



The effect of potassium silicate on the productivity and storability of spinach plants (*Spinacia oleracea* L.)

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Abstract

Spinach plants were subjected to salt stress with a (0, 10, 15 and 20g/L) NaCl solution to study the effects of foliar spraying with potassium silicate (400, 600 and 800 ppm/L) on vegetative growth, yield, storability and shelf life. In the second season, the number of leaves, plant height and leaf area revealed the most values with adding potassium silicate as foliar spray (800ppm) compared with control. Throughout seasons, total yield and leaf weight exhibited the best values with concentration (800ppm) of potassium silicate compared with control. Under salinity stress, leaf water potential, leaf osmotic potential, carotenoids and antioxidant enzymes' activity was markedly and gradually increased with the addition of potassium silicate (400ppm) compared with control. Meanwhile, oxalate content, total chlorophyll, proline content, hydrogen peroxide and Superoxide were reduced with added potassium silicate (600ppm) compared with control. After storage for two weeks in the refrigerator at (zero °C/ 95% RH), polyphenol oxidase, superoxide dismutase, catalase enzymes, total phenols, total flavonoids and carotenoids recorded the best values by adding potassium silicate (400ppm) compared with control. Weight loss percent and respiration rate showed the most values with adding potassium silicate (600ppm) compared to the control. Conversely, postharvest decay percent, super oxide dismutase, polyphenol oxidase and catalase enzymes observed increased with added potassium silicate (400 ppm) compared with control. Compared with control, ascorbic acid and total chlorophyll increased after storage with potassium silicate (800 ppm).

Keywords Salinity stress · Spinach · Postharvest · Potassium silicate

1 Introduction

Food security is a critical global issue, especially with the growing population. The task of increasing food production by 70% by 2050 to feed an additional 2.3 billion people is an enormous challenge that requires innovative solutions across several fronts (FAO 2016). Salinity-induced soil degradation is indeed a significant threat to global agricultural productivity and food security, particularly in arid and semi-arid regions. Soil salinization affects a substantial portion of irrigated lands worldwide. Climate change exacerbates this problem, with rising temperatures and fluctuating weather

patterns intensifying the frequency of droughts, floods, and salinity evolution. The accumulation of soluble salts in the soil, particularly sodium chloride (NaCl), calcium sulfate (CaSO₄), and magnesium sulfate (MgSO₄), can disrupt plant water uptake, impair root function through impacting on cellular function by increasing osmotic stress, making water absorption difficult, and causing ionic toxicity. The plants exposed to stress showed a response that starts with decreasing the ion independent growth, which leads to close stomata and inhibits cell expansion, then the creation of cytotoxic ion levels, slowing down metabolism and causing senescence and cell death. Silicon (Si) is often referred to as a "beneficial" element rather than an essential one, meaning that plants can still grow without it under normal conditions. However, its role in enhancing plant tolerance to various abiotic stresses, water relations, cell wall flexibility, membrane stability (Rehman et al. 2019; Tuladhar et al. 2021) and impacting several crucial metabolic pathways, including salinity, drought, heavy metals, temperature extremes, has been increasingly recognized Etesami and Jeong (2018). For

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instance, silicon can influence plant water relations, cell wall flexibility, and membrane stability. Spinach plants (*Spinacia oleracea* L.) belong to the family Amaranthaceae that originated in Southwestern and Asia. It is also a moderately salt-tolerant glycophyte in the winter, but sensitive to moderately-sensitive if cultivated in the spring and summer (Ferreira et al. 2020). Fresh spinach has medical value for containing nutrients, protein, vitamins and carotene. It is typically harvested by cutting just above the ground when it has at least 5 to 6 leaves, usually 40 to 70 days after seeding. Older spinach plants may have 10 to 12 leaves. Due to its high respiration rate, proper cooling is crucial. Spinach can be hydrocooled, bagged, and iced, with forced air or vacuum cooling as possible options. Its deterioration rate is affected by a variety of factors, including respiration, ethylene production, compositional changes, water loss, physiological and pathological disorders. Spinach can be stored for 10 to 14 days at 0° C temperatures and a relative humidity of 90% to 95%. It has a large leaf area and soft tissue makes it easily lose freshness due to water loss in the process of picking, transportation and sale, so it reduces the nutritional quality of spinach. The aim of the research is to investigate whether potassium silicate will alleviate the negative effects caused by salinity stress on growth, yield and enhance the plants'bioactive components, storability and quality in spinach plants.

2 Materials and methods

The pots experiment was conducted on the experimental farm of the Horticultural Research Station, Horticulture Research Institute of the Vegetable Handling Department in Dakahlia governorate, Mansoura city, Egypt, during two successive seasons between 2022 and 2023. The research was carried out to study the salinity stress at different levels (0, 10, 15 and 20 g/L) and the effects of potassium silicate when applied as foliar spray at concentrations (400, 600 and 800 ppm/L) on vegetative growth, yield, storability and shelf life of Spinach plants. Potassium silicate preparation: Potassium silicate was dissolved in ethyl alcohol (95% concentration). Seeds of spinach (*Spinacia oleracea* L.), Pacific variety, were sown on 12th December in cylindrical pots (40 cm in diameter, 40 cm in height, containing 10 kg of soil) (4 seeds/pot) at a depth of soil. The pots were divided into four replicates during both seasons and sprayed with potassium silicate on leaves under salinity conditions with tween 20 (0.05%) being added every two weeks to spray solutions as a wetting agent after only one month from planting. The experimental plot area was 768 m² [(no. of pots (12) × (no. of replicates (4) × (no. of salinity stress levels (4) × (no. of potassium silicate concentrations (4)]. The growth and yield parameters taken after three months from planting i.e., plant

height (cm), leaf area (cm²) was determined according to Wallance and Munger (1965) 's formula: [(fresh weight of leaves/fresh weight of disks) × Diameter of disks], number of leaves, leaves weight (g/plant) and total yield (g/plant).

Plants (500g/replicate) were harvested before flowering stage and packed directly with polypropylene film and stored in the refrigerator at (zero °C and 95% relative humidity) for two weeks. After the storage period, the equation of weight loss percentage (WLP%) adopted by A.O.A.C (2007) was used for estimating WLP % as (initial – final weight)/initial weight] × 100. Postharvest decay percentage (PDP %) was estimated as (number of plants showing decay symptoms/ number of total plants) × 100 according to El-Mougy et al. (2012).

2.1 Biochemical components preharvest (after three months from planting) and postharvest (after storage period at two weeks)

Samples were collected to determine the contents of proline that estimated using a spectrophotometer at wave length (540nm) against the standard curve of Toluine; expressed as (mg.g⁻¹) according to Bates et al. (1973). Total oxalate was evaluated according to Mazumdar and Majumder (2003). Ascorbic acid was evaluated according to Freed (1966), then calculated from the following formula: Ascorbic acid (mg.100g⁻¹) = Titer value × Dye factor × volume make up × 1000/Aliquot of extract for estimation × weight of sample (g). Total chlorophyll and carotenoids were determined according to Lichtenthaler (Lichtenthaler 1987)'s formula:

$$\text{Chl a} = 13.36A_{664} - 5.19A_{649}(\text{mg g}^{-1})$$

$$\text{Chl b} = 27.43A_{649} - 8.12A_{664}(\text{mg.g}^{-1})$$

$$\text{Carots.} = A_{470} \times 1000 - 2.27 \times \text{Chl (a)} - 81.4 \times \text{Ch (b)}(\text{mg.g}^{-1})$$

Chlorophyll (or carotenoids) content (mg.g⁻¹ FW) was calculated according to the following equation: = content (mg.g⁻¹) × volume of ethanol/1000 × weight of sample.

