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Silicon extends the shelf life of hydroponically grown lettuce

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Lettuce (*Lactuca sativa* L.) is the most common leafy vegetable consumed by people around the world. In this study, we explored the influence of varying silicon (Si) concentrations (25, 50, 75, and 100 mg L^{-1}) on hydroponically grown lettuce (*Lactuca sativa* L.) concerning growth, shelf life, and nutrient composition. Key metrics included plant growth parameters, shelf-life extension under different storage conditions, and physiological responses. Silicon supplementation at 75 mg L^{-1} significantly boosted total fresh weight by 17.7% over the control. Storage at 4 °C showed marked shelf-life improvement, with Si concentrations of 25, 50, 75, and 100 mg L^{-1} enhancing storage longevity by 40%, 40%, 60%, and 80%, respectively. Phosphorus content increased with higher Si, while other nutrients remained unaffected. These results indicate that Si application can enhance post-harvest quality and extend marketability under optimal conditions.

Keywords Chlorophyll, Gas exchange, Hydroponic floating system, *Lactuca sativa* L., Shelf life

Lettuce (*Lactuca sativa*) is one of the most widely consumed leafy vegetables worldwide. Water comprises 94–95% of the lettuce[1]. However, maintaining its freshness, long shelf-life, and nutritional value poses significant challenges, particularly during post-harvest handling and storage[2]. Hydroponic cultivation has gained a reputation recently due to its potential for higher yields, resource efficiency, and controlled environment benefits[3]. Despite these advantages, hydroponically grown lettuce often faces issues related to shelf-life and post-harvest deterioration, limiting its marketability and consumer appeal[4]. One promising solution to address this challenge is the application of silicon, a beneficial element known for its role in enhancing plant resistance to various stresses, including biotic and abiotic factors[5,6]. Epstein[7] referred to Si as being "quasi-essential" or "semi-essential". Recently, it has been argued that the deposition as silica (SiO_2, via biosilicification) within the extracellular matrix (particularly within the root endodermal and shoot tissues) acts simply as a protective agent against the numerous environmental stressors plants encounter[8]. Moreover, Samuels et al.[9] indicate that Si amendments have increased the physical strength of the epidermis tissues of both shoots and roots. Silicon is absorbed by plant roots primarily in the form of monosilicic acid ($Si(OH)_4$), the soluble and bioavailable form of silicon in hydroponic and soil systems[10]. Uptake is mediated by both passive diffusion and active transport mechanisms. Two key transporters, Lsi1 (an influx transporter located in root epidermal and cortical cells) and Lsi2 (an efflux transporter in endodermal cells), facilitate the directional movement of silicon into the stele[11]. Once inside the xylem, silicon is translocated to the shoots through the transpiration stream, where it accumulates mainly in the epidermis and cell walls[8]. In these tissues, it polymerizes as amorphous silica ($SiO_2 \cdot nH_2O$), forming phytoliths or cuticle–silica double layers that enhance structural integrity, reduce transpirational water loss, and provide abiotic and biotic stress resistance[10,11].

The improvement in postharvest quality with Si may be related to the formation of a cuticle-silica double layer which reduces water loss during the storage period[12]. While previous studies have demonstrated the beneficial effects of silicon on the postharvest physiology of leafy vegetables such as spinach and basil, relatively few have examined its impact on hydroponically grown lettuce, particularly under floating basin systems using root-applied silicon dioxide (SiO_2)[13,14]. Most existing research has focused on foliar application or highly soluble silicon sources, whereas the effectiveness of less soluble forms applied directly to the root zone remains underexplored. Moreover, there is limited information on the postharvest behavior of commercial lettuce cultivars such as Patagonia RZ in response to silicon supplementation. Therefore, this study aimed to evaluate the influence of root-zone SiO_2 application on the yield, mineral content, and postharvest shelf-life of hydroponically grown lettuce *Lactuca sativa* L. (Patagonia RZ) in a floating hydroponic system.

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Materials and methods

Experiment setup

This study was conducted within the greenhouse facilities of the Agricultural Research Station at the Faculty of Agriculture Jordan University of Science and Technology (32° 28′ 01.2″ N, 35° 58′ 31.5″ E) between April 4th and May 9th. Twenty experimental concrete basins (120 * 120 * 20 cm) were built inside the greenhouse covered with a thick plastic mulch (400 µm), as shown in Fig. 1. Oxygen rulers (40 cm Length) were installed in each experimental unit and connected by spaghetti net tubes to an oxygen pump that works automatically for ten minutes every hour. The planting density was 20.8 plants/m^2. Thirty lettuce seedlings of *Lactuca sativa* L. (variety: Patagonia RZ) were transplanted into each experimental unit.

The experiment involved five distinct treatments: (T1) standard nutrient solution (control), (T2) standard nutrient solution supplemented with 25 mg L^{-1} Si, (T3) standard nutrient solution supplemented with 50 mg L^{-1} Si, (T4) standard nutrient solution supplemented with 75 mg L^{-1} Si, (T5) standard nutrient solution supplemented with 100 mg L^{-1} Si. Each treatment was replicated four times, following a Complete Randomized Design (CRD) experimental layout. These concentrations were chosen based on a review of relevant literature where similar ranges have been found effective[15,16].

Plants were fertilized using a nutrient solution with the following chemical composition of macronutrient (4 $Ca(NO_3)_2$, 0.2 NH_4NO_3, 1 KH_2PO_4, 1.5 $MgSO_4.7H_2O$, 1 K_2SO_4, and 5 KNO_3 mmol L^{-1}), and micronutrient (40 Fe, 7 Mn, 7 Zn, 40 B, 1 Cu, and 1 Mo µmol L^{-1}) at EC 1.8 $mS.cm^{-1}$, pH adjusted to 6.0. The silicon element was sourced from Ultra 45 fertilizer from Manaseer Group (Jordan), which contains 44% SiO_2, the Ultra 45 fertilizer contains finely ground fertilizer with a maximum particle size of 45 µm. Although the intrinsic solubility of crystalline SiO_2 is low, the small particle size enhances surface area and dissolution rates, facilitating the formation of monosilicic acid ($Si(OH)_4$), the plant-available form of silicon. Moreover, the nutrient solution pH was maintained between 5.5 and 6.5 to enhance the stability and uptake of monosilicic acid. The nutrient solution was prepared once at the beginning of the experiment and was not replaced throughout the experimental period because the initial volume was sufficiently large relative to plant uptake, and visual monitoring indicated no significant reduction in solution level or signs of nutrient deficiency (e.g., chlorosis, stunted growth). Although no formal ion concentration analysis was performed during the trial, the relatively short growth cycle of lettuce and the moderate plant density minimized the risk of critical nutrient depletion. Silicon (Si) in the form of SiO_2 was added only once during the initial preparation of the nutrient solution at the designated concentrations. No additional Si was supplemented during the course of the experiment.

