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Quantitative, Qualitative, and Physicochemical Characteristics of Tomato as Affected by Foliar Application of Potassium Silicate

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ABSTRACT

Tomato fruit (*Solanum lycopersicum* L.) has high economic value and is a vital food source for human health due to its high nutritional value. After the availability of water, nutrition is the second factor that has the greatest impact on tomato production. As a result, chemical fertilizers are used to improve the quantitative and qualitative properties of tomatoes. In this study, the effect of foliar application of potassium silicate at four concentrations [0 (control), 0.1, 0.2, and 0.3%] was investigated on tomato plants in three stages at two-week intervals. Foliar application of potassium silicate was carried out in 2024 and 2055 on 'SV4129TH' tomato plants in a commercial greenhouse located in Markazi province, Iran. This study was conducted in a completely randomized design with four treatments and four replications. The results showed that the effect of nutritional treatments on leaf dry weight, fruit dry weight, fruit number, yield, and fruit fresh weight was significant, and the 0.3% potassium silicate treatment had the highest values. Based on the results obtained, the highest levels of potassium, calcium, iron, and zinc in tomato fruit were associated with the 0.3% potassium silicate treatment, which was significantly higher than the control treatment. Compared to fruits from unsprayed plants, fruits from plants fed with different concentrations of potassium silicate, especially 0.3% concentration, had significantly higher levels of chlorophyll a, total chlorophyll, and carotenoids. The results of the study showed that foliar application of potassium silicate has great potential for improving the quantitative and qualitative characteristics of tomato fruits.

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1. Introduction

The tomato has high economic value and a unique taste, and it is rich in nutrients, making it an essential vegetable product and a vital food source for health (Lahoz et al., 2016; Hernandez-Hernandez et al., 2019). Iran is one of the major tomato-producing countries with 73,559 hectares of cultivated area and an annual production of 3,367,599.2 tons (FAOSTAT, 2023), about 10% of which is produced in greenhouses. Tomato yield is about 45 tons per hectare, and the provinces of Fars, Hormozgan, Bushehr, Khorasan Razavi, and Kerman rank first to fifth in the country's tomato producers. These five provinces together provide about 67.31 percent of the country's total tomato production.

Most tomato cultivars are sensitive to drought stress, especially in the early stages of growth. The positive effects of silicon on leaf photosynthesis under drought conditions have been observed in various plants (Etesami and Jeong, 2018). Blossom-end rot is a physiological disorder that results from insufficient calcium supply to the terminal part of the fruit. Incorporating silicon into the standard nutrient solution for tomatoes significantly increased calcium concentrations in tomato leaves and fruit, thus simultaneously limiting the incidence of Blossom-end rot (Stamatakis et al., 2003).

After water availability, nutrition is the second factor that has the greatest impact on tomato quantity and quality (Ullah et al., 2021). As a result, chemical fertilizers are used for their fertilization. Recent research in several plant species has shown the importance of silicon fertilization through foliar application or soil application and from various sources (calcium silicate, potassium silicate, and silicic acid) for better agricultural production, reduced incidence of pests and diseases, and also as an increase in the nutritional quality of fruits (Al-Murad et al., 2020). Silicon is an important component of cell walls and increases their mechanical strength and stability. It can also improve the thickness and firmness of the fruit skin (Savvas and Ntatsi, 2015).

Silicon is not considered an essential nutrient, but it is of fundamental importance in physiological and biochemical processes, since although it does not directly affect the main metabolic pathways, it can increase plant tolerance to biotic and abiotic stresses. It has been reported that silicon deposition on the cell wall can improve the physicochemical quality of tomato fruits (Coutinho et al., 2020). In lettuce, improvements in ascorbic acid and soluble solids were observed (Lemos Neto et al., 2018). A study by Marodin et al. (2016) showed that silicon promotes better post-harvest preservation, as silicon application increases firmness and concentration of soluble solids, vitamin C, and lycopene in tomato fruits.