Hydrogen peroxide was determined in Spinach fresh leaves as follows: 0.5 g pieces of leaves were homogenized in an ice bath with 5 mL of 0.1% (m/v) TCA. The samples were centrifuged for 20 min at 12 000 × g and 4 °C, 0.5 mL of the supernatant was added to 0.5 mL of a 10 mM potassium phosphate buffer and 1 mL of 1 M KI. The concentration was recorded using a spectrophotometer at 390 nm. Hydrogen peroxide contents were measured using a standard curve according to Okuda et al. (1991). Superoxide was assessed using the method of Elstner and Heupel (1976) by observing nitrate formation from hydroxyl amine. Superoxide dismutase (SOD) and peroxidase (POD)

enzymes activities were measured according to Van Rossun et al. (1997) and Urbanek et al. (1991), respectively. For measuring water relations parameters in plant leaves, specifically leaf water potential and leaf osmotic potential. This technique involves excising young, fully expanded leaves at the flowering stage, followed by using the Scholander pressure chamber to measure leaf water potential and a vapor pressure osmometer for osmotic potential, according to Scholander et al. (1965). Total flavonoids were estimated spectrophotometrically at 510 nm as described by Heimler et al. (2005). Total phenols were determined according to Bray and Throp (1954). Polyphenoloxidase (PPO) and Catalase (CAT) activities were assayed with method (Aebi 1984; Maria et al. 1981), respectively. Respiration rate in a closed system by tracking changes in CO₂ concentration (Jacxsens et al. 1999). Physical and chemical characters of the experimental soil were planned by (Black 1965) method and shown in Table 1.

2.2 Statistical analysis

The experimental design was a randomized split-plot design with four replications, as described by Gomez and Gomez (1984). Data ($n=4$) were analyzed using a one-way analysis of variance (ANOVA). The statistical results showed the interaction between potassium silicate (subplot) and salinity levels (main plot) with the data presented as means and standard divisions.

3 Results

3.1 Vegetative growth, yield and its components

Data in Table 2 recorded the effect of applied potassium silicate as foliar spray on salinity levels, as well as their interaction on plant height (cm), leaf area (cm²), no. of leaves, leaf weight and total yield (g/plant). In the first season, plants grown under salinity stress levels (0, 10, 15 and 20 g/L) showed excess values of plant height with adding potassium silicate (600, 800 and 400 ppm) compared to the control. The maximum value of plant height was (36.53 cm) recorded with 600 ppm of potassium silicate and 10 g/L of salinity levels (36.58) compared to the control.

The interaction between potassium silicate (600 and 800 ppm) and salinity levels (0, 10, 15 and 20 g/L) recorded elevated values of leaf area compared with control. In the same table, the interaction between salinity levels (0, 10, 15 and

20 g/L) and potassium silicate (600 and 800 ppm) recorded the best values of leaf numbers compared with control.

Data in Table 3 revealed that the interaction between salinity levels (15, 20 and 10 g/L) and potassium silicate (400, 600 and 800 ppm) revealed great values of leaf weight compared with control. The salinity levels (10, 15 and 20 g/L) and potassium silicate (800 ppm) recorded the maximum values of total yield compared to the control. The mean of potassium silicate (800 ppm) and salinity level (20 g/L) recorded the best values of leaf area as (61.58 cm²) and total yield as (216.18 g/L), respectively, compared with control.

Meanwhile, the mean of potassium silicate (600 ppm) and salinity level (10 g/L) revealed elevated values of plant height (36.53 and 36.58 cm) respectively compared with control. The mean of potassium silicate (800 ppm) and salinity level (10 g/L) revealed the greatest values of leaf number (18.00 and 16.19 g/L), respectively, compared with control. The maximum values recorded the most effective value of mean leaf weight by adding potassium silicate (800 ppm) and salinity level (15 g/L) as (116.05 and 125.04 g/plant) respectively, compared with control.

In the second season, data in Table 2 showed the interaction between potassium silicate (800 ppm) and salinity levels (10, 15 and 20 g/L) recorded towering with plant height compared with control. The mean of potassium silicate (800 ppm) revealed excess plant height as (41.53 cm) and leaves number as (20.72) compared with control. The interaction between potassium silicate (600 and 800 ppm) with salinity levels (10, 15 and 20 g/L) recorded the greatest values of leaf area compared with control.

The mean salinity level (10 g/L) revealed the highest result with leaf area (62.19) compared with control. In the same table, the interaction between potassium silicate (600 and 800 ppm) and salinity levels (10, 15 and 20 g/L) recorded elevated values of leaf number (22.78, 26.00 and 20.11) respectively, compared with control. The mean salinity level (10, 20 and 15 g/L) recorded crest of plant height, leaf area and leaf number (39.72, 61.03 and 60.78) compared with control.

Data in Table 3 showed the mean salinity levels (15 and 20 g/L) recorded the maximum values of both leaf weight and total yield (125.04 and 216.18 g/plant) respectively, compared with control. Compared with control, the interaction between potassium silicate at rate of (400, 600 and 800 ppm) and salinity levels (10, 15 and 20 g/L) recorded towering values of leaf weight (120.77, 126.63 and 124.13 g/plant) respectively. The mean of potassium silicate at (800 ppm) revealed the best value of both leaf weight and

Table 1 Note: This data is mandatory. Please provide missing table caption

Sand	Silt	Clay	Texture	N mg.kg ⁻¹	P mg.kg ⁻¹	K mg.kg ⁻¹	CaCO ₃	pH	Organic matter
27.00	26.00	47.00	clay	58.95	12.00	215.00	2.59	7.71	1.30

Table 2 Effect of potassium silicate, salinity levels and their interactions on plant height (cm), leaf area (cm²) and number of leaves of spinach plants during both seasons 2022 and 2023

Salinity levels		First season															
A	Potassium silicate	Plant height cm				Leaf area cm ²				No. of leaves				Mean B	Mean B		
		0	10	15	20	Mean B	0	10	15	20	Mean B	0	10			15	20
B	0	30.56 ± 5.89	34.33 ± 5.46	31.78 ± 3.08	29.44 ± 4.19	31.53 ^d	30.11 ± 1.84	28.67 ± 6.24	36.55 ± 2.16	40.34 ± 4.75	33.91 ^d	6.67 ± 1.77	13.44 ± 1.50	18.67 ± 5.90	13.45 ± 6.77	12.45 ^d	
	400	31.22 ± 0.19	35.56 ± 4.86	33.56 ± 1.39	38.22 ± 1.54	34.64 ^{ab}	42.26 ± 5.17	36.78 ± 2.92	37.92 ± 2.64	42.56 ± 6.62	39.88 ^c	11.33 ± 1.20	17.78 ± 6.84	10.33 ± 0.58	17.22 ± 4.81	16.33 ^b	
	600	43.44 ± 7.52	34.67 ± 2.40	33.22 ± 2.91	34.76 ± 4.42	36.53 ^a	53.60 ± 7.82	42.76 ± 5.66	45.72 ± 5.26	53.57 ± 3.12	48.91 ^a	10.44 ± 0.77	21.00 ± 1.76	26.00 ± 1.00	10.44 ± 2.22	14.89 ^c	
	800	40.11 ± 1.65	41.78 ± 3.72	35.00 ± 5.79	23.44 ± 2.22	35.08 ^c	40.52 ± 10.75	45.96 ± 9.99	43.98 ± 2.26	55.86 ± 1.93	46.58 ^b	22.22 ± 4.95	12.56 ± 1.50	24.44 ± 2.22	17.78 ± 3.09	18.00 ^a	
	Mean A	36.33 ^{ab}	36.58 ^a	33.39 ^c	31.47 ^d		41.62 ^a	38.54 ^d	41.04 ^{ab}	40.08 ^c		12.67 ^b	16.19 ^a	19.86 ^a	14.72 ^{ab}		
LSD _{0.05}		A = 3.47 B = 3.50 A*B = 6.94														A = 3.39 B = 3.40 A*B = 6.77	
Second season																	
Salinity levels		First season															
A	Potassium silicate	Plant height cm				Leaf area cm ²				No. of leaves				Mean B	Mean B		
		0	10	15	20	Mean B	0	10	15	20	Mean B	0	10			15	20
B	0	26.89 ± 4.67	39.00 ± 20.00	32.44 ± 2.69	36.22 ± 0.69	33.64 ^c	36.16 ± 9.47	37.09 ± 3.39	37.42 ± 4.09	45.26 ± 0.62	38.98 ^d	7.33 ± 1.15	14.55 ± 1.35	18.67 ± 5.90	16.78 ± 2.55	14.33 ^b	
	400	34.41 ± 3.10	40.11 ± 1.02	35.00 ± 1.00	38.67 ± 1.77	37.05 ^{bc}	43.17 ± 3.58	54.67 ± 6.43	49.88 ± 2.47	60.72 ± 4.19	52.11 ^c	13.11 ± 1.96	21.11 ± 5.48	10.33 ± 0.58	18.00 ± 4.36	15.64 ^b	
	600	45.44 ± 7.00	34.89 ± 4.35	35.89 ± 1.02	40.11 ± 0.84	39.08 ^{ab}	52.76 ± 8.74	62.93 ± 5.42	56.57 ± 3.68	67.45 ± 1.36	59.93 ^b	12.11 ± 1.02	22.78 ± 2.67	26.00 ± 1.00	12.55 ± 2.67	18.36 ^a	
	800	41.11 ± 1.65	44.89 ± 4.03	36.33 ± 5.21	43.78 ± 3.34	41.53 ^a	66.00 ± 4.42	58.07 ± 3.08	54.98 ± 1.33	69.69 ± 0.31	62.19 ^a	23.22 ± 4.95	15.11 ± 0.84	24.44 ± 2.22	20.11 ± 2.34	20.72 ^a	
	Mean A	36.96 ^b	39.72 ^a	34.92 ^b	39.69 ^a		49.52 ^c	53.19 ^d	49.71 ^b	60.78 ^a		13.95 ^c	18.39 ^{ab}	19.86 ^a	16.86 ^b		
LSD _{0.05}		A = 2.69 B = 2.70 A*B = 5.39														A = 2.56 B = 2.60 A*B = 5.12	