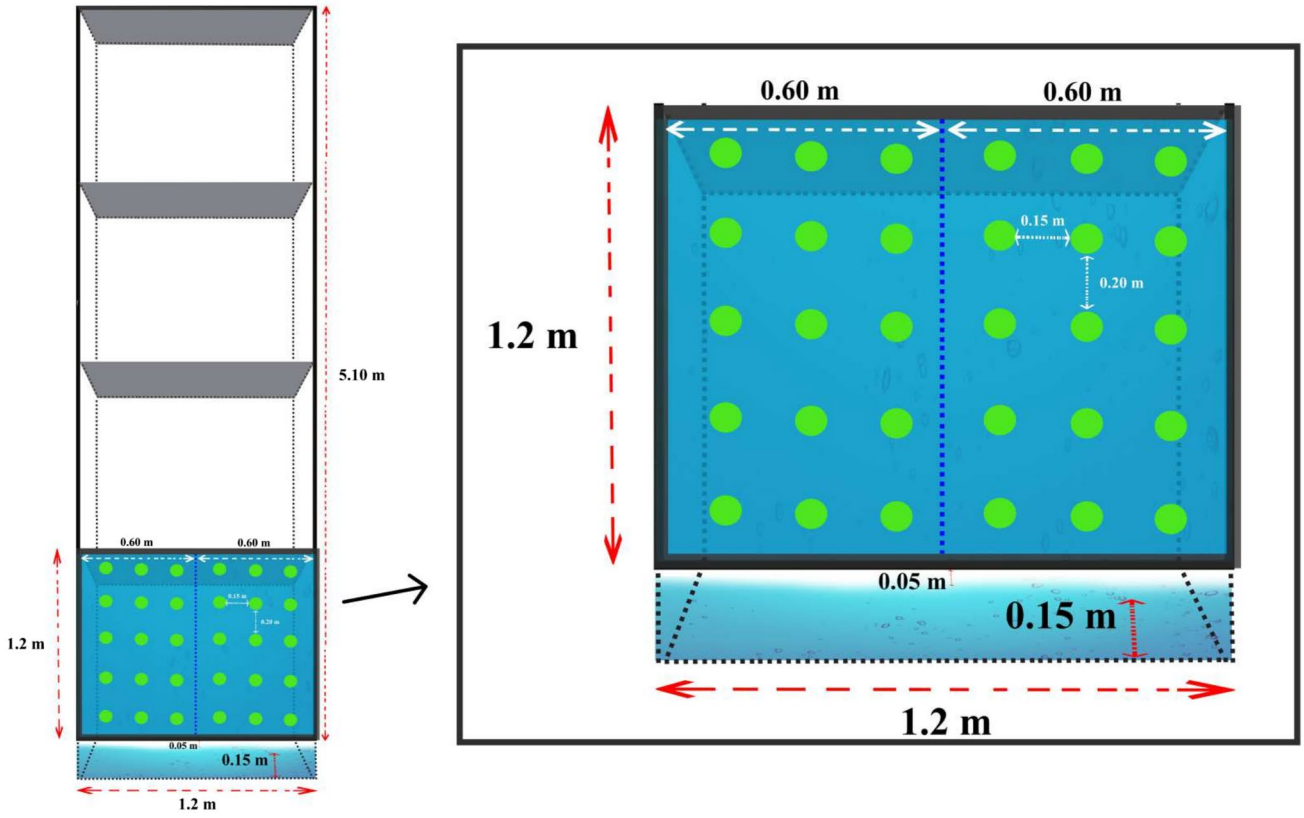

Fig. 1. The Schematic diagram for experimental concrete basins.

Field measurements

Microclimate measurements

Photosynthetically Active Radiation (PAR) was measured using a Sun System PAR Meter (HGC748205, Hawthorne Hydroponics LLC, China) inside the greenhouse. The device was installed at the same height as the lettuce plant in the center of the greenhouse and launched for a 30-min recording period. The readings were taken during the experiment at 6:00 AM and 6:00 PM, and the average PAR was 647.1 μmol/m^2/s. The relative humidity (RH) and air temperature were measured using the HOBO MX2301A Temp/RH Data Logger (Onset Computer Corporation, Bourne, MA, USA). Three data loggers were positioned at the beginning, center and the end of the greenhouse and set to a 10 min logging interval. The daily changes in the key climatic variables (air temperature, RH) are depicted in Fig. 2. Notably, no rainfall was recorded throughout the research period.

The diurnal fluctuations in temperature and relative humidity (RH) were recorded during the experiment (Fig. 2), the values of temperature consistently remained within the optimal ranges for lettuce growth, specifically between 15 and 25 °C. However, relative humidity (RH) occasionally dropped below optimal levels, with some daytime values falling below 40%. Such short-term fluctuations are common in passively ventilated greenhouse systems and were buffered by nighttime RH recovery. Lettuce plants are generally more sensitive to prolonged low RH rather than brief daily dips, and in this study, no symptoms of water stress, leaf wilting, or reduced biomass were observed. Moreover, since all treatments were exposed to the same environmental conditions, any minor RH-induced stress would have equally affected all groups, preserving the validity of treatment comparisons. Therefore, while RH fluctuations are acknowledged, they likely did not compromise the physiological integrity of the plants or the interpretation of silicon-related postharvest responses.

Nutrient solution measurements

Managing the EC value is crucial to ensure the plant receives the nutrients in the best possible conditions[17]. During the experiment, the electrical conductivity (EC) and pH changed due to lettuce plants' absorption of elements from the nutrient solution. Therefore, all experimental units' pH and EC of the nutrient solution were measured daily. The pH was measured using a portable pH meter (Walk lab Ti 9000, Trans Instruments, Singapore) and the pH was maintained between 5.5 and 6.5 using dilute nitric acid (HNO_3) or potassium hydroxide (KOH). The EC was measured using a portable electrical conductivity device (DDB-11A, Baoshishan, China).

Plant growth parameters

The following plant growth parameters were measured after crop harvest: plant height (PH), head circumference (HC), leaves number (LN), total fresh weight (TFW), shoot fresh weight (SFW), root fresh weight (RFW), root length (RL), stem diameter (SD), stem length (SL), shoot dry weight (SDW), and root dry weight (RDW) for lettuce plant. Using a balance, TFW, SFW, and RFW were measured immediately after harvest. SDW and RDW were measured after drying in the oven at 65 ℃ until they reached the constant weight[18,19]. PH, HC, SD, SL, and RL were measured using a meter. LN was measured by observation and counting.

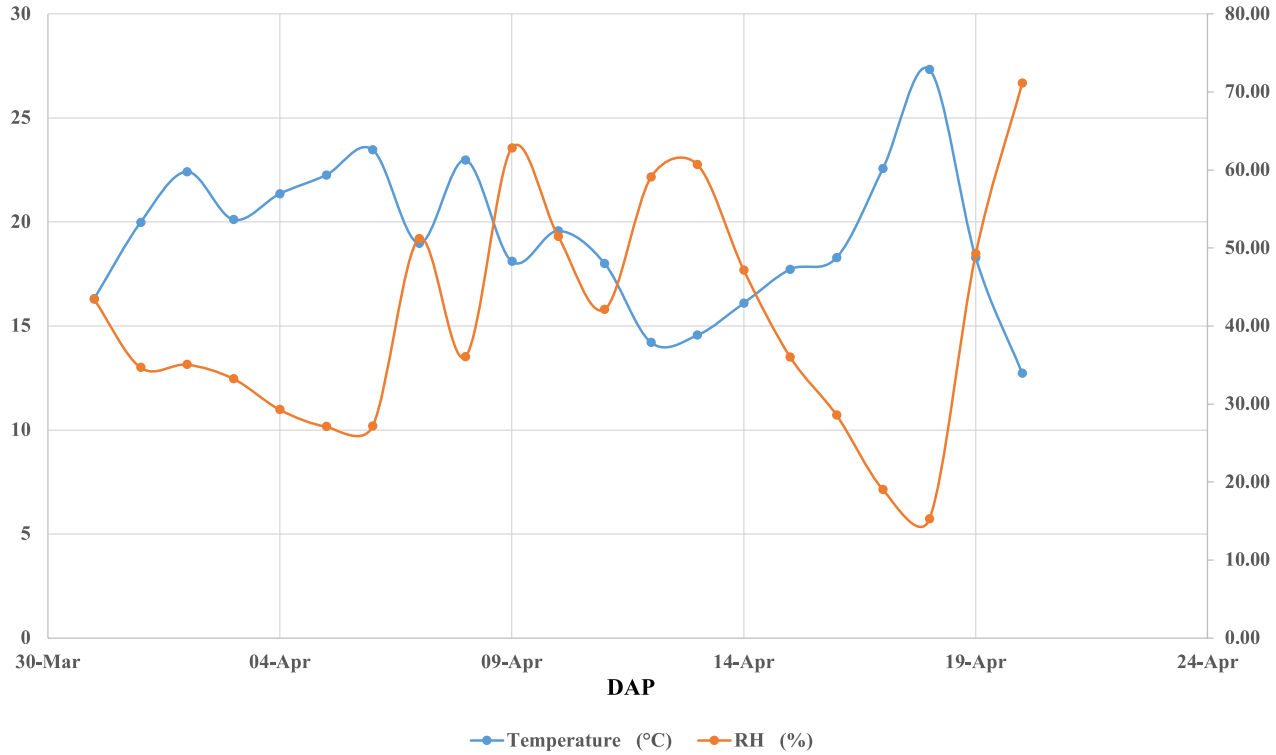

Fig. 2. Microclimatic weather data including air temperature (°C), relative humidity RH (%).

Physiological plant parameters

Shelf life and chlorophyll content

The shelf life of the lettuce was measured at room temperature and 4 °C after packing in perforated plastic bags. Immediately after harvesting, the chlorophyll content of fully expanded lettuce leaves was measured daily using a portable chlorophyll meter (SPAD-502; Konica Minolta Sensing, Osaka, Japan) without damaging the leaves until the acceptable limit was reached[20]. The chlorophyll content of lettuce leaves was determined on the 24th, 28th, 32nd, 36th, and 40th days after planting. Chlorophyll content was also measured daily after harvest to estimate the shelf life of lettuce at room temperature and a 4℃.