Considering the very important effects of silicon in increasing the quantitative and qualitative characteristics of tomato fruit (Savvas and Ntatsi, 2015), the valuable effect of this element in creating resistance to pests and diseases (Singh et al., 2005), as well as the positive effect of silicon on plant tolerance to a wide range of biotic and abiotic stresses such as drought, salinity, heat, cold, metal toxicity, and nutritional stresses (Chalmardi, 2013; Bhat et al., 2019; Arvin et al., 2026), this study aimed to investigate different concentrations of potassium silicate on the yield, qualitative, and biochemical traits of tomato cv. ‘SV4129TH’.

2. Materials and Methods

2.1. Nutrient treatments

Foliar application of potassium silicate was carried out in 2024 and 2055 on ‘SV4129TH’ tomato plants in a commercial greenhouse (Figure 1) located in Markazi province, Iran. Plants were grown in soil medium, with daytime temperatures ranging from 21 to 26 °C and nighttime temperatures ranging from 16 to 19 °C. This study was conducted in a completely randomized design with four treatments (potassium silicate at concentrations of 0.1, 0.2, and 0.3%, along with distilled water as the control treatment) and four replications. Foliar applications were done in three stages, each stage at an interval of two weeks. Ten days after the last stage of foliar spraying, the fruits were harvested, and the desired traits were measured. The plants selected for the experiment had identical conditions and were grown in a soil bed.

2.2. Morphological traits

In this experiment, morphological traits including plant height, stem diameter, petiole diameter, peduncle diameter, fruit number, and yield (about 3 months after cultivation) were measured. The fruits were harvested at three times and the yield is the average of these three harvest times. Plant height was measured from the crown at soil level to the end of the stem. Stem diameter, petiole diameter, and peduncle diameter were also measured using calipers.

Figure 1. The greenhouse where the experiment was conducted

2.3. Physiochemical traits of fruits

At the commercial maturity stage, tomato fruits were harvested. The selected harvested fruits from the second stage of harvesting were transferred to the laboratory of the Horticulture Department of Arak University within two hours. The selected fruits were uniform in size, shape, and color and free from any physical damage or contamination. Physicochemical characteristics of the fruit including firmness, total soluble solids (TSS), titratable acidity (TA), TSS to TA ratio, chlorophyll a, chlorophyll b, total chlorophyll, carotenoids, total phenos, electrical conductivity (EC), acidity (pH), ion leakage, organic matter, and potassium, calcium, iron, and zinc contents were measured.

2.4. Firmness

To determine the firmness of the fruits, a penetrometer (STEP SYSTEM, Germany) with a plunger tip with a diameter of 8 mm was used, and the results were expressed as kg cm^{-2}.

2.5. TSS, TA, and TSS/TA

Total soluble solids of tomato fruits were measured using a handheld refractometer (Atago, PAL-1, Japan), and the results were expressed as a percentage. To measure titratable acidity first, the pH and EC of tomato juice were measured using a pH meter (Az 86502, Taiwan) and an EC meter, and the numbers were recorded. Then, the titratable acid was determined by titrating the juice with 0.1 N sodium hydroxide to a pH of about 1.8. The TSS/TA ratio was calculated by dividing TSS by TA (ValizadehKaji and Almasian, 2025).

2.6. Ion leakage

To measure the level of ion leakage, a small piece of each replication was placed in 20 mL of water in a test tube. The samples were placed in an incubator for 60 min, and the level of ionic leakage was measured and recorded using an EC meter (A1). The samples were again placed in an oven at 70 °C for 120 min, and after the samples cooled, the ion leakage rate was read by the device (A2) and calculated according to the following formula (ValizadehKaji, 2022):

$$\text{ion leakage} = A2 / A1 \times 100$$

2.7. Total phenol

With a slight modification to the method of Singleton et al. (1999) and using the Folin-Ciocalteu reagent, the total phenolic content of tomato fruits was measured. Approximately 0.2 g of fresh fruit tissue was taken, ground in 80% methanol, and centrifuged at 6000 rpm for 10 min. It was then mixed with three milliliters of methanol extract and one milliliter of Folin-Ciocalteu reagent. After 5 min, one mL of 7% sodium carbonate solution was added to the mixture and shaken for 90 min at room temperature on a shaker. After that, the absorbance of the solution was determined using a spectrophotometer (Cary Win UV 100; Varian, Sydney, Australia) at a wavelength of 765 nm. Using the calibration curve prepared for the gallic acid standard solution, the total phenol content was calculated, and the results were presented as mg g^{-1} FW.