Table 3 Effect of potassium silicate, salinity levels and their interactions on leaf weight (g/plant) and total yield (g/plant) for spinach plants during both seasons 2022 and 2023

Salinity levels A	First season					Total yield g/plant					Mean B	Mean B
	Leaves weight g/plant					0						
Potassium silicate B	0	63.80 ± 7.37	109.80 ± 9.17	129.40 ± 5.86	120.47 ± 3.44	105.87 ^d	173.83 ± 7.32	211.30 ± 9.69	200.43 ± 4.25	222.57 ± 0.80	202.03 ^d	
	400	79.33 ± 13.04	115.47 ± 8.78	125.63 ± 7.72	123.17 ± 7.06	110.90 ^c	179.17 ± 12.98	219.87 ± 2.01	220.63 ± 7.72	233.17 ± 8.64	213.21 ^b	
	600	95.93 ± 0.67	115.63 ± 13.03	121.27 ± 6.60	124.13 ± 6.47	114.24 ^b	195.93 ± 0.67	205.63 ± 13.03	216.33 ± 4.73	227.17 ± 3.03	211.27 ^c	
	800	95.97 ± 3.13	120.77 ± 22.45	123.87 ± 3.44	123.60 ± 2.80	116.05 ^a	191.30 ± 11.06	221.60 ± 23.90	221.87 ± 3.44	229.93 ± 3.32	216.18 ^a	
	Mean A	83.76 ^d	115.42 ^c	125.04 ^a	122.84 ^{ab}		185.06 ^c	214.60 ^{ab}	214.82 ^b	228.21 ^a		
LSD _{0.05}	A = 8.38 B = 8.40 A*B = 16.76										A = 7.86 B = 7.90 A*B = 15.71	
Second season												
Salinity levels A	Leaves weight g/plant					Total yield g/plant					Mean B	Mean B
	0					10						
Potassium silicate B	0	66.97 ± 7.48	112.13 ± 10.39	125.73 ± 5.05	120.87 ± 7.73	106.43 ^d	168.23 ± 2.50	228.07 ± 6.90	230.70 ± 5.05	229.13 ± 14.39	214.03 ^b	
	400	82.83 ± 11.59	125.50 ± 5.27	130.10 ± 3.62	132.50 ± 2.80	117.73 ^c	182.10 ± 13.94	220.00 ± 1.61	226.27 ± 7.89	227.27 ± 2.44	213.91 ^{ab}	
	600	98.87 ± 1.20	130.80 ± 13.52	137.73 ± 7.54	139.67 ± 3.76	126.77 ^a	199.60 ± 1.13	235.03 ± 4.90	239.60 ± 9.72	231.83 ± 6.97	226.56 ^a	
	800	98.03 ± 2.15	128.83 ± 2.89	132.37 ± 5.90	138.13 ± 2.43	124.34 ^b	125.50 ± 5.06	224.03 ± 23.04	235.53 ± 3.38	230.50 ± 7.55	203.89 ^c	
	Mean A	86.68 ^d	124.32 ^c	131.49 ^b	132.79 ^a		168.86 ^d	226.78 ^c	233.03 ^a	229.69 ^b		
LSD _{0.05}	A = 5.66 B = 5.66 A*B = 11.33										A = 7.13 B = 7.10 A*B = 14.26	

total yield (116.05 and 216.18g/plant) compared with control. In the same table, the interaction between potassium silicate (600 ppm) and salinity levels (10, 15 and 20g/L) recorded excess values of total yield (199.60, 235.03, 239.60 and 231.80 g/plant) respectively compared with control.

3.2 Weight loss percent and postharvest decay percent after storage for two weeks in refrigerator at (zero ° C/Rh95%)

Results in Table 4, showed the interaction between salinity levels (0, 10, 15 and 20g/L) and potassium silicate (400and 600ppm) exhibited the best values of weight loss percent after storage for two weeks in refrigerator at (zero ° C/ Rh95%) as (21.13, 13.11, 17.23 and 11.11%) respectively compared with control. The mean of potassium silicate 600ppm and salinity level 20g/L recorded the maximum values of weight loss percent as (16.69 and 14.22) respectively compared to the control.

Potassium silicate (400ppm) recorded the greatest value of postharvest decay after storage for two weeks in refrigerator at (zero ° C/Rh95%) as (0.00%) compared with control. In the same context, the mean of both salinity level (10g/L) and Potassium silicate (400ppm) revealed elevated value of PDP% compared with control. The interaction between salinity levels (0, 10, 15 and 20g/L with potassium silicate (0, 400, 600 and 800 ppm) recorded excess values of post-harvest decay percent compared with control.

3.3 Proline, ascorbic acid contents and total oxalate under stress and after storage for two weeks in the refrigerator at (zero ° C/Rh95%)

Data in Table 5 showed the interaction between salinity levels (0, 10, 15 and 20g/L) and potassium silicate (400ppm) revealed the towering values of proline (18.62, 14.11, 13.23 and 12.48 mg.g⁻¹) respectively compared with control. The mean salinity level (10g/L) revealed the great of proline content (14.61 mg.g⁻¹) compared with control. The mean of potassium silicate at 0 ppm recorded the best value of proline (13.89mg.g⁻¹) compared with control. The interaction between salinity levels (0 and 15g/L) with (0ppm) of potassium silicate recorded the highest values of oxalate as (1083.00 and 968.50 mg.100g⁻¹) respectively compared with control. The mean salinity level (0g/L) recorded the maximum value as (1066.25) compared with control. The combined of salinity levels (10 and 20g/L) with (400ppm) of potassium silicate revealed excess values of oxalate as (981.50 and 950.00) respectively compared with control. Meanwhile, the mean of potassium silicate at (600ppm) recorded the lowest value of oxalate as (941.38) compared with control.