Sugar determination

The total soluble sugar content in lettuce leaves was determined using a digital portable Brix meter (BX-1, Trans Instruments, Japan), which measures the soluble solids content (SSC) and provides an indirect estimate of sugar concentration, expressed in degrees Brix (°Bx). To prepare the sample, fresh leaf tissue from each replicate was harvested and homogenized using a mortar and pestle. The homogenate was then transferred to a clean centrifuge tube and filtered through the Whatman No. 42 filter paper to remove particulate matter and obtain a clear extract. Care was taken to ensure that no air bubbles or residues remained in the extract to avoid measurement errors. Then, A few drops of the filtrate were carefully placed on the lens of the Brix meter, and the reading was recorded.

Total phenols determination

A 0.5 g of dry lettuce tissue was extracted using 100 mL methanol (HPLC grade), filtered through Whatman No. 42 filter paper, and shaken for 6 h at 125 rpm. The final volume was brought to 100 mL of methanol, then stored in the refrigerator at 4 ℃. The Folin-Ciocalteu colorimetric technique was used to measure extracts' total phenolic compound (TPC) concentration[21].

Briefly, gallic acid concentrations of 10, 20, 50, 100, 200, 400, and 600 mg L^{-1} were examined. To prepare the samples, 0.15 mL of the sample was transformed into a vial, and then 1.2 mL of 10% Folin-Ciocalteu reagent (FC) was added, followed by 2.4 mL of 10% Na_2CO_3 solution. The reaction must take place in complete darkness for one hour. Then, the absorbance at wavelength 760 nm was measured using a UV SpectroScan 50 spectrophotometer (Biotech Engineering Management, UK). The estimation of TPC was done in four replications, and the readings were computed using a calibration curve for gallic acid. Gallic acid equivalents (mg GAE/100 g on dry weight) were used to measure the total phenolic compound.

Antioxidant activity determination

The antioxidant activity was assessed by determining the scavenging stable DPPH free radicals. The stable 2,2-Diphenyl-picrylhydrazyl (DPPH) radical (Sigma, Steinheim, Germany) was utilized to measure the antioxidant activity of various extracts, according to Matthäus[22]. Briefly, 0.1 mL of methanol extracts were mixed with 0.2 mL of the DPPH solution in methanol (approximately 50 mg/100 mL). The combination was diluted to a final volume of 4.0 mL, after carefully combining the ingredients, the mixture was left to stand in a dark area for 45 min. Afterward, a UV SpectroScan 50 spectrophotometer (Biotech Engineering Management, UK) was used to detect the absorbance at 517 nm wavelength.

The following formula was used to express the tested samples' radical scavenging activity as a percentage of the free radicals that were inhibited %[23]:

$$Inhibition\,(\%) = \frac{(\text{absorbance of control} - \text{absorbance of sample})}{absorbance of control} \times 100$$

Plant nutrient content analysis

Plant samples preparation for analysis

Dry ashing was done at an ignition temperature of 550 °C to determine the concentration of elements. Briefly, the dry ash was done through the following steps: 0.5 g of dried lettuce was carefully weighed into porcelain crucibles, which were then placed in a cool muffle furnace. The temperature was gradually increased until reaching 550 °C, at which point ashing continued for an additional 5 h. After this, the muffle furnace was turned off, and after cooling, the porcelain crucibles were gently removed. The cooled ash was then mixed with a plastic rod after dissolving it in 5 mL increments of 2 N HCl. After 20 min, distilled water was added to dilute the mixture to 50 mL, and the resulting liquid was filtered through the Whatman No. 42 filter paper[24].

Determination of total plant N content

The total nitrogen content was determined in dry weight using the Kjeldahl method as described by Bremne [25], which included the three main operations of the Kjeldahl method: digestion, distillation, and titration. The Kjeldatherm nitrogen apparatus (UDK 149 Automatic Kjeldahl Nitrogen Protein Analyzer, Italy) was used.

Determination of phosphorus content

The phosphorous content of lettuce was determined following the Vanadate Molybdate yellow color method[26] after preparing dry ash samples using a spectrophotometer (PhotoLab 7600 UV–VIS, WTW GmbH, Germany). The absorbance was measured using a spectrophotometer set to 410 nm wavelength.

Determination of potassium and calcium content

After the plant extract solutions were prepared, the Flame Photometer (BWB XP 5 Channel Flame Photometer, UK) was calibrated, and it was used to measure the K at 767 nm wavelength[24], and the Ca at 622 nm wavelength[27].

Determination of magnesium content

To calculate the magnesium content in the lettuce extract, the calcium and magnesium content was first calculated using the titration method with 0.01 N EDTA[24]. After that, the magnesium content was calculated by the difference between the calcium and magnesium content together and the calcium content that was previously measured.

Determination of silicon content

The silicon content of lettuce was analyzed using the previously prepared plant extract[28]. The silicon content (SiO_2) was determined using a Silicon Test-kits (WTW Spectroquant test kits, WTW GmbH, Germany), and the concentrations were determined photometrically using a spectrophotometer (PhotoLab 7600 UV–VIS, WTW GmbH, Germany).

Briefly, a standard stock solution was prepared from silicon tetrachloride $SiCl_4$ (Sigma, Steinheim, Germany), and a series of standard solutions were prepared with concentrations of 20, 40, 60, 80, and 100 mg L^{-1}. After that, 5.0 mL of the extract samples were taken and placed in a test tube, 3 drops of Reagents (Si-1) (Sulfuric acid) were added and mixed, the samples were left for 3 min, then three drops of Reagent (Si-2) and 0.50 mL of Reagent (Si-3) (Methelaminophenol sulfate) were added in a test tube and mixed, the samples were left for 10 min. The samples were filled into the cell and measured by the spectrophotometer. The wavelength that was used to measure silicon was 665 nm. The silicon content of the plant was calculated using the following equation:

$$Siinplant\left(mg.g^{-1}\right) = \frac{mgSi\,(fromthecurve) \times 100ml \times 50ml\,(extract)}{aliquotvolume\,(ml) \times gofplantsample\,(ovendried) \times 1000}$$

Data statistical analysis

All data were subjected to one-way analysis of variance (ANOVA) using the statistical analysis software program R. When significant treatment effects were detected ($p \leq 0.05$), mean comparisons were performed using Tukey's Honest Significant Difference (HSD) test. Letters illustrated in the tables and figures indicate significant statistical differences between the means of treatments at probability level $p \leq 0.05$.

Results and discussion

Plant growth parameters

Table 1 presents the impacts of silicon addition at different concentrations in the lettuce nutrient solution. Introducing silicon into the lettuce nutrient solution resulted in a boost in the total fresh weight (TFW). The highest TFW (638.34 g) was achieved with a silicon concentration of 75 mg L^{-1}, surpassing the control treatment (542.09 g) (Table 1). Significant increase in TFW and SFW were observed when silicon was added at concentrations of 75 and 100 mg L^{-1}, as compared to both the control treatment and treatments with silicon concentrations of 25 and 50 mg L^{-1}. While there was a slight increase in SDW, RFW, and RDW, these increments were deemed insignificant in comparison to the control (Table 1).

These results could be explained by the ability of silicon to enhance plant vigor and strengthen cell walls, leading to increased water uptake and turgor pressure, which ultimately contributes to higher fresh weight without a corresponding increase in dry weight[18,29,30]. Moreover, Alayafi[14] reported that Si can be deposited in plant leaves which will reduce the transpiration rate and water loss through the cuticle due to its improved thickness. Conversely, Frasetya et al.[17] concluded that the application of silicon does not result in a significant alteration in fresh weight growth compared to the control. This variance could be due to the disparity in silicon sources. Frasetya et al.[17] used rice husk silica, whereas this study used silicon dioxide as a source of silicon.

Table 2 presents the effect of silicon addition at different concentrations in the lettuce nutrient solution on plant height, root length, head circumference, stem diameter, stem length, and leaves number. The results showed no significant differences between all treatments received silicon supplementation compared to the control.

These results could be explained by the fact that the lettuce height is affected by the received sunlight due to the weather conditions changes during the experimental period. Frasetya et al.[17] indicated that the average plant height of lettuce plants that receive full sunlight is 28.97 cm. Low light levels will affect plant height by reducing vegetative development. The use of rice husk silica extract on lettuce plant height did not have a significant effect[31,32].