2.8. Fruit chlorophyll and carotenoid

To measure the chlorophyll and carotenoid content of the fruit using acetone (80% v/v), about 0.1 g of tomato fruit flesh was used. After 10 minutes of centrifugation at 6000 rpm, the absorbance of the supernatant solution was determined using a spectrophotometer (Cary Win UV 100; Varian, Sydney, Australia) at wavelengths of 646, 663, and 470 nm, and the results were expressed as mg g^{-1} FW (fresh weight) (Lichtenthaler, 1987).

$$\text{Chlorophyll a} = [(12.25 \times A663) - (2.79 \times A646)]$$

$$\text{Chlorophyll b} = [(21.5 \times A646) - (5.1 \times A663)]$$

$$\text{Chlorophyll Total} = \text{chl a} + \text{chl b}$$

$$\text{Carotenoids} = [(1000 \times A470) - (1.82\text{chl a} - 85.02\text{ chl b})]/198$$

In these formulas, A is the absorbance reading at the wavelengths of interest.

2.9. Mineral content and organic matter

To measure the content of organic matter and mineral elements in tomato fruits, the samples were first dried in an oven at 120 °C for 72 hours. Then, 0.5 gr of dry matter was weighed and placed at high temperature for several hours until the samples turned into ash. At this stage, the samples weights were measured again. The difference between the content of dry matter and the content of the ashed sample is, in fact, the content of organic matter. Five mL of 2N hydrochloric acid was added to each sample, and finally, the volume was made up to 50 mL with distilled water. The resulting extract was directly used to measure the elements potassium, calcium, iron, and zinc using an ICP-OES device (Analytic Jena, Germany).

2.10. Data analysis

The experiment was conducted in a completely randomized design with four treatments and four replications. The data were analyzed using the GLM method of SAS software. Comparison of means was performed using Duncan's multiple range test at a probability level of 0.05 ($P \leq 0.05$).

3. Results

3.1. Morphological characteristics

The results of foliar application of different concentrations of potassium silicate on the morphological traits of the tomato plant and fruit are shown in Table 1. The results showed that potassium silicate treatments significantly affected plant height, fruit number, and yield, but the treatments had no significant effects on stem diameter, peduncle diameter, and petiole diameter (Table 1). The highest plant height (261 cm) was obtained with 0.3% potassium silicate, although there was no significant difference between the different potassium silicate concentrations. The control treatment showed the lowest value (235 cm) (Table 1).

Table 1. Effect of different concentrations of potassium silicate on morphological characteristics and yield of tomato

Concentration of Potassium silicate (%)	Plant height (m)	Stem diameter (mm)	Peduncle diameter (mm)	Petiole diameter (mm)	Fruit number	Harvest yield (gr)
0	2.35±0.04 b	11.26±0.59 a	2.95±0.08 a	2.75±0.21 a	14.00±3.36 b	1725.00±64.54 b
0.1	2.54±0.15 a	11.52±0.21 a	3.03±0.16 a	2.81±0.06 a	16.75±2.50 ab	1800.25±83.34 ab
0.2	2.58±0.05 a	11.71±0.46 a	3.10±0.23 a	2.83±0.17 a	18.00±2.94 ab	2001.50±251.77 a
0.3	2.61±0.02 a	11.70±0.30 a	3.11±0.11 a	2.82±0.16 a	20.25±1.25 a	2014.25±58.81 a
P-value	0.0064	0.4177	0.4802	0.9205	0.0370	0.0279
CV (%)	3.55	3.63	5.28	5.84	15.29	7.40

Mean values followed by the similar letters within a column are not significantly different from each other at $P \leq 0.05$ (Duncan’s multiple range test)

Plants sprayed with different concentrations of potassium silicate had higher fruit number and yield than untreated controls. The highest fruit number (20.25) and yield (2014.25 gr) were associated with 0.3% potassium silicate, which had no significant differences with the other two concentrations. The lowest fruit number (14.00) and yield (1725 gr) were for the control treatment (Table 1).