Table 4 Mean of potassium silicate, salinity levels and their interactions on weight loss percent and post-harvest decay percent of spinach plants after storage for two weeks in refrigerator at (zero ° C/Rh95%) during both seasons 2022 and 2023

Salinity levels A	Potassium silicate B	The mean and standard deviation of 2022 and 2023 after storage for two weeks in refrigerator at (zero ° C/Rh95%)										
		Weight loss percent					Postharvest decay percent					
		0	10	15	20	Mean B	0	10	15	20	Mean B	
0		30.75 ± 5.24	25.69 ± 6.60	24.01 ± 2.82	18.81 ± 5.46	24.82 ^a	91.67 ± 14.43	25.00 ± 25.00	16.67 ± 14.43	0.00 ± 0.00	33.33 ^a	
400		21.13 ± 13.31	16.45 ± 2.01	20.02 ± 4.43	13.63 ± 3.18	17.81 ^c	0.00 ± 0.00	8.33 ± 14.43	0.00 ± 0.00	0.00 ± 0.00	2.08 ^d	
600		25.30 ± 6.74	13.11 ± 5.09	17.23 ± 2.58	11.11 ± 4.43	16.69 ^d	16.67 ± 28.87	0.00 ± 0.00	25.00 ± 0.00	41.67 ± 14.43	20.83 ^b	
800		29.75 ± 18.37	17.95 ± 4.72	19.38 ± 4.38	13.34 ± 2.17	20.11 ^b	25.00 ± 43.30	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	6.25 ^c	
Mean A		20.45 ^a	18.30 ^c	20.16 ^{ab}	14.22 ^d	Mean B	33.33 ^a	8.33 ^b	10.42 ^b	10.42 ^b	Mean B	
LSD 0.05		A = 6.05 B = 6.00 A*B = 12.09					A = 13.43 B = 13.40 A*B = 26.86					

Table 5 Mean of potassium silicate, salinity levels and their interactions on proline (mg.g⁻¹), Ascorbic acid (mg.100 g⁻¹) and oxalate (mg.100 g⁻¹) of spinach plants after storage for two weeks in refrigerator at (zero ° C/Rh95%) during both seasons 2022 and 2023

Salinity levels A		The mean and standard division of 2022 and 2023													
Potassium silicate B		Proline mg.g ⁻¹				Mean B				Oxalate mg.100 g ⁻¹				Mean B	
		0	10	15	20					0	10	15	20		
0			18.48 ± 1.05	13.90 ± 3.25	13.21 ± 3.10	9.95 ± 2.97	13.89 ^a			1083.00 ± 23.33	979.50 ± 74.25	968.50 ± 61.52	937.00 ± 83.44	992.13 ^a	
400			18.62 ± 1.02	14.11 ± 3.21	13.23 ± 3.38	12.48 ± 3.08	12.80 ^b			1070.00 ± 26.87	981.50 ± 94.05	966.50 ± 79.90	950.00 ± 83.44	992.00 ^a	
600			17.72 ± 1.06	11.61 ± 3.20	11.09 ± 3.16	10.19 ± 3.05	12.07 ^b			1054.50 ± 4.95	926.50 ± 74.25	899.00 ± 69.30	885.50 ± 62.93	941.38 ^a	
800			17.91 ± 1.01	11.58 ± 3.57	10.75 ± 3.32	12.19 ± 2.97	13.11 ^b			1057.00 ± 18.38	927.50 ± 95.46	913.00 ± 66.47	901.50 ± 61.52	949.75 ^a	
Mean A			14.44 ^a	14.61 ^a	12.65 ^a	12.54 ^a				1066.25 ^a	953.75 ^b	936.75 ^b	918.50 ^b		
LSD 0.05			A = 2.98 B = 3.00 A*B = 5.96												
After storage for two weeks in refrigerator at (zero °C/Rh95%)															
Salinity levels A		Ascorbic acid mg.100 g ⁻¹				Mean B				Oxalate mg.100 g ⁻¹				Mean B	
		0	10	15	20					0	10	15	20		
0			9.97 ± 0.33	11.46 ± 0.91	11.72 ± 0.91	13.02 ± 0.58	11.54 ^a			1121.00 ± 21.21	1035.00 ± 52.33	1018.50 ± 48.79	1018.50 ± 48.79	1029.13 ^a	
400			10.09 ± 0.30	11.62 ± 0.89	11.94 ± 0.98	13.17 ± 0.43	11.70 ^a			1135.50 ± 27.58	1049.50 ± 54.45	1043.00 ± 62.23	1043.00 ± 62.23	1047.63 ^a	
600			10.27 ± 0.40	12.11 ± 1.12	12.37 ± 1.12	12.77 ± 1.33	11.88 ^a			1105.50 ± 23.33	999.50 ± 61.52	976.50 ± 62.93	976.50 ± 62.93	1007.88 ^a	
800			10.35 ± 0.59	12.22 ± 1.09	12.48 ± 1.12	12.50 ± 1.36	11.99 ^a			1125.50 ± 13.43	1021.00 ± 47.38	999.50 ± 47.38	999.50 ± 47.38	1031.50 ^a	
Mean A			10.17 ^c	11.85 ^b	12.13 ^{ab}	12.98 ^a				1121.88 ^a	1024.38 ^{ab}	1009.38 ^b	1009.38 ^b		
LSD 0.05			A = 0.96 B = 1.00 A*B = 1.93												
A = 52.33 B = 52.30 A*B = 104.66															

Data in Table 5 exhibited the interaction between salinity levels (0, 10, 15 and 20g/L) and potassium silicate (400 and 800ppm) recorded the crest of ascorbic acid after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons as (10.35, 12.22, 12.48 and 13.17mg.100g⁻¹) respectively compared with control. In the same table, the mean of potassium silicate (400ppm) revealed the highest values of oxalate compared with control after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons. The mean salinity level (0ppm) recorded the towering of oxalate as (1121.88mg.100g⁻¹) compared with all salinity levels after storage for two weeks in the refrigerator at (zero° C/Rh95%) during both seasons.

3.4 Total chlorophyll, carotenoids content, hydrogen peroxide (H₂O₂) and superoxide (O₂⁻) under salinity stress

Data in Table 6., the mean of potassium silicate at (600 ppm) recorded elevated of total chlorophyll compared with control. The mean salinity level (15g/L) showed the best value of total chlorophyll compared with control. Meanwhile, the interaction between potassium silicate (600 and 400ppm) and salinity levels (10, 15 and 20g/L) revealed a crest of total chlorophyll compared with control.

The interaction between salinity levels (0, 10, 15 and 20g/L) and potassium silicate (400 and 800ppm) recorded the best values of carotenoids compared with control. The mean of salinity level (10g/L) and potassium silicate (400ppm) recorded the maximum values of carotenoids (4.40 and 6.27 mg.g⁻¹) compared with control.

Table 6., exhibiting the combined with salinity levels (10, 15 and 20g/L) and potassium silicate (600 and 800ppm) revealed the best value of both H₂O₂ compared with control. While, the interaction between salinity levels (0 and 20g/L) and potassium silicate (0 and 400ppm) recorded a crest of H₂O₂ and O₂⁻ compared with control. The mean of potassium silicate (600ppm) recorded the greatest value of H₂O₂ and O₂⁻ compared with control. The mean of salinity level 20g/L recorded the least value of H₂O₂ and O₂⁻ as (0.95 and 0.88 mmol.g⁻¹) respectively compared to the control.

3.5 Superoxide dismutase (SOD) and peroxidase (POD) enzymes operate under salinity

Data in Table 7 showed the interaction between salinity levels (0, 10, 15 and 20g/L) and potassium silicate (0 and 400ppm) recorded the towering of superoxide dismutase enzyme as (53.88, 41.21, 39.44, and 36.92 min⁻¹.g⁻¹) respectively compared with control. The mean of potassium silicate (400ppm) recorded an elevated value of the superoxide dismutase enzyme compared with control.

