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Temperature-Dependent Effects of Foliar Applications of Potassium Silicate on Strawberry Growth, Yield, and Fruit Quality

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Abstract. **Strawberry plants are sensitive to high temperatures, resulting in suppressed vegetative growth and reduced fruit quality. Potassium silicate (K_2SiO_3) is recognized for its potential to mitigate heat stress and increased reproductive growth, but its efficacy under varying temperature regimes remains poorly documented. This study investigated the effects of foliar application of K_2SiO_3 at three doses (0 mg·L^{-1} or control, 50 mg·L^{-1}, and 100 mg·L^{-1}) and three temperatures (20 °C, 24 °C, and 28 °C) on 'Cabrillo' strawberry plants in indoor farming conditions across two fruit harvest cycles. At 28 °C, K_2SiO_3 treatments enhanced shoot fresh weight by 37%, shoot dry weight by 35%, crown diameter by 50%, and soil plant analysis development (SPAD) index by 27% compared with the control, while plants under optimal temperatures (20 and 24 °C) showed no significant response. These results indicated that K_2SiO_3 mitigated the vegetative growth and SPAD index of strawberry plants under heat stress. Additionally, K_2SiO_3 reduced the time to first flower by 29% and increased fruit set by 47% at 28 °C during cycle 1. Flower numbers increased with the 100 mg·L^{-1} K_2SiO_3 application in both cycles, whereas marketable fruit yield improved only in cycle 1. Fruit quality was consistently enhanced in both cycles by K_2SiO_3, with soluble solids increasing by 30% to 33% and acidity decreasing by 14% to 16%. These results demonstrated that foliar application of K_2SiO_3 at both 50 and 100 mg·L^{-1} enhanced vegetative growth, time to first flower, and fruit quality primarily under elevated temperatures, with limited effects under optimal conditions. Its benefits were organ-specific, yet it consistently improved fruit sweetness regardless of temperature. The effectiveness of K_2SiO_3 also depends on careful management of environmental factors, including light intensity and root zone salinity.**

Strawberry (*Fragaria ×ananassa*) is a fruit crop with high economic value, important nutritional benefits, and strong consumer demand. Globally, the strawberry market has been valued at approximately USD 25.6 billion, with production distributed in 81 countries. China is the leading producer, followed by the United States, Turkey, Egypt, and Mexico (Food and Agriculture Organization of the United Nations 2022). In the United States, the demand for strawberries continues to grow. In 2023, fresh strawberry imports reached 589 million pounds, which was a 4% increase from 2022; additionally, 2023 was the fifth year in a row with increasing imports (US Department of Agriculture 2025). Mexico supplied an average of 98% of these imports between 2022 and 2024. More than half of this volume enters during the first quarter of the year when US production is low (Collen 2025).

This seasonal reduction in domestic supply is mainly caused by the sensitivity of strawberry plants to environmental conditions. In the United States, most strawberries are grown in California and Florida, which together produce more than 90% of the national supply. These states mainly rely on open-field cultivation. However, open-field systems are becoming more vulnerable to extreme weather, especially in the summer. In California, harvesting runs from January to October, with a peak between April and June. Florida's season starts in late November and continues through March (US Department of Agriculture 2022). Because strawberry fruits are harvested in several flushes, planting in the fall allows harvests to continue through spring and early summer. However, when these harvests overlap with the summer season, high temperatures can reduce yield and quality. Notably, in recent years, farmers have noticed more problems during hot summers, including smaller berries, sour taste, fewer fruits per plant, and lower marketable yield (Gutiérrez 2024). The optimal day temperature for strawberry growth is between 20 and 23 °C (Wagstaffe and Battey 2006). Higher temperatures accelerate flowering but reduce flower and fruit size. This leads to smaller, less sweet berries caused by lower carbon fixation and changes in flower structure (Menzel 2023). Thus, even small decreases in fruit size or quality can lead to large financial losses. For instance, a 10% to 15% decrease in marketable yield during the main harvest period can result in millions of dollars in losses (Guan et al. 2025) and increase dependence on imports.