Silicon concentrations	Total fresh weight (g)	Shoot fresh weight (g)	Shoot dry weight (g)	Root fresh weight (g)	Root dry weight (g)
Control (0 mg L^{-1})	542.1 ± 45.5b	451.7 ± 45.4b	33.8 ± 1.5	60.4 ± 3.1	5.1 ± 0.8
25 mg L^{-1}	534.2 ± 36.1b	445.0 ± 21.3b	33.6 ± 1.1	59.2 ± 2.5	3.2 ± 0.5
50 mg L^{-1}	521.7 ± 58.6b	432.5 ± 33.5b	31.4 ± 1.0	59.2 ± 2.8	4.6 ± 1.4
75 mg L^{-1}	638.3 ± 46.3a	546.7 ± 45.2a	34.9 ± 2.6	61.7 ± 1.2	5.6 ± 1.3
100 mg L^{-1}	633.2 ± 47.3a	536.9 ± 41.7a	35.4 ± 1.4	66.3 ± 0.8	6.7 ± 1.7

Table 1. Effect of silicon concentrations on the total fresh weight, shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight of the lettuce in raft hydroponic system. Values are means ± standard error. Means followed by different letters are significantly different at $p < 0.05$ according to the LSD test. Treatments with no letters are not significantly different.

Silicon concentrations	Plant height (cm)	Root length (cm)	Head circumference (cm)	Stem diameter (cm)	Stem length (cm)	Leaves number
Control (0 mg L^{-1})	24.6 ± 0.7	25.1 ± 3.0	42.2 ± 1.7	2.4 ± 0.0	12.6 ± 0.7	31 ± 1.6
25 mg L^{-1}	23.9 ± 0.8	21.6 ± 1.9	41.7 ± 1.6	2.2 ± 0.1	13.0 ± 0.9	30 ± 0.8
50 mg L^{-1}	23.4 ± 1.6	23.8 ± 3.3	41.2 ± 2.1	2.2 ± 0.1	11.9 ± 0.4	31 ± 1.8
75 mg L^{-1}	25.1 ± 0.6	27.1 ± 4.4	44.6 ± 0.6	2.3 ± 0.1	13.2 ± 0.6	33 ± 1.0
100 mg L^{-1}	25.7 ± 0.4	26.4 ± 4.0	43.9 ± 1.8	2.4 ± 0.1	13.2 ± 0.4	34 ± 0.8

Table 2. Effect of silicon concentrations on the plant height, root length, head circumference, stem diameter, stem length, and leaves number of the lettuce in a raft hydroponic system. Values are means ± standard error. Means followed by different letters are significantly different at $p < 0.05$ according to the LSD test. Treatments with no letters are not significantly different.

Silicon concentrations	Amount of sugar (BRIX units)	Total phenols (mg/100 g)	Antioxidants activity (Inhibition %)
Control (0 mg L^{-1})	5.1 ± 0.1	567.4 ± 49.0	19.6 ± 2.5
25 mg L^{-1}	5.5 ± 0.7	632.6 ± 83.9	18.6 ± 4.3
50 mg L^{-1}	5.3 ± 0.4	680.5 ± 99.8	19.7 ± 2.3
75 mg L^{-1}	5.0 ± 0.2	732.4 ± 3.8	20.7 ± 1.8
100 mg L^{-1}	6.1 ± 0.4	845.5 ± 60.0	24.6 ± 2.6

Table 3. Effect of silicon concentrations on the amount of sugar, total phenols, and antioxidant activity of the lettuce in raft hydroponic system. Values are means ± standard error. Means followed by different letters are significantly different at $p < 0.05$ according to the LSD test. Treatments with no letters are not significantly different.

This is consistent with what was mentioned in previous studies, that there were no significant differences when adding silicon to the number of lettuce leaves compared to not adding silicon[29]. The difference could be explained as in cases of biotic or abiotic stress, the element silicon can help plant growth and affect the number of leaves. In this study, there was no biotic or abiotic stress, and therefore the number of lettuce leaves was not affected by the addition of silicon.

Physiological parameters of lettuce

Amount of sugar

The amount of sugar in lettuce was measured using the BRIX device, which represents the amount of sugar in the liquid. The addition of silicon to the nutrient solution of lettuce plants was not significant. However, it showed a slight increase in the sugar content inside the leaves of the lettuce plant. This increase began at a concentration of 25 mg L^{-1} of silicon, where the sugar content was recorded 5.5 BRIX units. The maximum value of liquid sugar content was recorded at a silicon concentration of 100 mg L^{-1} (6.1 BRIX units), and the minimum value of liquid sugar content was recorded when the control treatment (5.1 BRIX units). These differences in the amount of liquid sugar in lettuce were not significant when compared with the control (Table 3).

Total phenols

Increasing the concentration of silicon in the lettuce nutrient solution at a concentration of 25 mg L^{-1} led to an increase in the total content of phenols as recorded (632.6 mg/100 g) compared to the control treatment, which was recorded as (567.4 mg/100 g), the increase began to appear gradually at a concentration of 50 mg L^{-1} (680.5 mg/100 g) and 75 mg L^{-1} (732.4 mg/100 g) until it reached the highest concentration of silicon 100 mg L^{-1}, which recorded the highest value of the total content of phenols (845.5 mg/100 g). These changes in all treatments were not statistically significant differences compared to the control treatment (Table 3).

These changes in the total phenols content could be explained by D'Imperio et al.[33] who mentioned in their research that silicon's defense systems generally involve the accumulation of lignin and phenolic compounds. Hogendorp[34] has reported that the formation of phenols and lignin is a result of silicon catalyzing an active defensive response process known as "systemic acquired resistance" (SAR). Silicon enhances protection against abiotic stress and increases phenols and production[33].

Antioxidants activity

The inhibition of antioxidants was slightly increased by adding silicon to the lettuce nutrient solution at a concentration of 25 mg L^{-1} (18.6%) compared to the control treatment (19.6%), but the inhibition of antioxidants gradually increases at concentrations of 50 mg L^{-1} (19.7%) and 75 mg L^{-1} (20.7%) until it reached the highest silicon concentration of 100 mg L^{-1}, which was recorded (24.6%). These minor changes in all treatments were not statistically significant differences compared to the control (Table 3).

These changes in antioxidant activity can be explained by Khanum et al.[35] who mentioned in their research that silicon can help plants' defense system by minimizing oxidative stress damage (An imbalance in the system

of oxidants and antioxidants towards the production of more oxidants) and changing the way antioxidant enzymes work.

Chlorophyll content

The effect of adding silicon at different concentrations on the chlorophyll content in lettuce leaves during the experiment is illustrated in Fig. 3. The chlorophyll content in lettuce leaves was measured on days 24, 28, 32, 36, and 40 days after planting (DAP) by a SPAD device. On the 24th day after planting (DAP), the highest chlorophyll content was in the silicon concentration treatment of 50 mg L^{-1} (51.8), and the lowest value was when the silicon concentration was 75 mg L^{-1} (46.3). These differences were not significant when compared to the control treatment (47.6). Likewise, also on the 28th DAP, the highest content of chlorophyll was in the silicon concentration treatment of 50 mg L^{-1} (57.5), and the lowest value when the silicon concentration was 75 mg L^{-1} (49), these differences were not significant when compared to the control treatment (54.3).

On the 32nd DAP, the highest content of chlorophyll was in the treatment of silicon concentration of 100 mg L^{-1} (52.6), and the lowest value when the treatment of silicon concentration of 25 mg L^{-1} (44.9), these differences were not significant when compared to the control treatment (45). Likewise, on the 36th DAP, the highest content of chlorophyll was in the silicon concentration treatment of 100 mg L^{-1} (55.5), and the lowest value when the silicon concentration of 25 mg L^{-1} (46.6), these differences were not significant when compared to the control treatment (51.3). As for the 40th DAP, the greatest content of chlorophyll in the treatment of silicon concentration was 25 and 75 mg L^{-1} (52.2), and the lowest value in the control treatment (49.2), these differences were not significant. Based on the above, the addition of silicon to the lettuce nutrient solution did not affect the chlorophyll content in lettuce leaves during the growing days (Fig. 3).

Chlorophyll is a key component of the photosynthetic system, which is in charge of collecting, dispersing, and converting light. Under stress conditions, it is typical to notice a significant drop in chlorophyll levels[36]. Under extreme stress, silicon treatment decreased gas exchange and total chlorophyll, indicating a reduction in the impact of stress on these parameters. As a consequence, adding Si to lettuce had a positive impact on salinity-related conditions[37]. Based on the above, the results of this research can be explained by the fact that silicon did not affect the chlorophyll content in lettuce leaves because there were no abiotic stresses among the treatments.