While the mean salinity level (20g/L) revealed the lowest value of the superoxide dismutase enzyme compared with control. The mean of potassium silicate (400ppm) revealed the highest result for the peroxidase enzyme (2.56) compared with control. The interaction between salinity levels (0, 10, 15 and 20g/L) with (0 and 400ppm) of potassium silicate recorded the greatest values of peroxidase enzyme compared with control. The mean salinity level (20ppm) revealed the minimum of the peroxidase enzyme compared with control.

In the same table, the interaction between salinity levels (0, 10, 15 and 20g/L) with 400ppm of potassium silicate recorded the highest values of leaf water potential (2.58, 2.17, 2.09 and 2.03 Mpa⁻¹) respectively compared with control. The interaction between 400ppm of potassium silicate and (0, 10, 15 and 20g/L) salinity levels revealed an excess of leaf osmotic potential (1.55, 1.13, 1.04 and 0.99 Mpa⁻¹) respectively compared with control. The mean of potassium silicate (0 and 400ppm) revealed the towering of leaf water and osmotic potential compared with control. The mean salinity level (20 g/L) revealed down of leaf water potential as (1.91 Mpa⁻¹) and leaf osmotic potential as (0.87 Mpa⁻¹) respectively, compared with control.

3.6 Total chlorophyll, carotenoids, total flavonoids and total phenols after storage for two weeks at (zero° C/Rh95%)

Data in Table 8, the interaction between salinity levels (0, 10, 15 and 20g/L) with potassium silicate (0, 600 and 800ppm) revealed elevated total chlorophyll after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons as (29.81, 29.73, 20.10 and 21.72 mg.g⁻¹) respectively compared with control. The mean salinity level at 20g/L recorded the maximum value of carotenoids as (6.64 mg.g⁻¹), while 10g/L of salinity level revealed 25.14 mg.g⁻¹ for total chlorophyll after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons compared with all salinity levels. The combined salinity levels (0, 10, 15 and 20g/L) with potassium silicate (0, 400 and 600ppm) recorded the greatest result of carotenoids after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons as (6.29, 8.36, 5.95 and 13.46 mg.g⁻¹) respectively compared with control. In the same table, the mean of potassium silicate (400ppm) revealed the highest values of total flavonoids and total phenols compared with control after storage for two weeks in refrigerator at (zero° C/Rh95%) during both seasons. The mean salinity level (0ppm) recorded the towering of total flavonoids (20.57 mg.g⁻¹) and total phenols (42.26mg.g⁻¹) compared with all salinity levels after storage for two weeks in the refrigerator at (zero° C/Rh95%) during both seasons.

Table 6. Mean of potassium silicate, salinity levels and their interactions on total chlorophyll ($\text{mg}\cdot\text{g}^{-1}$), carotenoids ($\text{mg}\cdot\text{g}^{-1}$), reactive oxygen species (H_2O_2^- and O_2^-) ($\text{mmol}\cdot\text{g}^{-1}$) of spinach plants during both seasons 2022 and 2023

Salinity levels A		The mean and standard division of 2022 and 2023									
Potassium silicate B		Total chlorophyll mg.g ⁻¹									
		0	10	15	20	Mean B	Carotenoids mg.g ⁻¹				
							0	10	15	20	Mean B
0		30.13 ± 2.37	22.17 ± 3.92	37.26 ± 3.75	22.22 ± 2.20	27.95 ^c	3.98 ± 1.62	3.04 ± 2.92	5.96 ± 0.79	4.97 ± 0.45	4.48 ^b
400		32.61 ± 1.88	27.28 ± 4.99	39.12 ± 4.30	37.77 ± 4.13	34.20 ^b	7.53 ± 5.20	5.68 ± 3.22	7.05 ± 3.25	4.80 ± 1.99	6.27 ^a
600		38.83 ± 2.90	30.80 ± 6.94	41.90 ± 5.95	32.09 ± 5.02	35.91 ^a	6.35 ± 3.90	4.03 ± 0.60	5.95 ± 3.35	4.65 ± 2.85	5.24 ^a
800		40.88 ± 2.57	28.45 ± 4.31	30.17 ± 3.53	33.34 ± 1.53	33.21 ^{ab}	6.38 ± 2.85	4.86 ± 0.74	4.85 ± 0.57	6.19 ± 1.63	5.57 ^a
Mean A		35.61 ^b	27.18 ^d	36.86 ^a	31.36 ^c		6.06 ^a	4.40 ^a	5.95 ^a	5.15 ^a	
LSD _{0.05}		A = 3.45 B = 3.50 A*B = 6.90									
The mean and standard division of 2022 and 2023											
Salinity levels A		H ₂ O ₂ ⁻ mmol.g ⁻¹									
Potassium silicate B		0	10	15	20	Mean B	O ₂ ⁻ mmol.g ⁻¹				
							0	10	15	20	Mean B
0		1.82 ± 0.13	1.28 ± 0.37	1.20 ± 0.37	1.12 ± 0.36	1.35 ^c	1.87 ± 0.15	1.25 ± 0.44	1.18 ± 0.40	1.05 ± 0.40	1.34 ^c
400		1.85 ± 0.11	1.27 ± 0.41	1.22 ± 0.42	1.09 ± 0.38	1.36 ^{ab}	1.87 ± 0.18	1.28 ± 0.43	1.16 ± 0.45	1.04 ± 0.44	1.34 ^c
600		1.73 ± 0.13	1.01 ± 0.39	0.92 ± 0.35	0.80 ± 0.40	1.11 ^a	1.76 ± 0.14	0.89 ± 0.51	0.80 ± 0.52	0.72 ± 0.45	1.04 ^{ab}
800		1.73 ± 0.09	1.03 ± 0.40	0.90 ± 0.42	0.82 ± 0.40	1.12 ^a	1.79 ± 0.15	0.92 ± 0.50	0.79 ± 0.49	0.69 ± 0.44	1.05 ^a
Mean A		1.78 ^a	1.15 ^b	1.06 ^b	0.95 ^c		1.82 ^a	1.08 ^b	0.98 ^b	0.88 ^c	
LSD _{0.05}		A = 0.36 B = 0.40 A*B = 0.73									
		A = 0.43 B = 0.43 A*B = 0.86									

Table 7 Mean of potassium silicate, salinity levels and their interactions with super oxide dismutase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$), peroxidase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$), leaf water potential (Mpa^{-1}) and leaf osmotic potential (Mpa^{-1}) of spinach plants during both seasons 2022 and 2023