To mitigate the effects of heat stress, researchers have studied silicon (Si)-based fertilizers like potassium silicate. Foliar application of potassium silicate offers substantial amount of Si, which is known to strengthen plant cell walls, improve antioxidant enzyme activity, and support photosynthesis under stress (Liang et al. 2015; Savvas and Ntatsi 2015). In strawberries, Si-based fertilizer foliar sprays have been linked to better fruit size, firmness, and shelf life (Miyake and Takahashi 1983; Peris-Felipo et al. 2020). However, the effects of potassium silicate under both normal and high temperature conditions have not been sufficiently studied. However, heat stress may induce flowering, but it often leads to poor fruit set, meaning many flowers do not develop into marketable fruit. This leads to important research questions, such as whether Si can improve fruit set and yield under heat stress and whether Si can increase the number of flowers or fruits under normal temperatures. These questions are still unanswered in the current scientific literature. To study these, we need to understand the interactive effects between temperatures and potassium silicate doses. We hypothesized that foliar application of potassium silicate would have different effects on strawberry plants under optimal and high-temperature conditions. Therefore, the objective of this study was to evaluate how potassium silicate affects flowering, fruit set, marketable yield, and fruit quality in strawberry plants grown under different temperature regimes in indoor farms.

Materials and Methods

Plant materials

The experiment was conducted using strawberry (*Fragaria ×ananassa*) cultivar Cabrillo, which is a day-neutral cultivar known for its large, firm, bright red fruit with a balanced sweet–tart flavor. Bare root plants were obtained from Cedar Point Nursery (Dorris, CA, USA) and planted in 2.6-L containers filled with a substrate mix consisting of 50% perlite, 25% coconut coir, and 25% all-purpose BM6 (Berger, Saint-Modeste, Quebec City, Canada). The coconut coir was washed thoroughly with tap water to remove salts before mixing with other ingredients. The mother plants were grown in a greenhouse from Jul 2024 to Nov 2024 (5 months) at 23.4 ± 1.9 °C, relative humidity of 53.5% ± 14.7%, and average daily light integral of 15.1 ± 4.8 mol·m^{-2}·d^{-1}.

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Transplant propagation

Runners with uniform sizes were collected from healthy mother plants, with each containing one to two clones, and stored in the dark room at 4 °C for 1 week. Before planting the runners, the basal ends were treated with Hormex rooting powder (Maia Products Inc., Westlake Village, CA, USA) and planted in 7-cm × 7-cm × 7.7-cm (length × width × height) deep, square, plastic pots filled with BM6 all-purpose mix. For the first week, unrooted runners (transplants) were maintained under a humidity dome at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light intensity with a 12-h photoperiod in a temperature-controlled (~23–25 °C) propagation rack. After the establishment of rooting, the humidity domes were removed and plants were transferred back to the greenhouse. Plants were irrigated, alternately with tap water and Yamazaki nutrient solution [average electrical conductivity (EC), EC = 0.99 ± 0.03 $dS \cdot m^{-1}$, pH = 6.1 ± .01] containing the following ($mg \cdot L^{-1}$): nitrogen (N), 150; phosphorus (P), 30; potassium (K), 193; calcium (Ca), 135; magnesium (Mg), 40; sulfur (S), 52; iron (Fe), 2.00; boron (B), 0.31; manganese (Mn), 0.21; zinc (Zn), 0.11; copper (Cu), 0.05; and molybdenum (Mo), 0.05 ppm. Pests were controlled by spraying plants twice per week with soapy water, which was made by mixing 3.5 mL of olive oil and 6.9 mL of liquid soap into 3 gallons of water. When plants reached the three-leaf to four-leaf stage, they were transplanted into round pots (top diameter, 10-cm; height, 9-cm) containing a potting mix composed of 50% perlite, 25% coco coir, and 25% BM6 all-purpose mix. The same irrigation and pest management practices were followed throughout the culture period.