Shelf life

The SPAD index values were used to assess how the edible tissues' quality changed while being stored at 4 ℃ and room temperature after harvest. The decrease in the values of the SPAD index indicates a degradation of chlorophyll content, which indirectly indicates the loss of the green color[38]. The marketable SPAD index for lettuce leaves indicates the minimum acceptable green color change that can be perceived by consumers[38].

The degradation of chlorophyll content that drastically reduces storage life occurs post-harvest and is mostly caused by physiological and/or biochemical processes caused after harvest[39]. The type and cultivar affect lettuce's quality and shelf life[40].

Shelf life at room temperature

Figure 4 shows the degradation of chlorophyll content with time after the harvest period in lettuce at room temperature, expressed in SPAD index values. During the first three days after harvest (DAH), lettuce's

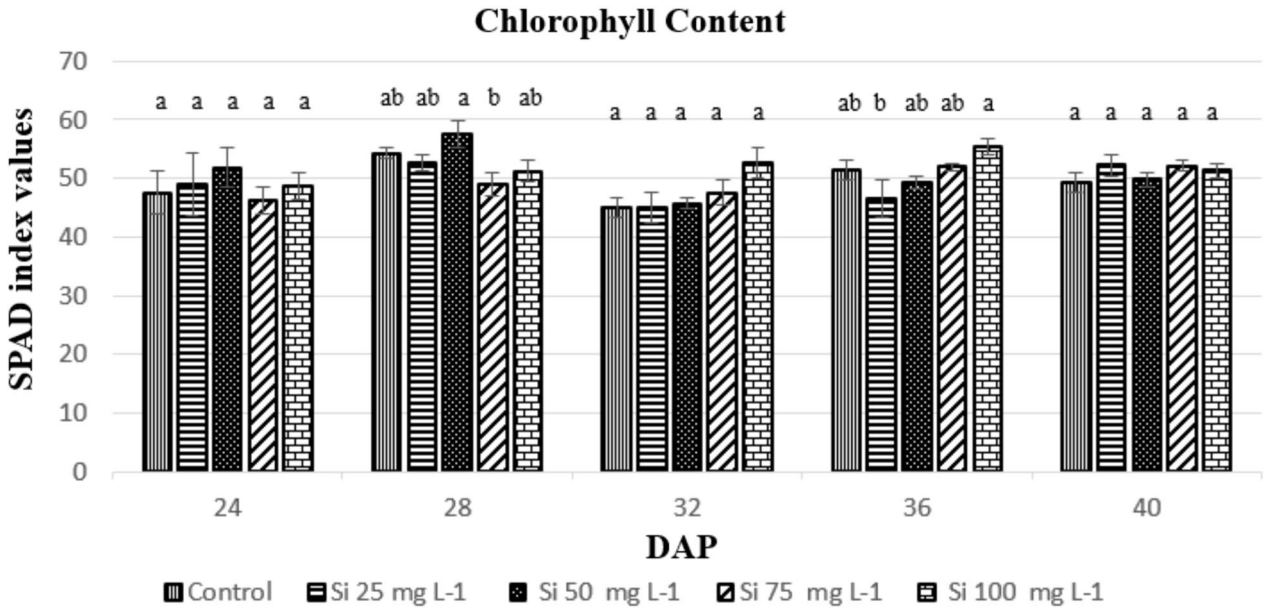

Fig. 3. The effect of silicon concentrations on chlorophyll content in lettuce with days after planting (DAP), expressed in SPAD index values.

chlorophyll content degradation rate was steady and slow. The chlorophyll content degradation rates were (10.5, 13.7, 16.6, 22.6, and 13.9%) in silicon concentration treatments (0, 25 50 75, and 100 mg L^{-1}), respectively. On the fourth DAH, the chlorophyll content degradation rate doubled to reach (27.8, 33.5, 30.4, 45.4, and 33.7%) in the silicon concentration parameters (0, 25 50 75, and 100 mg L^{-1}), respectively. On the seventh DAH, the rate of degradation in the chlorophyll content increased more and more clearly until the rates of degradation reached (75, 74.5, 73.1, 74.5, and 76.9%) in the silicon concentration treatments (0, 25 50 75, and 100 mg L^{-1}), respectively. On the ninth DAH, the chlorophyll content in lettuce reached the lowest values, as the degradation rates reached (94.9, 95.7, 95, 97.5, and 97.7%) in silicon treatments (0, 25 50 75, and 100 mg L^{-1}), respectively. The chlorophyll content measurements were stopped after the ninth DAH for lettuce plants stored at room temperature because the reading of the SPAD device reached 1 SPAD unit. The values of the degradation rate are equivalent to the values of the SPAD index.

There was no effect of adding silicon fertilizer to the nutrient solution of lettuce plants on the shelf life of lettuce plants at room temperature after harvest. The shelf life of lettuce plants at room temperature was 9 days in all silicon treatments compared with the control treatment. This is consistent with what Frasetya et al., (2021) showed in their study, where they observed that the shelf life of the lettuce plants at room temperature was unaffected by silicon fertilization.

Shelf life at 4 ℃

The rate of deterioration in the chlorophyll content in the lettuce was evaluated when storing it at a temperature of 4 ℃ by measuring the values of the SPAD Index as an indicator of the shelf life. Figure 5 shows the deterioration of the chlorophyll content in the days after harvesting (DAH) with the storage at 4 ℃, expressing the values of the SPAD index.

The decrease in the values of the SPAD index (chlorophyll content) began gradually with time in all treatments. During the first five days after harvesting (DAH), the rates of degradation in chlorophyll content were 15.8, 19.6, 13.0, 8.3, and 8.4% in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1}, respectively. On the tenth DAH, the percentage of degradation in chlorophyll content increased to reach 40, 32.1, 26.8, 19.8, and 8.4% in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1}, respectively. We notice a significant increase in the rate of degradation of chlorophyll content in the control treatment compared to other treatments, which indicates that there was a possible effect of adding silicon fertilizer to the nutrient solution of lettuce on the shelf life.

On the 15th DAH, the degradation in the chlorophyll content was 72.7, 54.6, 45.6, 53, and 30% in silicon concentration transactions 0, 25, 50, 75, and 100 mg L^{-1}, respectively. On the 20th DAH, the degradation rate increased to 81.2, 64.0, 72.6, 59.8, and 45.7% in silicon concentration transactions 0, 25, 50, 75, and 100 mg L^{-1}, respectively.

Figure 6 shows pictures of lettuce samples in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1} at 19 DAH in measuring the shelf life of lettuce at a temperature of 4 °C. The difference in the rate of degradation of chlorophyll content between the treatments was also clear visually, we note the difference in the rate of loss of green color between the treatments. The higher the silicon concentration, the slower the rate of chlorophyll degradation and the slower the green color loss.

On the 25th DAH, the degradation in the chlorophyll content was 95.5, 79.1, 80.3, 73.8, and 64% in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1}, indicating the end of the shelf life (because the reading of the SPAD device reached 1 SPAD unit) of lettuce in the control treatment (25 days) while the shelf life of the other treatments remains continuous. On the 30th DAH, the percentage of degradation in chlorophyll content was 87.4, 89.1, 83.6, and 71.5% in the silicon concentration parameters 25, 50, 75, and 100 mg L^{-1}, respectively.

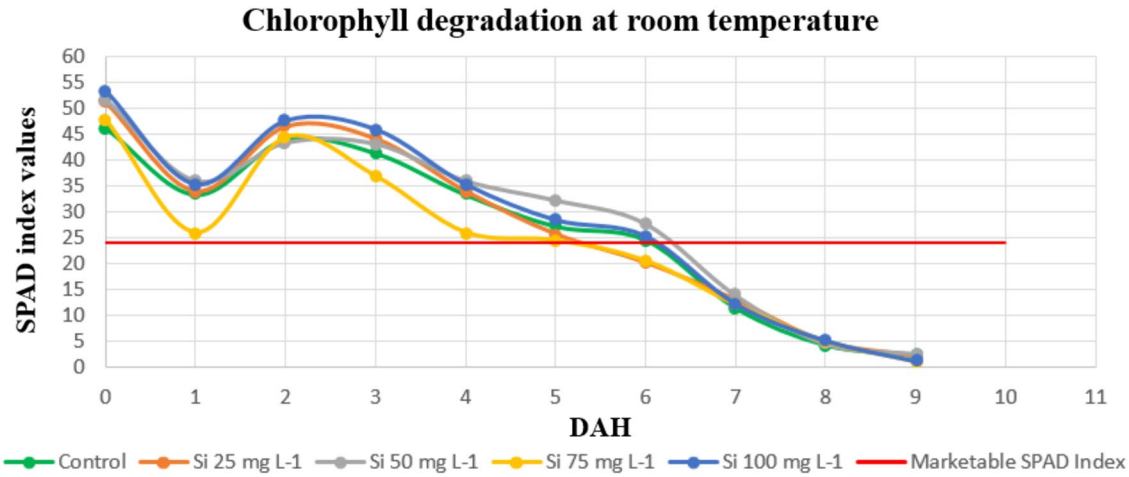

Fig. 4. The effect of silicon concentrations on the degradation of chlorophyll content in days in lettuce at room temperature expressed in SPAD index values.