Salinity levels A		The mean and standard division of 2022 and 2023									
Potassium silicate B		Super oxide dismutase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$)									
		0	10	15	20	Mean B	Peroxidase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$)				
0		53.63 ± 2.95	41.21 ± 8.75	39.44 ± 9.14	36.73 ± 9.26	42.75 ^a	0	10	15	20	Mean B
400		53.88 ± 2.76	41.17 ± 8.98	39.29 ± 8.53	36.92 ± 8.53	42.81 ^a	3.25 ± 0.19	2.43 ± 0.63	2.31 ± 0.57	2.16 ± 0.57	2.53 ^a
600		51.75 ± 2.64	35.18 ± 8.53	33.82 ± 6.97	31.96 ± 7.72	38.18 ^a	3.30 ± 0.18	2.43 ± 0.53	2.32 ± 0.66	2.18 ± 0.64	2.56 ^a
800		51.75 ± 3.22	35.05 ± 7.92	33.87 ± 7.45	31.86 ± 7.37	38.13 ^a	3.12 ± 0.18	2.00 ± 0.62	1.94 ± 0.62	1.72 ± 0.70	2.19 ^a
Mean A		52.75 ^a	38.15 ^b	36.60 ^b	34.37 ^b	38.13 ^a	3.17 ± 0.17	2.01 ± 0.63	1.86 ± 0.64	1.72 ± 0.61	2.20 ^a
LSD _{0.05}		A = 7.77 B = 7.80 A * B = 5.49									
Salinity levels A		Leaf water potential (Mpa^{-1})									
Potassium silicate B		Leaf osmotic potential (Mpa^{-1})									
		0	10	15	20	Mean B	0	10	15	20	Mean B
0		2.56 ± 0.11	2.13 ± 0.31	2.05 ± 0.30	1.99 ± 0.28	2.18 ^a	1.53 ± 0.08	1.09 ± 0.37	1.04 ± 0.35	0.99 ± 0.34	1.16 ^a
400		2.58 ± 0.11	2.17 ± 0.31	2.09 ± 0.29	2.03 ± 0.28	2.22 ^a	1.55 ± 0.08	1.13 ± 0.39	1.03 ± 0.39	0.95 ± 0.34	1.16 ^a
600		2.49 ± 0.09	1.93 ± 0.30	1.88 ± 0.29	1.80 ± 0.27	2.02 ^a	1.48 ± 0.06	0.91 ± 0.35	0.82 ± 0.24	0.76 ± 0.23	0.99 ^a
800		2.53 ± 0.11	1.97 ± 0.30	1.87 ± 0.33	1.80 ± 0.21	2.04 ^a	1.48 ± 0.11	0.94 ± 0.36	0.83 ± 0.38	0.80 ± 0.35	1.01 ^a
Mean A		2.54 ^a	2.05 ^b	1.97 ^b	1.91 ^b	2.04 ^a	1.51 ^a	1.02 ^b	0.93 ^b	0.87 ^b	
LSD _{0.05}		A = 0.27 B = 0.30 A * B = 0.54									
		A = 0.32 B = 0.31 A * B = 0.64									

Table 8 Mean of potassium silicate, salinity levels and their interactions on ascorbic acid ($\text{mg} \cdot 100 \text{ g}^{-1}$), total chlorophyll ($\text{mg} \cdot \text{g}^{-1}$), carotenoids ($\text{mg} \cdot \text{g}^{-1}$), oxalate ($\text{mg} \cdot 100 \text{ g}^{-1}$), total phenols and total flavonoids ($\text{mg} \cdot \text{g}^{-1}$) after storage for two weeks in refrigerator at (zero °C/Rh95%) of spinach plants during both seasons 2022 and 2023

Salinity levels A		After storage for two weeks in refrigerator at (zero ° C/Rh95%)									
Potassium silicate B		Total chlorophyll mg.g ⁻¹				Carotenoids mg.g ⁻¹				Mean B	
		0	10	15	20	Mean B	0	10	15	20	Mean B
0		15.25 ± 3.59	29.73 ± 6.29	7.42 ± 4.44	4.85 ± 2.82	14.31 ^a	5.87 ± 1.40	8.36 ± 0.95	5.59 ± 0.83	13.46 ± 1.13	8.32 ^a
400		20.33 ± 7.05	28.15 ± 1.80	12.43 ± 1.59	11.68 ± 4.31	18.15 ^a	6.29 ± 3.48	7.07 ± 1.91	4.78 ± 1.80	5.17 ± 2.04	5.83 ^b
600		29.81 ± 5.17	24.74 ± 2.71	19.44 ± 5.22	12.35 ± 3.34	21.59 ^a	5.77 ± 2.42	7.35 ± 1.36	5.95 ± 2.08	3.41 ± 0.95	5.62 ^b
800		28.01 ± 1.18	17.94 ± 0.93	20.10 ± 2.46	21.72 ± 3.75	21.97 ^a	6.04 ± 2.87	3.69 ± 1.55	4.96 ± 2.35	4.52 ± 1.13	4.80 ^b
Mean A		23.35 ^a	25.14 ^a	14.85 ^b	12.65 ^c		5.99 ^a	6.62 ^a	5.32 ^a	6.64 ^a	Mean B
LSD _{0.05}		A = 3.15 B = 3.14 A*B = 6.30									
After storage for two weeks in refrigerator at (zero ° C/Rh95%)											
Salinity levels A		Total flavonoids mg. g ⁻¹				Total phenols mg. g ⁻¹				Mean B	
Potassium silicate B		0	10	15	20	Mean B	0	10	15	20	Mean B
0		20.60 ± 0.33	19.40 ± 0.74	19.16 ± 0.74	18.12 ± 0.44	19.32 ^a	42.64 ± 1.24	22.85 ± 18.16	37.00 ± 3.07	32.69 ± 1.82	33.79 ^a
400		20.78 ± 0.21	19.49 ± 0.71	19.22 ± 0.78	18.25 ± 0.42	19.43 ^a	42.77 ± 1.28	37.96 ± 3.09	37.12 ± 3.01	32.75 ± 1.70	37.65 ^a
600		20.37 ± 0.35	18.85 ± 0.87	18.66 ± 0.84	18.37 ± 0.99	19.06 ^a	41.75 ± 1.24	35.72 ± 3.65	34.86 ± 3.66	33.55 ± 4.25	36.47 ^a
800		20.55 ± 0.47	18.99 ± 0.78	18.90 ± 0.88	18.54 ± 0.7	19.25 ^a	41.88 ± 1.27	35.90 ± 3.59	35.05 ± 3.68	33.77 ± 4.39	36.65 ^a
Mean A		20.57 ^a	19.18 ^b	18.98 ^{bc}	18.32 ^c		42.26 ^a	33.10 ^b	36.01 ^b	33.19 ^b	
LSD _{0.05}		A = 0.75 B = 0.80 A*B = 1.51									
A = 5.69 B = 5.70 A*B = 11.38											

3.7 Antioxidant enzymes activities and respiration rate after storage for two weeks at (zero ° C/Rh95%)

Data in Table 9 observed the integrated of salinity levels (0, 10, 15 and 20g/L) and potassium silicate (400 and 600) recorded the best values of polyphenol oxidase and superoxide dismutase compared with control after storage for two weeks in refrigerator at (zero ° C/Rh95%) during both seasons. Incorporated of salinity levels (0, 10, 15 and 20g/L) with (400 and 800ppm) of potassium silicate recorded the towering of the catalase enzyme compared with control after storage for two weeks in refrigerator at (zero ° C/Rh95%) during both seasons. The mean of potassium silicate at a rate of (400ppm) recorded the highest values of polyphenol oxidase, superoxide dismutase, catalase and respiration rate after storage for two weeks in the refrigerator at (zero ° C/Rh95%) during both seasons as respectively compared with control. However, the mean salinity level at a rate of (20g/L) revealed excess of polyphenol oxidase, superoxide dismutase, catalase and respiration rate after storage for two weeks in the refrigerator at (zero ° C/Rh95%) during both seasons compared with control.

4 Discussion

4.1 Impact of salinity stress on vegetative growth and biochemical constituents

Soil salinity is a very serious problem resulting from natural processes or from crop irrigation with saline water, which occurs in many arid and semi-arid regions of the world. In salt-affected areas, plant growth is severely affected by salinity through water deficit and salt-specific damage. Based on the results, the reduction in growth parameters observed under salinity stress occurs because the accumulation of excess salts (Na^+ and Cl^-) in the root zone disrupts physiological and biochemical processes within plant cells, leading to toxicity. The total concentration of salt solution negatively affects root and shoot growth, photosynthesis, respiration, soil microbial activity (Yang et al. 2020), nutrient availability, competitive uptake, and the transport or partitioning of nutrients within the plant. These disruptions ultimately lead to wilting (Ahmad et al. 2016). The adverse effects of high salt on plants can be attributed to several key factors:

5.1.1. Low water potential of soil solution, resulting in water stress (Winterbourn 2019).

5.1.2. Increased electrical conductivity (EC), driven by high chloride ion concentrations, which can reduce nitrate availability (Bonasia et al. 2017).

