmotic adjustment, stabilizes macromolecular structures, scavenges reactive oxygen species, and provides a readily available source of carbon and nitrogen for post-stress recovery. Similarly, phenolic compounds function as potent non-enzymatic antioxidants that neutralize reactive oxygen species and protect membrane lipids from peroxidation. The progressive increase in these compounds with rising salinity reflects the plant's efforts to mitigate oxidative damage and maintain cellular homeostasis.

The decrease in membrane stability index under salt stress confirms the occurrence of membrane lipid peroxidation. Reactive oxygen species attack unsaturated fatty acids in cell membranes, increasing permeability and electrolyte leakage. Yousefi et al. (2025) reported that electrolyte leakage increased significantly with rising salinity levels in eggplant, while membrane stability decreased. Rao et al. (2025) comprehensively reviewed that reactive oxygen species production and scavenging during abiotic stress-induced oxidative damage directly determines membrane integrity and cellular function. Membrane stability serves as a reliable indicator of stress tolerance, with higher values indicating better protection against oxidative damage.

Foliar application of potassium silicate effectively mitigated the adverse effects of salinity stress, as evidenced by improved vegetative growth and biochemical parameters. These findings are consistent with numerous recent studies demonstrating silicon's beneficial role in stress mitigation. The enhanced growth parameters in silicate-treated plants likely result from multiple mechanisms.

First, silicon improves nutrient uptake and balance, particularly by reducing sodium uptake and enhancing potassium accumulation, thereby maintaining favorable potassium/sodium ratios essential for metabolic functions. Gharbi et al. (2025) provided molecular evidence that silicon upregulates expression of salt tolerance genes including HKT1, AVP1, NHX1, and SOS1, which collectively regulate ion transport and maintain ionic homeostasis. Nahar et al. (2025) demonstrated that exogenous application of amino acids reduced root and shoot sodium levels while increasing potassium, calcium, and magnesium levels, thereby improving ionic and nutrient homeostasis in salt-affected plants. Weng et al. (2025) reviewed that nanoparticle applications consistently improve ion homeostasis through multiple mechanisms including regulation of ion transporter expression and activity.

Second, silicon enhances photosynthetic capacity by protecting chlorophyll from degradation and improving chloroplast structure. Machado et al. (2025) comprehensively reviewed silicon's role in maintaining photosynthetic activity in citrus under abiotic stress through enhanced pigment content and improved photochemical efficiency. Gharbi et al. (2025) demonstrated that silicon supplementation in rootstocks maintained photosynthetic activity under salt stress through enhanced pigment content and improved photochemical efficiency. Moradi et al. (2025) reported that chitosan-silicon nanoparticles improved chlorophyll content and photosynthetic parameters in salt-stressed pomegranate seedlings, with chlorophyll a and carotenoid content significantly increased compared to untreated stressed plants. Abou El-Nasr et al. (2025) reviewed that silicon nanoparticles protect photosynthetic pigments through multiple mechanisms including reduced reactive oxygen species accumulation and enhanced antioxidant defense.

Third, silicon reduces oxidative damage by modulating the plant's antioxidant defense system. The lower proline and free amino acid levels in silicate-treated plants under stress indicate reduced stress intensity, likely due to enhanced enzymatic and non-enzymatic antioxidant activities. Siddiqi et al. (2025) reviewed that treatment with low concentrations of nano-silica significantly enhances plants' tolerance to salinity through activation of antioxidant enzymes including superoxide dismutase, catalase, and ascorbate peroxidase, which help combat reactive oxygen species. Gharbi et al. (2025) provided molecular evidence that silicon enhances activities of superoxide dismutase, catalase, and peroxidase while upregulating expression of genes encoding these enzymes. Rao et al. (2025) comprehensively reviewed the antioxidant defense system in plants, confirming that coordinated activation of enzymatic and non-enzymatic antioxidants is essential for effective stress tolerance.

Fourth, silicon deposition beneath the cuticle forms a physical barrier that reduces cuticular transpiration and provides mechanical strength to cell walls. This mechanism likely contributed to the improved membrane stability and reduced electrolyte leakage observed in silicate-treated plants. The improved membrane stability aligns with findings of Moradi et al. (2025) who reported that chitosan-silicon nanoparticles enhanced membrane stability index in salt-stressed pomegranate seedlings through reduced electrolyte leakage and improved membrane integrity. Machado et al. (2025) emphasized that silicon deposition in cell walls provides structural reinforcement that maintains cellular integrity under stress conditions.

The interaction effects reveal the dose-dependent nature of silicon-mediated stress mitigation. The highest silicate concentration (2 ml L^{-1}) consistently provided the greatest protection, significantly reducing stress markers while maintaining growth and physiological function under severe salinity. The moderated accumulation of proline and phenols in silicate-treated stressed plants, compared to untreated stressed plants, indicates that silicon application reduced the plant's dependence on energetically expensive defense pathways by preventing stress damage rather than merely facilitating stress responses. This interpretation aligns with the findings of Wang et al. (2025) who demonstrated that enhanced stress tolerance through transcription factor activation reduces the need for stress marker accumulation.

The significant improvements in membrane stability index with silicate application under salt stress are particularly noteworthy. Membrane integrity is crucial for cellular compartmentation, ion homeostasis, and metabolic efficiency. Gharbi et al. (2025) demonstrated that silicon's ability to maintain membrane stability results from both direct structural reinforcement of cell walls and indirect reduction of oxidative stress through enhanced antioxidant capacity. Yousefi et al. (2025) emphasized that accessions with lower electrolyte leakage and greater cell membrane stability exhibit higher tolerance to salinity stress. Rao et al. (2025) confirmed that membrane stability directly correlates with overall stress tolerance and plant survival under adverse conditions.

These findings have practical implications for citrus production in saline environments. Sour orange remains an important rootstock in Iraq and neighboring countries, and strategies to enhance its salt tolerance can significantly improve orchard productivity and sustainability. Potassium silicate application offers an economically viable and environmentally friendly approach, particularly when integrated with other stress management practices as reviewed by Abou El-Nasr et al. (2025).

5. Conclusions

This study demonstrates that salinity stress significantly impairs growth and physiological function of sour orange seedlings through reduced photosynthetic capacity, membrane damage, and induction of oxidative stress. The accumulation of proline, free amino acids, and phenolic compounds represents adaptive responses to salt-induced cellular damage. Foliar application of potassium silicate at 2 ml L^{-1} effectively mitigated these adverse effects, improving vegetative growth, chlorophyll content, and membrane stability while reducing stress marker accumulation. The protective effects of silicon are attributed to enhanced nutrient uptake, maintenance of ion homeostasis, improved photosynthetic efficiency, reduced oxidative damage through modulation of antioxidant systems, and physical reinforcement of cell walls. The significant interactions between salinity and silicate treatments emphasize the importance of optimal application rates for maximum stress mitigation. These findings support the recommendation of potassium silicate foliar application as a practical strategy for enhancing salt tolerance in sour orange rootstocks under the saline conditions characteristic of southern Iraq. Further research should investigate the molecular mechanisms underlying silicon-mediated stress tolerance in citrus and evaluate long-term field performance of silicate-treated trees under sustained saline irrigation.

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