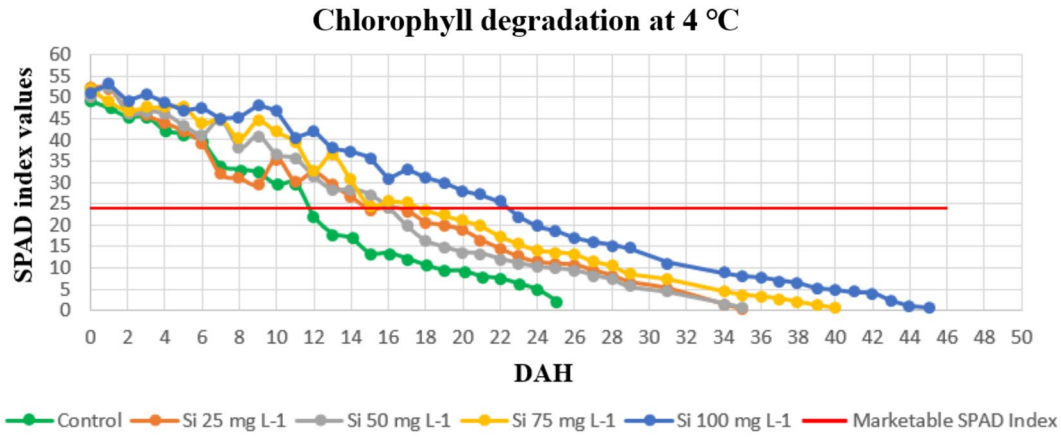

Fig. 5. The effect of silicon concentrations on the deterioration of chlorophyll content in lettuce with DAH at 4 °C, expressed in SPAD index values.

Fig. 6. lettuce samples in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1} at 19 DAH in measuring the shelf life of lettuce at a temperature of 4 °C.

On the 35th DAH, the percentage of degradation in chlorophyll content was 99.5, 98.9, 92.9, and 84.5% in the silicon concentration treatments 25, 50, 75, and 100 mg L^{-1}, respectively, which indicates the end of the shelf life of lettuce in the silicon concentration treatment of 25 and 50 mg L^{-1} (because the reading of the SPAD device reached 1 SPAD unit), which was 35 days. On the 40th DAH, the percentage of degradation in chlorophyll content was 98.8, and 90.6% in the silicon concentration treatments 75, and 100 mg L^{-1}, respectively, which indicates the end of the shelf life (because the reading of the SPAD device reached 1 SPAD unit) of lettuce in the treatment of silicon concentration 75 mg L^{-1}, which was 40 days. On the 45th DAH, the percentage of degradation in the chlorophyll content in the silicon concentration treatment was 100 mg L^{-1} 98.9%, which indicates that the shelf life (because the reading of the SPAD device reached 1 SPAD unit) of lettuce in this treatment has ended (45 days). The values of the degradation rate are equivalent to the values of the SPAD index.

The above results can be summarized through Table 4, which represents the shelf life of lettuce in days, which was stored at 4 ℃, as follows.

The control group (0 mg L^{-1} Si) maintained acceptable postharvest quality for 25 days, while increasing Si concentrations extended this to 35 days (25 and 50 mg L^{-1}), 40 days (75 mg L^{-1}), and up to 45 days at 100 mg L^{-1}. These values correspond to shelf-life increases of 40%, 60%, and 80%, respectively (Table 4) compared to the control as reference.

The observed shelf-life and visual quality enhancement of Si-treated lettuce can be attributed to several physiological mechanisms. Silicon, absorbed as monosilicic acid, is translocated to the shoots where it polymerizes beneath the cuticle, forming a cuticle–silica double layer. This structure reduces cuticular water loss by lowering permeability and reinforcing the epidermal barrier[9,41]. Furthermore, silicon has been reported to delay leaf senescence by modulating cytokinin biosynthesis, suppressing senescence-associated genes and maintaining chlorophyll content[42]. These combined effects contribute to improved water retention and prolonged shelf-life in lettuce. The beneficial effects of silicon observed in this study may be partially attributed to its role in reinforcing plant biochemical defenses. Silicon is known to stimulate lignin biosynthesis, which enhances cell wall rigidity and reduces tissue permeability — properties that are particularly important for maintaining postharvest quality in leafy vegetables[41].

In conclusion, adding silicon fertilizer at a concentration of 25, 50, 75, and 100 mg L^{-1} can increase the shelf life of lettuce by 40, 40, 60, and 80%, respectively, compared to the control treatment. Thus, since the refrigerator temperature was 4 °C and the relative humidity (RH) was more than 95% generally, these conditions helped to increase the shelf life of lettuce when storing it at a temperature of 4 ℃. These results are consistent with the results obtained by Gottardi et al.[38] who found that including Si as part of the nutrient solution can slow down chlorophyll breakdown, extending the shelf life of these edible tissues.

Marketable SPAD index of lettuce at 4 ℃

Regardless of treatments, the SPAD index values gradually reduced throughout, indicating that the leaves are becoming less green, resulting in a drop in the amount of chlorophyll[43]. The shelf life of lettuce at 4 ℃ was evaluated based on changes in the SPAD index value due to the significance of lettuce color on its overall sensory acceptability[44]. The acceptable limit (marketable SPAD index) was determined by the SPAD index value linked with the smallest color shift that consumers might be able to detect[38].

The marketable limit for the SPAD value was 24 SPAD index values of leaf lettuce, based on the minimum acceptable limit change in green color potentially perceivable by the consumers. We note that the shelf life of the marketable index of SPAD for lettuce in the control treatment was approximately 12 DAH, and at a concentration of 25, 50, 75, and 100 mg L^{-1} of silicon, it was 15, 16, 18, and 22 DAH, respectively (Fig. 5). This means that when the silicon concentrations in the treatments were 25, 50, 75, and 100 mg L^{-1}, the shelf life of the lettuce marketable index of SPAD increased by 25, 33.3, 50, and 83.3%, respectively compared to the control. This can also be seen in Fig. 6, which represents lettuce samples in silicon concentration treatments 0, 25, 50, 75, and 100 mg L^{-1} at 19 DAH in measuring the shelf life of lettuce at a temperature of 4 ℃.

Plant nutrients content

The effect of adding different concentrations of silicon on lettuce leaf nutrients is depicted in Table 5. The addition of silicon fertilizer to the lettuce nutrient solution did not affect the total nitrogen content. The maximum value of nitrogen (3.74%) was recorded in the silicon concentration treatment of 75 mg L^{-1}, while the minimum value of 3.57% was recorded in the silicon concentration of 100 mg L^{-1}. These differences were not significant compared to the control 3.70% (Table 5). This is consistent with Olle[45] that the nitrogen content was not affected by the addition of silicon to the lettuce nutrient solution.

When silicon fertilizer was added to the lettuce nutrient solution at a concentration of 100 mg L^{-1}, the phosphorus content of the lettuce (5.92 mg/g) significantly increased compared to the control treatment (4.76 mg/g), but the phosphorus content of the other silicon treatments was unaffected. The percentage increase in the phosphorus content at a concentration of 100 mg L^{-1} was 24.37% compared to the control (Table 5). This is consistent with Olle research[46] where phosphorus content in iceberg lettuce transplants was 25% greater in the Si variation than in the control. This could be explained by the competing of Si with P for binding sites on root surfaces, maintaining P in soluble forms rather than precipitating with cation[45,47,48]. Although competition between silicate and phosphate ions for root uptake sites has been reported, particularly in soil systems, such antagonism is less pronounced in hydroponic conditions where P remains highly available. In fact, silicon can improve P uptake by competing with cations like Ca^{2+} and Fe^{3+}, which otherwise precipitate phosphate into insoluble forms[47,49]. Additionally, Si has been shown to enhance the release of organic acids such as malate

Silicon concentrations	Shelf life in days	Percentage increase in shelf life
Control (0 mg L^{-1})	25	
25 mg L^{-1}	35	40%
50 mg L^{-1}	35	40%
75 mg L^{-1}	40	60%
100 mg L^{-1}	45	80%

Table 4. Effect of silicon concentration on the shelf life of lettuce in days and percentage increase at 4 °C.