5.1.3. Inhibition of enzymatic activity (Debouba et al. 2006, 2007).

5.1.4. Nutrient imbalances and disturbances in ionic homeostasis.

5.1.5. Specific ion effects, contributing to salt stress Bakhat et al. (2018).

5.1.6. Overproduction of reactive oxygen species (ROS), leading to oxidative stress Zorb et al. (2018).

Under salt stress, reductions in total chlorophyll, carotenoids, total phenols, flavonoids, and oxalates vary depending on the severity of the salinity (Seven and Sağlam 2020; Kim et al. 2021). Moreover, a decrease in stomatal conductance and transpiration process, which, in halophytic plants, is often compensated by the uptake and accumulation of Na^+ in vacuoles. Although stomatal closure under saline conditions helps maintain higher leaf water content, it also reduces CO_2 assimilation rates (Mohammadi et al. 2024).

4.2 Effect of potassium silicate on vegetative growth and biochemical constituents

Silicon (Si) plays an important role in enhancing the resistance of plants under stress conditions, including salinity stress. The mechanisms of silicon for salt tolerance have been suggested to have a main role in:

5.2.1 Strengthening Cell Walls: Silicon is deposited in plant cell walls, where it forms a physical barrier that improves structural integrity. This reinforcement can reduce the negative impact of osmotic stress caused by salinity, helping to maintain turgor pressure and overall plant structure (Darvizheh et al. 2019).

5.2.2 Improving Water Regulation: By increasing the strength and rigidity of cell walls, silicon can help plants regulate water more efficiently, reducing water loss through transpiration. This is especially beneficial under saline conditions, where maintaining water balance is a challenge. In other words, silicon contributes to better water management by improving leaf water potential, transpiration rate, photosynthesis, stomatal conductance, and leaf uprightiness (Tuladhar et al. 2021; Wang et al. 2023).

5.2.3 Enhancing Photosynthesis and Gas Exchange: Silicon can improve stomatal conductance and the efficiency of photosynthetic processes. Under saline stress, plants decline in photosynthetic efficiency, but silicon can help mitigate this by improving gas exchange, which in turn supports better overall growth Kramer and Mau (2020).

5.2.4 Antioxidant System Activation: Silicon has been shown to enhance the activity of antioxidant enzymes such as (SOD), (CAT) and (POD). These enzymes play a key role in scavenging free radicals which tend to accu-

Table 9 Mean of potassium silicate, salinity levels and their interactions on polyphenol oxidase, Super oxide dismutase, catalase enzymes activities ($\text{min}^{-1} \cdot \text{g}^{-1}$) and respiration rate ($\text{mmol H}_2\text{O}/\text{m}_2 \cdot \text{s}$) after storage for two weeks in refrigerator at ($\text{zero}^\circ \text{C/Rh95\%}$) of spinach plants during both seasons 2022 and 2023

Salinity levels A		After storage for two weeks in refrigerator at ($\text{zero}^\circ \text{C/Rh95\%}$)					Super oxide dismutase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$)					Mean B				
Potassium silicate B		Polyphenol oxidase enzyme ($\text{min}^{-1} \cdot \text{g}^{-1}$)					0					10				
0		51.77 $\pm$ 1.03					36.43 $\pm$ 1.23					38.64 $\pm$ 6.24				
400		51.90 $\pm$ 0.99					37.63 $\pm$ 1.23					38.77 $\pm$ 6.22				
600		51.03 $\pm$ 1.04					30.69 $\pm$ 19.98					34.25 $\pm$ 7.49				
800		51.11 $\pm$ 1.06					30.79 $\pm$ 19.99					34.38 $\pm$ 7.62				
Mean A		51.45 ^a					33.89 ^a					36.51 ^{ab}				
LSD _{0.05}		A = 2.79 B = 2.80 A*B = 5.59					A = 9.76 B = 9.80 A*B = 19.52					A = 9.76 B = 9.80 A*B = 19.52				
After storage for two weeks in refrigerator at ($\text{zero}^\circ \text{C/Rh95\%}$)																
Salinity levels A		Catalase enzyme activity $\text{min}^{-1} \cdot \text{g}^{-1}$					Respiration rate $\text{mmol H}_2\text{O}/\text{m}_2 \cdot \text{s}$					Mean B				
Potassium silicate B		0					0					15				
0		68.19 $\pm$ 2.74					11.46 $\pm$ 0.52					9.28 $\pm$ 1.15				
400		68.42 $\pm$ 2.52					11.54 $\pm$ 0.54					9.45 $\pm$ 0.99				
600		66.24 $\pm$ 2.76					11.12 $\pm$ 0.50					8.45 $\pm$ 1.41				
800		66.32 $\pm$ 2.76					11.26 $\pm$ 0.57					8.60 $\pm$ 1.50				
Mean A		67.29 ^a					11.34 ^a					8.94 ^{bc}				
LSD _{0.05}		A = 6.26 B = 6.30 A*B = 12.53					A = 1.17 B = 1.20 A*B = 2.34									

mulate under saline stress and cause oxidative damage to plant cells (Coskun et al. 2016; Wang et al. 2023).

5.2.5 Nutrient Uptake: Silicon also influences the uptake and assimilation of other essential nutrients like potassium, calcium, and nitrogen, which can prevent absorbing it under saline conditions (Zargar et al. 2019). By improving nutrient balance, silicon helps maintain plant metabolism and growth (Amin et al. 2018; Kramer and Mau 2020). And promoting the accumulation of organic compounds such as proline as well as antioxidant activities, all of which are crucial for plant survival under stress.

5.2.6 Regulation of Osmotic Adjustment: Silicon can also contribute to osmotic regulation by influencing the accumulation of dissolved substances like proline and sugars, which help maintain cell turgidity under osmotic stress (Liu et al. 2015; Coskun et al. 2016).

Based on previous results, potassium silicate serves as an important dual-purpose compound in agricultural production, providing both potassium and soluble silicon to plants. It is particularly valued for improving crop quality and supporting vegetative growth. It serves as an important source of potassium absorption; it enhances critical physiological functions in plants, including the synthesis of sugars, starch, proteins, and the promotion of cell division and growth. It also plays a role in fruit formation, size, flavor, and color improvement. Additionally, potassium is vital for maintaining the plant's water balance, photosynthesis, and nutrient movement. It aids in carbohydrate synthesis and storage, significantly affecting the quality of crops. Moreover, potassium silicate improves the nutrient profile of crops, such as increasing of nitrogen, phosphorus, and potassium concentrations, and promoting better growth and yield components. These results agree with those of (Marschner 2012; Salim et al. 2014). Beyond these direct benefits to plant growth, potassium also enhances plant resistance to disease. A potassium-deficient plant is more susceptible to bacterial and fungal infections; thus, potassium stress can lead to increased damage from such diseases. This underscores potassium's role not only in promoting plant growth but also in strengthening its defense mechanisms against external stressors. The main role of potassium silicate (K_2SiO_3) enhances the plant's defending system, particularly through the modulation of phenolic compounds like flavonoids and phenolic acids, which are key players in plant immunity. These compounds are produced via the phenylpropanoid metabolic pathway and serve multiple functions, both as phytoalexins (antimicrobial compounds) and phytoanticipins (preformed defenses) and antioxidant activity. Potassium silicate (K_2SiO_3) has a positive effect on plant defense systems, notably by increasing the synthesis of phenolic compounds. On the same line, plants treated with (K_2SiO_3) presented higher levels of proline content. Similar results

were obtained by Zahedi et al. (2020), Salim et al. (2021) on squash plants and Tuladhar et al. (2021). These compounds are important for defending against biotic stress and abiotic stress. Silicon is considered a key player in improving a plant's tolerance to various stresses (Yaghubi et al. 2019; Mohammadi et al. 2024). Under stressed conditions, silicon helps plants maintain cellular function and mitigate damage caused by environmental stressors.