3.2. Physiochemical traits of fruits

Foliar application of potassium silicate treatments statistically affected firmness, ion leakage, total phenol, chlorophyll a, total chlorophyll, and carotenoid of tomato fruits, but the treatments did not influence TSS, TA, EC, pH, and chlorophyll b (Tables 2 and 3).

Table 2. Effect of different concentrations of potassium silicate on firmness, TSS, TA, EC, and pH of tomato fruits

Concentration of Potassium silicate (%)	**Firmness (kg cm^{-2})**	**TSS (°Brix)**	**TA (%)**	**EC**	**pH**
0	11.60±1.87 b	3.90±0.11 a	4.20±0.33 a	3.68±0.29 a	3.97±0.09 a
0.1	11.95±1.36 b	3.95±0.19 a	4.30±0.35 a	3.46±0.18 a	4.01±0.07 a
0.2	12.70±0.47 a	4.02±0.05 a	4.57±0.26 a	3.38±0.28 a	4.05±0.13 a
0.3	12.77±0.56 a	4.05±0.19 a	4.40±0.35 a	3.35±0.22 a	4.09±0.14 a
P-value	0.0474	0.4927	0.4522	0.2993	0.5573
CV (%)	9.94	3.75	7.55	7.25	2.87

Mean values followed by the similar letters within a column are not significantly different from each other at $P \leq 0.05$ (Duncan’s multiple range test)

Table 3. Effect of different concentrations of potassium silicate on the values of ion leakage, total phenols, chlorophyll and carotenoids in tomato fruits

Concentration of Potassium silicate (%)	**Ion leakage (%)**	**Total phenol (mg/g)**	**Chlorophyll a (mg/g)**	**Chlorophyll b (mg/g)**	**Total chlorophyll (mg/g)**	**Carotenoid (mg/g)**
0	9.84±1.72 c	0.02±0.01 b	0.061±0.00 b	0.02±0.00 a	0.08±0.00 b	0.22±0.04 b
0.1	9.17±0.90 b	0.03±0.005 a	0.064±0.005 a	0.02±0.00 a	0.09±0.009 a	0.26±0.01 a
0.2	9.14±1.06 b	0.04±0.005 a	0.072±0.00 a	0.02±0.00 a	0.09±0.005 a	0.28±0.02 a
0.3	9.01±1.08 a	0.04±0.008 a	0.073±0.005 a	0.02±0.00 a	0.09±0.005 a	0.30±0.01 a
P-value	0.04781	0.0271	0.0018	0.4262	0.0191	0.0043
CV (%)	13.30	28.15	5.23	12.12	6.80	9.62

Mean values followed by the similar letters within a column are not significantly different from each other at $P \leq 0.05$ (Duncan’s multiple range test)

3.3. Firmness

Potassium silicate treatments increased the firmness of tomato fruits. The highest fruit firmness (12.77 kg cm^{-2}) was due to treatment with 0.3% potassium silicate, which was not significantly different from 0.2% potassium silicate. On the other hand, the control and 0.1% potassium silicate had the lowest firmness (Table 2).

3.4. Ion leakage

The application of different concentrations of potassium silicate significantly decreased the ion leakage of tomato fruits (Table 3). The lowest value (9.01%) was related to 0.3% potassium silicate, and this effect was greater than that of the other treatments. In contrast, the highest value of ion leakage (9.84%) was recorded in fruits of the control treatment (Table 3).

3.5. Total phenol

Foliar application of potassium silicate significantly increased the total phenol contents of tomato fruits (Table 3). Fruits of trees sprayed with 0.3% potassium silicate showed the greatest total phenol content (0.04 mg g^{-1}), which was not statistically different from 0.1% and 0.2% potassium silicate. Conversely, fruits of the control treatment had the lowest value of total phenol (0.02 mg g^{-1}) (Table 3).

3.6. Chlorophyll and carotenoid content

Potassium silicate treatments increased the chlorophyll a, total chlorophyll, and carotenoid of tomato fruits. Fruits of plants sprayed with 0.3% potassium silicate showed the highest chlorophyll a, total chlorophyll, and carotenoid; however, potassium silicate treatments were not significantly different from each other. In contrast, the lowest chlorophyll a, total chlorophyll, and carotenoid of fruits was observed in the control (Table 3).