Silicon concentrations	% Total nitrogen	Phosphorus (mg/g)	Potassium (mg/g)	Calcium (mg/g)	Magnesium (mg/g)	Silicon (mg/g)
Control (0 mg L^{-1})	3.7 ± 0.1	4.8 ± 0.2a	43.7 ± 3.4	2.8 ± 0.5	18.7 ± 0.7	0.0 ± 0.0c
25 mg L^{-1}	3.7 ± 0.1	4.3 ± 0.3a	43.9 ± 3.0	2.6 ± 0.5	17.9 ± 0.9	17.7 ± 0.3b
50 mg L^{-1}	3.7 ± 0.1	4.4 ± 0.1a	48.96 ± 1.8	3.7 ± 0.2	17.5 ± 0.7	17.9 ± 0.7b
75 mg L^{-1}	3.7 ± 0.1	4.6 ± 0.1a	47.39 ± 2.2	3.8 ± 0.1	17.1 ± 0.5	19.0 ± 0.2b
100 mg L^{-1}	3.6 ± 0.1	5.9 ± 0.5b	46.29 ± 0.8	3.5 ± 0.3	13.3 ± 0.4	22.7 ± 0.6a

Table 5. The effect of adding different concentrations of silicon on lettuce leaf nutrients. Values are means ± standard error. Means followed by different letters are significantly different at $p < 0.05$ according to the LSD test. Treatments with no letters are not significantly different.

and citrate from roots, which help solubilize phosphate in the rhizosphere[48]. These synergistic effects likely contributed to the elevated phosphorus concentrations measured in Si-treated lettuce plants.

The addition of silicon fertilizer to the nutrient solution of lettuce did not affect the potassium content. The maximum value of potassium content (48.96 mg/g) was recorded in the treatment of silicon concentration 50 mg L^{-1}, while the minimum value (43.71 mg/g) was recorded in the control (Table 5). However, these differences were not significant compared to the control. Similarly, the potassium content in lettuce leaves dry matter was not affected by silicon treatment[45].

The addition of silicon fertilizer to the lettuce nutrient solution had no impact on the amounts of calcium and magnesium in the leaves (Table 5). Similarly, the magnesium content in lettuce was not statistically different when silicon was added to the nutrient solution[45]. Conversely, on plants treated with Si, the amounts of calcium and magnesium in the dry matter of the lettuce leaves were higher[41]. The lack of a statistically significant effect of silicon on K, Ca, and Mg uptake contrasts with some earlier studies that reported Si-enhanced mineral accumulation in leafy greens. In our experiment, slight increases in K and Ca concentrations were observed under higher Si treatments (Table 5), but these did not reach statistical significance. There are two possible reasons for this difference. First, the form of silicon used may influence plant response: previous studies often applied monosilicic acid, a highly soluble form, whereas our study used silicon dioxide (SiO_2). Second, the method of application could play a role. While prior research frequently involved foliar spraying, our approach involved adding Si to the root-zone nutrient solution, which may affect uptake kinetics and translocation. In contrast to these nutrients, phosphorus availability is more sensitive to ionic interactions and solubility dynamics. Silicon has been shown to enhance P uptake by promoting organic acid exudation and reducing P precipitation in solution[48]. These factors likely contributed to the observed increase in P content without corresponding significant changes in K, Ca, or Mg.

The addition of silicon fertilizer to the lettuce nutrient solution led to the accumulation of silicon within the lettuce leaves. The silicon concentration in the control treatment was zero because the silicon element was not added to the nutrient solution, nevertheless, when the treatments had silicon concentrations of 25, 50, 75, and 100 mg L^{-1} in the nutrient solutions, the silicon content in the leaves was 17.70, 17.87, 19.00, and 22.71 mg/g, respectively (Table 5). The differences in silicon content in lettuce leaves were significant in all treatments 25, 50, 75, and 100 mg L^{-1} compared with the control. There were no significant differences in silicon content in lettuce leaves at treatments 25, 50, and 75 mg L^{-1}. There were significant differences in the silicon content in lettuce leaves between the treatments of 25, 50, and 75 mg L^{-1} when compared with the silicon concentration treatment of 100 mg L^{-1}.

This indicates that silicon absorption inside plant tissues increased as silicon concentration increased in the lettuce plants' nutrition solution. These increases in silicon content in plant tissues improved the growth of lettuce plants with the addition of silicon to the nutrient solution, and this explains the increase in the previously mentioned growth parameters, such as LN, TFW, SFW, SDW, and SL. The maximum value of silicon absorption and accumulation inside the lettuce leaf tissues was in the silicon concentration treatment of 100 mg L^{-1} (22.71 mg/g). This is consistent with what Kleiber et al.[50] mentioned in their study that the treatment with the most concentration of Si nutrition demonstrated the highest Si absorption. The amount of silicon absorbed relies on its concentration in the root zone[51]. This could be explained by the direct root-solution contact and maintaining optimal pH, which preserves Si bioavailability[38].

Silicon in the lettuce crop had an impact on some nutrients' uptake and distribution while not affecting others[52]. This is also consistent with the current research; the silicon treatment improved some nutrient absorption (phosphorus) while not affecting other nutrient absorption (nitrogen, potassium, calcium, and magnesium).

Conclusion

This study demonstrates that adding silicon at specific concentrations, particularly 75 mg L^{-1}, enhances lettuce's total fresh weight and significantly extends its shelf life when stored at 4 °C. While other growth parameters were unchanged, Si notably improved phosphorus absorption. These findings recommend applying silicon in nutrient solutions to optimize growth and post-harvest preservation in hydroponic lettuce cultivation. Future research should investigate silicon's broader role in stress resistance and nutrient dynamics to further support sustainable hydroponic agriculture.

Data availability

Data is provided within the manuscript.