4.3 Effect of potassium silicate on storability and bioactive components after storage at low temperatures (zero °C and 95 % relative humidity)

Mechanism of action for silicon on quality characteristics and nutritional value under cold storage conditions:

5.2.7 Pre- and Postharvest Physical Damage: Physical damage to fruits and vegetables can occur at any point from the field to the market, leading to bruising, cuts, or other injuries that can make produce more susceptible to microbial contamination and spoilage. Proper handling and transport practices are critical in minimizing such damage.

5.2.8 Microbial Pathogens: Microbial pathogens (bacteria, fungi) and insect pests can infect and damage fruit and vegetable crops, leading to spoilage. These pathogens can enter the produce through wounds or natural openings and grow rapidly if conditions such as humidity and temperature are conducive. Pest infestation during storage or transportation can significantly reduce quality, but adding silicon reduces decay percent and increases dry matter content, resulting in longer storage and shelf life for handling.

5.2.9 Quality criteria: quality of produce at harvest can be influenced by pre-harvest factors like temperature, light intensity, water supply, and agrochemical use. These factors can affect plant metabolism, which in turn impacts the product's nutritional content, quality of crops, appearance, and resistance to diseases.

5.2.10 Metabolism and Post-harvest Quality: Plant metabolism during the pre-harvest period affects both the quality at harvest and how well the produce is stored after harvesting. Stressful conditions can reduce the crop's shelf life by impairing its ability to withstand storage conditions. This overview highlights the complexity of factors affecting the postharvest life and quality of fruits and vegetables, with implications for both producers and consumers. Management of these factors requires a comprehensive approach that considers environmental, genetic, and physiological elements throughout the entire growing and post-harvesting process. Post-harvest losses are often linked to unfavorable storage conditions, which

can result in a range of quality factors, including loss of flavor, texture, and pigments, as well as softening of tissues, the onset of decay, dehydration or weight loss, and reduction in nutritional value. The obtained results are in accordance with the findings (Nishikawa et al. 2003) on broccoli plants, (Prithiviraj et al. 2014) on spinach plants and Saleh et al. (2024) on potatoes.

5.2.11 The research results proved that storing at the optimum temperature can prevent oxidative stress that leads to several dysfunctions associated with senescence. These include repression of enzyme activities, loss of pigments (one of the first visible signs of senescence is the breakdown of chlorophyll, resulting in the yellowing of outer leaves, which accelerates carotenoid degradation) and the increased production of ethylene along with the disintegration of cell membranes. Cold storage is indeed one of the most effective methods for prolonging the shelf life of fresh produce. It slows down the biological and biochemical activities that would otherwise lead to spoilage and deterioration. Low temperatures can reduce respiration, ethylene production (which accelerates ripening), moisture loss, and the growth of pathogens. Our data agree with previous studies, which reported that low temperature was beneficial to maintain the carotenoids content according to (Griffiths et al. 2007; Yang et al. 2010). Carotenoids, particularly the chain carotenoids, play a key role in protecting fresh produce from oxidative stress, which can damage cell membranes and other cellular components. Spinach plants stored at zero°C with 95% relative humidity for two weeks in a refrigerator showed the lowest rates of respiration and senescence. Several studies have reported that silicon is effective in controlling various fungal and bacterial diseases, which is reflected in a decrease in decay percentage, as demonstrated by Onuorah and Orji (2015) on tomato plants. The degradation of phenolic compounds and flavonoids in fruits and vegetables is closely linked to the loss of membrane integrity and reduced antioxidant enzyme activity which resists enzymatic browning. Polyphenol oxidase, superoxide dismutase and peroxidase are responsible for the degradation of phenolic compounds by converting monophenols into diphenols and then colorless quinones, which in turn aggregate (polymerize) and interact with amino acids and proteins in the cells, giving compounds with a reddish-brown color. Silicon has been shown to influence the activity of phenylalanine ammonia-lyase (PAL), an enzyme involved in phenolic compounds synthesis, including flavonoids. PAL catalyzes the first step in the phenylpropanoid pathway, which is crucial for producing various phenolic compounds that are involved in plant defense. By increasing PAL activity, silicon treatment could enhance the synthesis of flavonoids, potentially improving the plant's resilience to oxidative stress under

low temperature. The relationship between silicon and flavonoid biosynthesis suggests that silicon treatment could be a useful agronomic strategy for improving storability. The results are consistent with Navarro et al. (2006) on pepper plants and Wang et al. (2023). Also, they observed that plants with higher levels of antioxidants, whether constitutive or induced, show greater resistance to oxidative damage. Similarly Mostafa et al. (2023) on crisp head lettuce and Geransayeh et al. (2015) on strawberry fruits suggest that POD plays a key role in the decomposition of hydrogen peroxide (H_2O_2). Ascorbic acid acts as a potent antioxidant in plants, helping to neutralize free radicals. This ability is critical because free radicals can damage cellular structures, proteins, and DNA, leading to oxidative stress. The results indicate a significant decrease in ascorbic acid under low-temperature storage conditions with packaging polypropylene compared to control. By scavenging reactive oxygen species, Ascorbic acid helps maintain cellular integrity: **1) Response to Salt Stress:** Many agricultural plants experience salt stress, which can negatively impact growth, yield, storability and marketing. Ascorbic acid plays a role in mitigating this stress by activating various defense mechanisms within the plant, such as increasing the expression of antioxidant enzymes and other protective proteins. **2) Ascorbate–Glutathione Pathway:** Ascorbic acid acts as a potent antioxidant in plants, helping to neutralize free radicals. This ability is critical because free radicals can damage cellular structures, proteins, and DNA, leading to oxidative stress. The results indicate a significant decrease in ascorbic acid under low-temperature storage conditions with packaging polypropylene compared to control. By scavenging reactive oxygen species, Ascorbic acid helps maintain cellular integrity: **1) Response to Salt Stress:** Many agricultural plants experience salt stress, which can negatively impact growth, yield, storability and marketing. Ascorbic acid plays a role in mitigating this stress by activating various defense mechanisms within the plant, such as increasing the expression of antioxidant enzymes and other protective proteins. **2) Ascorbate–Glutathione Pathway:** AsA's involvement in the ascorbate–glutathione pathway, a crucial biochemical route for dealing with oxidative stress under low temperature. Specifically, AsA acts as a substrate for ascorbate peroxidase (APX), an enzyme that reduces hydrogen peroxide (H_2O_2), a harmful free radical. This pathway is essential for maintaining cellular redox balance and protecting plants from oxidative damage. The results are in harmony with those of Spinardi et al. (2010) spinach and lettuce baby leaf and Ali and Majid (2023) on broccoli. The research indicates that potassium silicate results in a decrease in oxalate content in spinach plants. This is significant because oxalates, particularly calcium oxalate, are compounds that can bind with essential min-

erals i.e., calcium and iron, potentially reducing their bio-availability and contributing to kidney stone formation. The results are consistent with Sajad and Thakur (2020). The research also suggests that the application of potassium silicate improves the storage efficiency and quality of spinach, especially when stored under conditions of low temperature (0°C with 95% relative humidity) in polypropylene packaging.

5 Conclusion

Potassium silicate enhances the plant's potential via inducing the activities of the antioxidant enzymes such as superoxide dismutase, peroxidase and catalase, as well as increasing non-enzymatic antioxidants, i.e., ascorbic acid, proline content, total phenols and total flavonoids. Also, potassium silicate (600 and 800ppm) causes a decline in oxidative stress by reducing super oxide and hydrogen peroxide contents, which improves membrane stability and cell viability response. Potassium silicate is one of the materials that has proven its efficiency in resisting salt stress, as well as increasing the shelf life for trading and marketing while maintaining the quality characteristics and nutritional value of the leaves.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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