Experimental design and treatments

The experiment was conducted in three growth chambers at the Texas A&M AgriLife Research and Extension Center, Dallas, TX, USA (32.77°N, 96.80°W) from Dec 2024 to Apr 2025. Uniform plants with a single crown were selected, and older leaves, runners, and flowers were pruned, retaining an average of five to six healthy leaves per plant. The study followed a split-plot factorial design with temperature [20 °C (T20); 24 °C (T24); and 28 °C (T28)] as the main plot factor and potassium silicate (K_2SiO_3) doses [0 $mg \cdot L^{-1}$ (control); 50 $mg \cdot L^{-1}$ (Si_{50}); and 100 $mg \cdot L^{-1}$ (Si_{100})] as the subplot factor. Three walk-in growth chambers (2.9 m × 1.4 m × 2.4 m; Growtainers®, Sycamore, IL, USA) were assigned to temperature treatments. Within each chamber, three compartments (1.22 m × 0.6 m × 0.62 m) were constructed using three-layer growth racks and reflective cardboard, with each compartment receiving a different K_2SiO_3 dose. Each compartment contained two trays of three plants each, resulting in six biological replications per treatment combination. The experiment included two harvest cycles. During cycle 1 (60 d), light intensity at the canopy level was maintained at 286 ± 3.39 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (n = 12) under a 12-h photoperiod. The vapor pressure deficit was maintained at approximately 1.0 ± 0.13 kPa during both cycles.

At the time of the first harvest, some leaves turned reddish instead of normal green, and these symptoms (red leaves) were more predominant under K_2SiO_3 application (Fig. 1A and Supplementary Fig. 1). The reddish leaves were counted for each plant; then, the reddish leaf percentage was calculated using the following equation: (number of affected leaves/plant × 100)/total number of leaves. Consequently, after the first harvest, light intensity was reduced to 180 ± 5.61 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (n = 12) for cycle 2 (57 d), and plants were pruned by removing older and damaged leaves, runners, flowers, and fruits. Plants were irrigated through the substrate surface alternatively with tap water (EC = 0.39 $dS \cdot m^{-1}$ and pH = 7.02) and the aforementioned Yamazaki nutrient solution whenever substrate became dry during cycle 1; however, in cycle 2, plants were sub-irrigated through the holding trays. From 2 weeks of treatment exposure, salinity symptoms appeared in old leaves, and leachate was collected from the second to sixth weeks (Fig. 1B). After irrigating each plant with 300 mL of distilled water, the EC of the drained solution was measured using a Bluelab Combo Meter (HI98129; Hanna Instruments, Smithfield, RI, USA). Nutrient solutions containing K_2SiO_3 were applied as foliar supplements twice weekly, coinciding with the irrigation schedule.

Data collection

Growth data and chlorophyll content. Plants were harvested after 117 d of treatment, including two fruit harvesting cycles. At harvest, shoot fresh weight (FW), shoot dry weight (DW), root FW, root DW, canopy area (CA), crown diameter (CD) expansion percentage, and chlorophyll content [soil plant analysis development (SPAD)] were measured. Plants were cut at the substrate surface level, and FWs of shoots and roots were recorded immediately. Then, samples were dried in an oven (Thermo Fisher Scientific, Waltham, MA, USA) at 80 °C for 72-h to determine DWs. Top-view images of plants with a black background were captured using a high-resolution digital camera (Apple Inc., Cupertino, CA, USA). The CD expansion percentage was calculated as the percentage increase from the initial CD measured before treatment to the final CD at the end of the experiment using the following formula: CD expansion % = $[(CD_{final} - CD_{intial}) \times 100/CD_{initial}]$. The CA was quantified using a custom Python script executed in Spyder (Anaconda, Python 3.11). Images were processed using the OpenCV library, where they were converted from RGB (red, green, and blue) to HSV (hue, saturation, and value) color space to enhance separation of green canopy pixels from the black background. A defined HSV threshold range was applied to segment the canopy region, and the number of green pixels was counted. Then, pixel values were converted to the actual CA (cm^2) using a calibration factor. The CD was measured with a Vernier caliper, and leaf greenness was recorded using a SPAD-502 m (Konica Minolta Sensing Inc., Tokyo, Japan).