3.7. Mineral content and organic matter

Foliar application of potassium silicate significantly affected the concentration of minerals in the tomato fruits, but the treatments had no significant effect on organic matter ($P = 0.7099$) (Table 4). Fruits of plants sprayed with 0.3% potassium silicate showed the highest concentration of K (9.58%) and Ca (0.35%), which was not significantly different from the other potassium silicate treatments. In contrast, the lowest value of K (5.44) and Ca (0.14%) was for the control (Table 4). The greatest fruit concentration of Zn (290.66 ppm) was obtained with 0.3% potassium silicate, which was not significantly different from 0.2% potassium silicate (Table 4). The control showed the lowest value of Zn (84.43 ppm), although no significant difference was detected between the control and 0.1% potassium silicate (Table 4). Fruits of plants sprayed with 0.3% potassium silicate showed the highest Fe concentration (57.66 ppm), which was significantly different from the other treatments. The lowest fruit concentration of Fe (25.73 ppm) was for the unsprayed plants, although no significant difference was detected among the control, 0.2% potassium silicate, and 0.1% potassium silicate (Table 4).

Table 4. Effect of different concentrations of potassium silicate on the contents of organic matter and the mineral elements in tomato fruits

Concentration of Potassium silicate (%)	Organic matter (%)	K (%)	Ca (%)	Zn (ppm)	Fe (ppm)
0	0.33±0.03 a	5.44±2.04 b	0.14±0.05 b	84.43±11.16 b	25.73±3.07 b
0.1	0.33±0.04 a	7.12±0.48 ab	0.25±0.03 ab	103.33±8.38 b	29.83±2.91 b
0.2	0.34±0.02 a	8.09±1.15 ab	0.27±0.13 ab	258.00±101.66 a	30.50±2.78 b
0.3	0.31±0.20 a	9.58±1.31 a	0.35±0.005 a	290.66±77.25 a	57.66±2.51 a
P-value	0.7099	0.0328	0.0465	0.0026	0.0001
CV (%)	9.31	18.04	28.36	28.73	7.87

Mean values followed by the similar letters within a column are not significantly different from each other at $P \leq 0.05$ (Duncan's multiple range test)

4. Discussion

Plant height is one of the important parameters of plant growth, indicating better development of aerial organs and increased photosynthetic capacity, and usually indicates the positive effect of environmental conditions and proper nutrition on plant growth (Rahmani and Sabzalian, 2014). Silicon application increases the efficiency of photosynthesis and directly contributes to biomass accumulation, which leads to increased plant height and stem length (Cooke and Leishman, 2011). It has been reported that the application of silicon in greenhouse cultivation of cucumber significantly increases plant height and better root development (Savvas et al., 2011). It has also been emphasized that silicon increases plant longitudinal growth by increasing cell thickness and tissue strength (Takahashi et al., 2016), as proven in this research (Table 1).

Fruit diameter, as one of the important indicators of the product's visual quality, plays a decisive role in marketability and consumer preference and is influenced by genetic and management factors, including nutrition and growing conditions (Lopez-Gomez et al., 2013). Hosseini et al. (2018) recorded a significant increase in fruit diameter in bell pepper at the early stages of harvest due to the application of potassium silicate. It has also been reported that the effects of silicate on fruit morphological traits may decrease with the progression of the growth period and be less visible in the final stages (Rodrigues et al., 2011).

In accordance with the results of this study (Table 1), Dehghanipoodeh et al. (2018) and Jalali et al. (2022) reported that foliar application of silicon in tomatoes increases fruit volume and yield. Qin et al. (2016) reported that silicon supplementation in hydroponic systems increased fruit number and yield in tomato plants, which is consistent with our results. In addition, Dehghanipoodeh et al. (2018) and Jalali et al. (2022) reported that foliar application of silicon increased tomato fruit volume and yield.