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References

1. Shi, M. et al. Phytochemicals, nutrition, metabolism, bioavailability, and health benefits in lettuce—A comprehensive review. *Antioxidants* **11**, 1158 (2022).
2. Varzakas, T. et al. Aquaphotomics monitoring of lettuce freshness during cold storage. *Foods* **12**, 258 (2023).
3. Meselmani, M., Albalasmeh, A. & Mahmoud, K. Hydroponics: review paper. *Nat. Appl. Sci. Ser.* **1**, 13–30 (2023).
4. Manzocco, L. et al. Influence of hydroponic and soil cultivation on quality and shelf life of ready-to-eat lamb's lettuce (Valerianella locusta L. Laterr). *J. Sci. Food Agric.* **91**, 1373–1380 (2011).
5. Zargar, S. M., Mahajan, R., Bhat, J. A., Nazir, M. & Deshmukh, R. Role of silicon in plant stress tolerance: opportunities to achieve a sustainable cropping system. *3 Biotech* **9**, 1–16 (2019).
6. Misra, V. et al. Silicon as a beneficial nutrient for productivity augmentation and abiotic/biotic stress tolerance in sugarcane. *Biocatal. Agric. Biotechnol.* **54**, 102944 (2023).
7. Epstein, E. Epstein_1999_Silicon. *Annu. Rev. Plant Physiol.* **50**, 641–664 (1999).
8. Coskun, D., Deshmukh, R., Shivaraj, S. M., Isenring, P. & Bélanger, R. R. Lsi2: A black box in plant silicon transport. *Plant Soil* **466**, 1–20 (2021).
9. Samuels, A. L., Glass, A. D. M., Ehret, D. L. & Menzies, J. G. The effects of silicon supplementation on cucumber fruit: Changes in surface characteristics. *Ann. Bot.* **72**, 433–440 (1993).
10. Epstein, E. Silicon. *Annu. Rev. Plant Biol.* **50**, 641–664 (1999).
11. Ma, J. F. & Yamaji, N. Silicon uptake and accumulation in higher plants. *Trends Plant Sci.* **11**, 392–397 (2006).
12. Mitani, N. & Jian, F. M. Uptake system of silicon in different plant species. *J. Exp. Bot.* **56**, 1255–1261 (2005).
13. Khan, N. A., Pál, M., Noh, K. & Jeong, B. R. Silicon supplementation alleviates adverse effects of ammonium on Ssamchoo grown in home cultivation system. *Plants* **11**, 2882 (2022).
14. Alayafi, A. H., Al-Solaimani, S. G. M., Abd El-Wahed, M. H., Alghabari, F. M. & Sabagh, A. E. Silicon supplementation enhances productivity, water use efficiency and salinity tolerance in maize. *Front. Plant Sci.* **13**, 953451 (2022).
15. Sun, S. et al. Silicon enhances plant resistance to Fusarium wilt by promoting antioxidant potential and photosynthetic capacity in cucumber (Cucumis sativus L.). *Front. Plant Sci.* **13**, 1011859 (2022).
16. Helms, K. M., Dickson, R. W., Bertucci, M. B., Rojas, A. A. & Gibson, K. E. Metal micronutrient and silicon concentration effects on growth and susceptibility to pythium root rot for hydroponic lettuce (Lactuca sativa). *Horticulturae* **9**, 670 (2023).
17. Frasetya, B., Subandi, M. & Sofiani, I. H. The effect of silica source concentration to improve growth of Lactuca sativa L. on floating hydroponic system. *IOP Conf. Ser. Earth Environ. Sci.* **782**, 042054 (2021).
18. Othman, A. J. et al. Dataset on the effect of foliar application of different concentrations of silicon dioxide and organosilicon compounds on the growth and biochemical contents of oak leaf lettuce (Lactuca sativa var. crispa) grown in phytotron conditions. *Data Brief* **38**, 107328 (2021).
19. D'Imperio, M. et al. NaCl stress enhances silicon tissue enrichment of hydroponic "baby leaf" chicory under biofortification process. *Sci. Hortic.* **235**, 258–263 (2018).
20. Madar, Á. K. & Hájos, M. T. Evolution of quality parameters of different lettuce (Lactuca sativa L.) varieties under unheated plastic tunnel. *Acta Univ. Sapientiae Agric. Environ.* **13**, 88–99 (2021).
21. Singleton, V. L. & Rossi, J. A. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *Am. J. Enol. Vitic.* **16**, 144–158 (1965).
22. Matthäus, B. Antioxidant activity of extracts obtained from residues of different oilseeds. *J. Agric. Food Chem.* **50**, 3444–3452 (2002).
23. Brand-Williams, W., Cuvelier, M. E. & Berset, C. Use of a free radical method to evaluate antioxidant activity. *LWT Food Sci. Technol.* **28**, 25–30 (1995).
24. Sun, J. T. et al. Development of ceramic friction pairs applied to large space manipulator brake. *Huanan Ligong Daxue Xuebao J. S. China Univ. Technol. (Nat. Sci.)* **40**, 83–89 (2012).
25. Bremner, J. M. Determination of nitrogen in soil by the Kjeldahl method. *J Agric Sci.* **55**(1), 11–33 (1960).
26. Olsen, S.R., Cole, C., Watanabe, F., & Dean, L. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. US Department of Agriculture. Circular, 939 (1954).
27. Schrenk, W. G., Lentz, C. F. & Glendening, B. L. Determination of calcium using the flame photometer as an excitation source for the spectrograph. *Kansas Acad. Sci.* **124**, 420–425 (1951).
28. Montesano, F. F. et al. Green bean biofortification for Si through soilless cultivation: plant response and Si bioaccessibility in pods. *Sci. Rep.* **6**, 1–9 (2016).
29. Pozo, J., Urrestarazu, M., Morales, I. & Jessica, S. Effects of silicon in the nutrient solution for three horticultural plant families on the vegetative growth, cuticle, and protection against Botrytis cinerea. *HortScience* **50**, 1447–1452 (2015).
30. Garibaldi, A., Gilardi, G., Cogliati, E. E. & Gullino, M. L. Silicon and increased electrical conductivity reduce downy mildew of soilless grown lettuce. *Eur. J. Plant Pathol.* **132**, 123–132 (2012).
31. Frasetya, B., Subandi, M., Ginandjar, S. & Setiati, Y. The effect of rice husk silicate extract on plant height, electrical conductivity and pH of paddy hydroponics. *IOP Conf. Ser. Earth Environ. Sci.* **334**, 012026 (2019).
32. Frasetya, B., Rahmatullah, P. & Subandi, M. Application of rice husk silicate extract to increment growth of indoor hydroponic lettuce. *IOP Conf. Ser. Earth Environ. Sci.* **542**, 012025 (2020).
33. D'Imperio, M. et al. Silicon biofortification of leafy vegetables and its bioaccessibility in the edible parts. *J. Sci. Food Agric.* **96**, 751–756 (2016).
34. Hogendorp, B. K. Effects of silicon-based fertilizer applications on the development and reproduction of insect pests associated with greenhouse-grown crops. PhD thesis, University of Illinois at Urbana-Champaign (2008).
35. Khanum, S., Rahman, A., Roghayeh, M. T., Abdel, K. & Al, R. Beneficial effects of supplementation silicon on the plant under abiotic and biotic stress. *SILICON* **9**, 2481–2491 (2022).
36. Rastogi, A. et al. Impact of warming and reduced precipitation on photosynthetic and remote sensing properties of peatland vegetation. *Environ. Exp. Bot.* **160**, 71–80 (2019).
37. Souza, H. D., Neto, L., Guimarães, M. D. A. & Mesquita, R. O. Silicon supplementation induces physiological and biochemical changes that assist lettuce salinity tolerance. *SILICON* **15**, 4075–4089 (2020).
38. Gottardi, S. et al. Beneficial effects of silicon on hydroponically grown corn salad (Valerianella locusta (L.) Laterr) plants. *Plant Physiol. Biochem.* **56**, 14–23 (2012).
39. Wills, R. & Golding, J. *Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables* (UNSW press, 2016).
40. Lopez-galvez, G., Saltveit, M. & Cantwell, M. The visual quality of minimally processed lettuces stored in air or controlled atmosphere with emphasis on romaine and iceberg types. *Postharvest Biol. Technol.* **8**, 179–190 (1996).

41. Liang, Y., Nikolic, M., Bélanger, R., Gong, H. & Song, A. Silicon in agriculture: From theory to practice. In *Silicon in Agriculture: From Theory to Practice* (Springer, 2015).
42. Markovich, O. et al. Silicon promotes cytokinin biosynthesis and delays senescence in Arabidopsis and Sorghum. *Plant Cell Environ.* **40**, 1189–1196 (2017).
43. Netto, A. T., Campostrini, E., De Oliveira, J. G. & Bressan-Smith, R. E. Photosynthetic pigments, nitrogen, chlorophyll a fluorescence and SPAD-502 readings in coffee leaves. *Sci. Hortic.* **104**, 199–209 (2005).
44. Ragaert, P., Verbeke, W., Devlieghere, F. & Debevere, J. Consumer perception and choice of minimally processed vegetables and packaged fruits. *Food Q. Prefer.* **15**, 259–270 (2004).
45. Olle, M. Short communication: The effect of silicon on the organically grown iceberg lettuce growth and quality. *Agraarteadus* **28**, 82–86 (2019).
46. Olle, M. Short communication: The effect of silicon on the organically grown leaf lettuce growth and quality. *Agric. Sci.* **30**, 82–86 (2017).
47. Ma, J. & Takahashi, E. *Soil, Fertilizer, and Plant Silicon Research in Japan* (Elsevier, 2002).
48. Kostic, L., Nikolic, N., Bosnic, D., Samardzic, J. & Nikolic, M. Silicon increases phosphorus (P) uptake by wheat under low P acid soil conditions. *Plant Soil* **419**, 447–455 (2017).
49. Uhuegbue, P. O., Stein, M., Kalbitz, K. & Schaller, J. Silicon effects on soil phosphorus availability: results obtained depend on the method used. *Front. Environ. Sci.* **12**, 1461477 (2024).
50. Kleiber, T., Krzesiński, W., Przygocka-cyna, K. & Spiżewski, T. The response of hydroponically grown lettuce under Mn stress to differentiated application of silica sol. *J. Elem.* **20**, 609–619 (2015).
51. Lee, J., Park, J. & Han, K. Effects of potassium silicate on growth, photosynthesis, and inorganic ion absorption in cucumber hydroponics. *J. Korean Soc. Hortic. Sci.* **41**, 480–484 (2000).
52. Greger M, Landberg T, Vaculik M, Lux A. Silicon influences nutrient status in plants. In *Proceedings of the 5th International Conference on Silicon in Agriculture, Beijing, China*. 57–58. (2011).

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A.A.A. Conceptualization, investigation, methodology, data analysis, funding acquisition, visualization, project management, writing—original draft preparation. A.K.A. investigation, methodology, data analysis, visualization, writing—review and editing. I.M. data curation, writing—review and editing. O.M. writing—review and editing and M.A writing—review and editing.

Declarations

Competing interests

The authors declare no competing interests.

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