Floral traits, yield, and fruit quality. Floral and yield traits recorded at each fruit harvest cycle included time to first flower, number of flowers, percentage of fruit set, and percentage of marketable fruit. Fruits that weighed more than 10 g exhibited uniform red coloration (covering more than 90% of fruit surface) and were free from visible spots were classified as marketable. The first mature marketable-grade fruits from each inflorescence were sampled to measure the total soluble solids (°Brix) and acidity (%) using an ATAGO pocket Brix and acidity meter (ATAGO Co., Tokyo, Japan). For the °Brix measurement, a single drop of fresh strawberry juice was placed directly on the meter. For acidity measurements, 1 g of strawberry juice was diluted with distilled water to a total weight of 50 g, thoroughly mixed, and a single drop of the diluted solution was placed on the meter to obtain the acidity reading.

Statistical analysis

Data regarding growth, morphology, and the SPAD index were collected at the whole-plant harvest and analyzed using a two-way analysis of variance (ANOVA) to determine the effects of temperature, potassium silicate

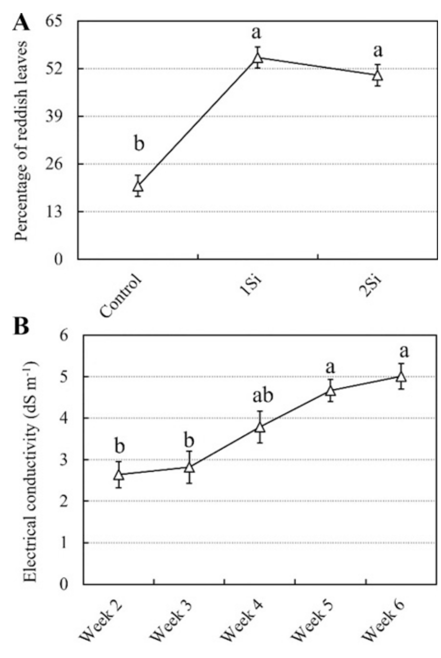

Fig. 1. Percentage of reddish leaves in individual plants at the end of cycle 1 (**A**) and electrical conductivity (EC) of leachate from weeks 2 to 6 during cycle 2 (**B**). Vertical error bars represent standard errors (percentage of reddish leaves: n = 6; EC: n = 5). Different letters indicate significant differences at $P \le 0.05$ tested by Tukey's honestly significant difference (HSD) among potassium silicate treatments (0 $mg \cdot L^{-1}$, control; 50 $mg \cdot L^{-1}$, Si_{50}; and 100 $mg \cdot L^{-1}$, Si_{100}) across the combined temperatures (20, 24, and 28 °C).

Table 1. Summary of analysis of variance (ANOVA) of the effects of three temperatures (20, 24, and 28 °C) and three potassium silicate doses (0 or control, 50, and 100 $mg \cdot L^{-1}$) on growth parameters: shoot fresh weight (FW), shoot dry weight (DW), root FW, root DW, canopy area, % crown diameter expansion, and relative chlorophyll content (SPAD).

Factor	Shoot FW (g)	Shoot DW (g)	Root FW (g)	Root DW (g)	Canopy area (cm^2)	Increased crown diam (%)	SPAD
T	**	**	***	***	***	***	***
Si	**	**	NS	NS	NS	NS	***
T × Si	*	*	NS	NS	NS	**	**

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
DW = dry weight; FW = fresh weight; SPAD = soil plant analysis development; T = temperatures; Si = potassium silicate doses.

dose, and their interaction. Floral traits, yield, and fruit quality were measured separately at each of the two fruit harvest cycles. For each temperature, a one-way ANOVA was performed to assess the effect of K silicate dose, and results for the two harvest cycles were presented individually. A one-way ANOVA was also conducted for the reddish leaf percentage in cycle 1 (there were no reddish leaves in cycle 2). Additionally, Pearson's correlation matrix analysis was performed using the "corrplot" package in Rstudio software (version 4.4.2) to gain insight into the potential influence of photoinhibition on other variables. An ANOVA was conducted in RStudio using the "agricolae" package, and data visualization was performed using Microsoft Excel 365 (Redmond, WA, USA). Significant differences among means were determined using Tukey's honestly significant difference (HSD) test at the 5% probability level.