Fruit firmness plays a major role in determining postharvest quality. Increasing the firmness or thickness of the fruit cell wall increases shelf life and resistance to transportation. Similar to the results of this study (Table 2), the application of potassium silicate increased the cuticle thickness and firmness of bell pepper fruit, which is probably due to increased mechanical strength of the fruits (Jayawardana et al., 2014). In addition, Isa et al. (2010) reported that by spraying different concentrations of silicon on tomato leaf surfaces, the firmness of tomato fruit skin increased, which could be due to the increased concentration of silicon in the cell wall of the fruit skin.

Ion leakage is an important physiological indicator in assessing the health of cell membranes; with increasing membrane damage or reduced structural integrity of tissues, the rate of ion leakage increases. Reduced ion leakage is considered an indicator of maintaining membrane integrity and delaying the onset of fruit aging symptoms (Lurie and Watkins, 2012). A study has shown that treatment of plum fruits with potassium silicate reduced cell permeability and ion leakage compared to control fruits (Nasar et al., 2013), which is consistent with our results (Table 3).

Phenolic compounds increase the nutritional value and organoleptic quality of tomato fruit (Tohge and Fernie, 2015). Consistent with the findings of this study (Table 3), the application of potassium silicate increased phenolic content in cucumber (Savvas et al., 2011) and tomato (Han et al., 2018). In bell pepper, silicon can activate the phenolic synthesis pathway by increasing the activity of the enzyme phenylalanine ammonia-lyase (PAL) (Rezende et al., 2019). Another study also found that silicon increased the level of phenolics (Rahman et al., 2015).

Similar to the results of this study (Table 3), foliar application of potassium silicate increased leaf chlorophyll in potato (Talebi et al., 2015). Chlorophyll content is an indicator for assessing the nutritional status, health, and efficiency of the plant's photosynthetic system (Taiz et al., 2015). Silicon increases light-use efficiency by strengthening chloroplast structure, increasing pigment synthesis, and reducing chlorophyll degradation caused by environmental stresses. This improvement in the photosynthesis process increases the plant's ability to produce carbohydrates and grow reproductive organs. Potassium silicate also helps balance nutrients such as nitrogen and magnesium, key elements in chlorophyll formation, thereby increasing the stability of this pigment (Hosseini et al., 2018). The improvement in chlorophyll content in cucumbers treated with silicon has been attributed to increased water use efficiency and stress reduction (Kaya et al., 2006). The increase in leaf area and chlorophyll stabilization has also been linked to the protective role of silicon on chloroplasts (Savvas et al., 2011). The increase in yield observed in this study could be due to improved leaf structure, increased photosynthetic efficiency, and greater stiffness of leaf tissues due to silicon deposition (Silva et al., 2021).

Carotenoids are antioxidant compounds whose nutritional value is of great interest (Khachik et al., 1992). Therefore, the high concentration of pigments present in tomatoes increases their internal quality (De Pascale et al., 2001). Researchers reported that the application of silicon increases the carotenoid content of cucumber under salt stress and helps maintain fruit quality (Zhang et al., 2017). In addition, potassium silicate increases the accumulation of antioxidant pigments, including carotenoids, by improving the physiological state of the plant (Wang and Song, 2020), which is consistent with our results. Under salt stress, the addition of silicon to the nutrient solution of tomato plants can significantly increase the content of lycopene and beta-carotene in tomato fruits (Stamatakis et al., 2003).

According to the findings of this research (Table 4), the positive effect of silicon in improving the mineral elements of leaves and fruits has been proven in various studies (Hosseini et al., 2017; Silva et al., 2021). Silicon has been shown to reduce the negative effects of iron deficiency by facilitating iron availability in the rhizosphere and root apoplasm. In addition, silicon helps in the accumulation and redistribution of iron in different plant tissues (Nikolic et al., 2019; Pavlovic et al., 2021). Silicon can increase the distribution of zinc in the plant and reduce the effects of zinc deficiency (Mehrabanjoubani et al., 2015; Pascual et al., 2016).

Conclusion

Foliar application of different concentrations of potassium silicate, especially 0.3%, improved fruit yield and quality of the tomato cv. ‘SV4129TH e’ due to increased morphological traits, leaf minerals, firmness, chlorophyll, carotenoid, and total phenol. Thus, applying potassium silicate could cause enhanced production of tomato, especially in a greenhouse.

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