Results

Temperature significantly influenced all vegetative traits and SPAD content, while the K_2SiO_3 dose (Si) affected shoot FW, shoot DW, and the SPAD index (Table 1). Significant interactions between temperature and Si concentration were observed in shoot FW and DW, increased CD (%), and the SPAD index (Table 1). For flower and fruit quality traits, temperature had significant effects on time to first flower, fruit set (%), and acidity (%) in cycle 1, but only on time to first flower and acidity in cycle 2 (Table 2). However, K_2SiO_3 doses did have significance for all flower and fruit quality parameters in cycle 1 except fruit weight, while in cycle 2, it affected time to first flower, brix, and acidity (%). In addition, significant interactions were only found for days to first flower and fruit set (%) in cycle 1. In addition to vegetative, flower, and fruit quality traits, in cycle 1, the reddish leaf percentage increased by approximately 64% and 60% with Si_{50} and Si_{100}, respectively, compared with the control (Fig. 1A and Supplementary Fig. 1). Pearson's correlation matrix from cycle 1 demonstrated that the incidence of reddish leaves had a prominent (ã50%) positive correlation (R^2 = 0.77) with the brix (Supplementary Fig. 2).

Vegetative traits and SPAD index

The two-way interactive effects (temperature × Si) were significant for shoot FW and DW, with K_2SiO_3 dose effects evident only under elevated temperatures (Table 1, Fig. 2A, 2B). At T28, shoot FW increased by approximately 37% at both doses of K_2SiO_3 and shoot DW increased by approximately 35% compared with the control. Root FW and DW did not show responses to K_2SiO_3 doses (Fig. 2C, 2D). However, with increasing temperatures from T20 to T28, both root FW and DW decreased by approximately 54% (Fig. 2C, 2D). An increased CD was significantly affected by the Si dose at T28, when the lower dose increased expansion by 50% compared with the control, while the higher dose showed no additional effect (Fig. 2E). The CA decreased by 35% at T28 compared with the control, whereas no significant differences were observed among Si treatments (Fig. 2F). At 28 °C, Si spray at both doses increased SPAD values by 27% relative to the control (Fig. 2G); however, at T20 and T24, Si treatments had no effect on SPAD.

Flower and fruit quality traits

In cycle 1, at T24 and T28, time to flower was reduced, regardless of K_2SiO_3 doses (Fig. 3A). At T24, Si_{50} decreased the time to first flower by 18% compared with the control, whereas Si_{100} showed no significant difference compared with the control and Si_{50}. Moreover, at T28, both Si doses decreased time to first flower by approximately 29% relative to the control. In cycle 2, a similar trend was observed at T28, with reductions of approximately 26% in both Si_{50} and Si_{100}, in contrast to control; however, Si treatments did not affect time to first flower at other temperatures (Fig. 3B).

Fruit set (%) responded to Si treatment only under T28 across both cycles and increased by 47% relative to the control for both Si_{50} and Si_{100} (Fig. 3C, 3D). Flower number was influenced by K_2SiO_3 application, particularly at the Si_{100} in both cycles (Fig. 3E, 3F). In cycle 1, flower number increased by 28% and 19% for Si_{100}, compared with the control and Si_{50}; in cycle 2, increases of 33% and 22% were observed for Si_{100} compared with the control and Si_{50}. Marketable fruit (%) increased only in cycle 1 under Si_{50} and showed a 21% increase over the control, whereas Si_{100} did not confer further benefits compared with both the control and Si_{50} (Fig. 3G, 3H). Single fruit FW was unaffected by temperatures, by K_2SiO_3 doses, and between cycles (Fig. 3I, 3J).

Strawberry fruit brix content was unaffected by temperature but responded positively to both K_2SiO_3 doses compared with the control in both cycles (Fig. 4A, 4B). In cycle 1, brix increased by 33% and 31% for Si_{50} and Si_{100}, respectively; in cycle 2, it increased by 32% and 30%, respectively, compared with the control. Acidity was affected by both temperature and K_2SiO_3 doses individually. With increasing temperature from T20 to T28, acidity increased by approximately 41%, while K_2SiO_3 applications reduced acidity by 16% and 14% for Si_{50} and Si_{100}, respectively, relative to the control (Fig. 4C). A similar trend was also noticed in cycle 2 for K_2SiO_3 doses. However, in cycle 2, no significant differences were observed at T20 and T24, whereas T28 was associated with the highest acidity (1.65%) (Fig. 4D).

Table 2. Summary of the analysis of variance (ANOVA) of the effects of three temperatures (20, 24, and 28 °C) and three potassium silicate doses (0 or control, 50, and 100 $mg \cdot L^{-1}$) for both cycles 1 and 2 on time to first flower, number of flowers, fruit set (%), marketable fruit (%), and single fruit fresh weight.

Factor	Time to first flower (d)	Number of flowers	Fruit set (%)	Marketable fruit (%)	Single fruit fresh wt (g)	Brix	Acidity (%)
Cycle 1							
T	***	NS	**	NS	NS	NS	***
Si	***	**	**	*	NS	***	***
T × Si	**	NS	***	NS	NS	NS	NS
Cycle 2							
T	**	NS	NS	NS	NS	NS	**
Si	**	NS	NS	NS	NS	**	*
T × Si	NS	NS	NS	NS	NS	NS	NS

Fruit quality traits: brix and acidity (%).
NS, *, **, *** Nonsignificant and significant at $P \leq 0.05$, 0.01, and 0.001, respectively. T = temperatures; Si = potassium silicate doses.

Discussion

Effects of potassium silicate foliar application on plant growth are temperature-dependent and organ-specific

Strawberries generally perform best within a moderate temperature range of 20 to 25 °C, where growth and physiological processes such as photosynthesis, transpiration, and nutrient assimilation function efficiently without significant stress (Balasooriya et al. 2018). In our study, at T20 and T24, shoot FW, DW, and CD showed no significant differences between control and Si-treated plants, indicating that under favorable temperature regimes plants were able

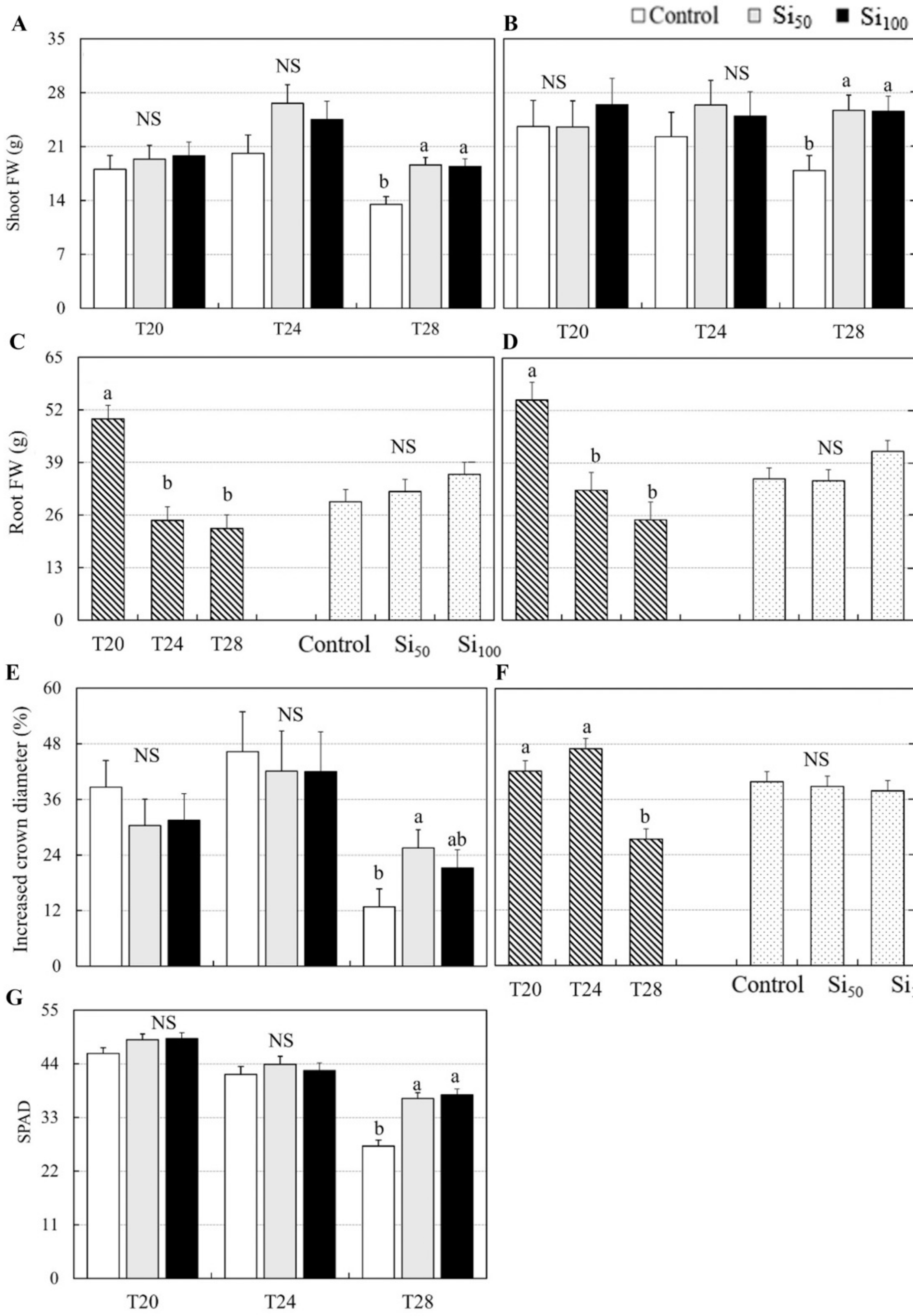

Fig. 2. Shoot fresh weight (**A**), shoot dry weight (**B**), root fresh weight (**C**), root dry weight (**D**), percent change in crown diameter (**E**), canopy area (**F**), and soil plant analysis development (SPAD) values (**G**) of 'Cabrillo' strawberry plants grown under three temperatures (20 °C, T20; 24 °C, T24; and 28 °C, T28) and three potassium silicate foliar application treatments (0 mg·L^{-1}, control; 50 mg·L^{-1}, Si_{50}; and 100 mg·L^{-1}, Si_{100}). Data were pooled across temperatures or potassium silicate doses for root fresh weight, root dry weight, and canopy area, while the remaining parameters showed interactive effects of temperature and potassium silicate doses. Vertical error bars represent standard errors (*SE*s) (n = 5). Different letters indicate significant differences at $P \leq 0.05$ tested by Tukey's honestly significant difference. NS = no significant differences.

to maintain normal growth without requiring additional protection from potassium silicate. However, at T28, heat stress noticeably suppressed growth in the control plants, whereas K_2SiO_3-treated plants exhibited increased shoot FW, DW, and CD. This beneficial effect under stress may be attributed to Si-mediated reinforcement of cell wall structures and improved tissue water status, which collectively enhances mechanical stability and growth (Ma and Yamaji 2015; Zhu and Gong 2014). In addition to growth-related traits, K_2SiO_3-treated plants sustained higher chlorophyll levels and SPAD index, maintaining photosynthetic activity at elevated temperatures. This suggests that Si plays a protective role in limiting oxidative stress and preserving photosynthetic efficiency (Muneer et al. 2017; Xiao et al. 2022).

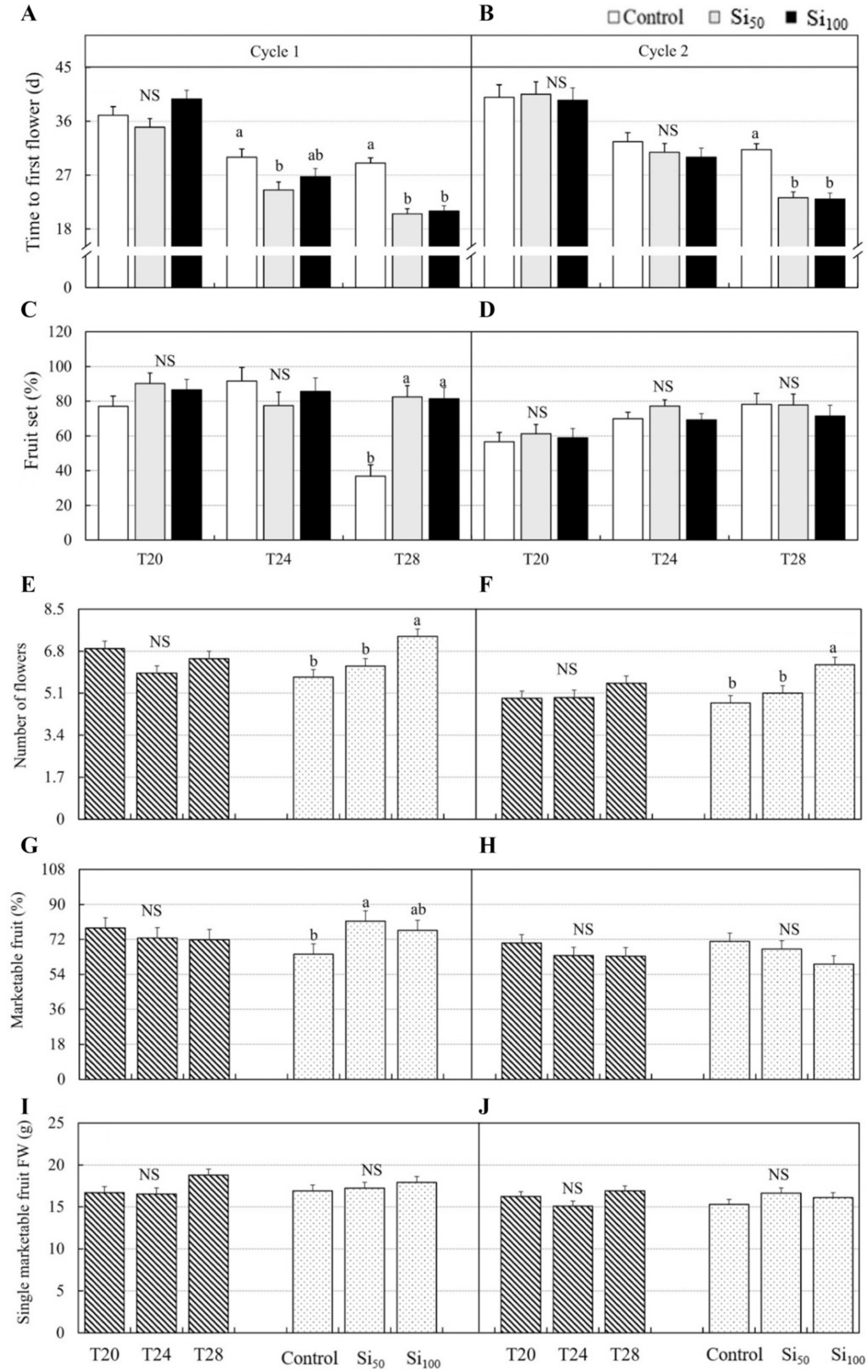

Fig. 3. Days to first flower (**A**, **B**), fruit set (%) (**C**, **D**), number of flowers (**E**, **F**), marketable fruit (%) (**G**, **H**), single fruit fresh weight (**I**, **J**) of 'Cabrillo' strawberry plants grown under three temperatures (20 °C, T20; 24 °C, T24; and 28 °C, T28) and three potassium silicate foliar application treatments (0 mg·L^{-1}, control; 50 mg·L^{-1}, Si_{50}; and 100 mg·L^{-1}, Si_{100}). Data were pooled across temperatures or potassium silicate doses for number of flowers, marketable fruit, and single fruit fresh weight, while the remaining parameters showed interactive effects of temperature and potassium silicate. The left graphs correspond to cycle 1, and the right graphs correspond to cycle 2. Vertical error bars represent standard errors (*SE*s) (n = 5). Different letters indicate significant differences at $P \leq 0.05$ tested by Tukey's honestly significant difference. NS = no significant differences.

These improvements reflect stronger tissue development and delayed chlorophyll degradation, which help plants maintain photosynthetic capacity under stress (Hattori et al. 2005; Liang et al. 2015; Soundararajan et al. 2017).

In contrast, root FW and DW were not significantly affected, highlighting the restricted translocation of foliar-applied Si to belowground tissues. This observation is consistent with those of previous studies of strawberry and other crops, for which foliar application enhanced shoot growth but provided limited direct benefit to roots, which respond more effectively to Si applied through the soil or nutrient solution (Dehghanipoodeh et al.

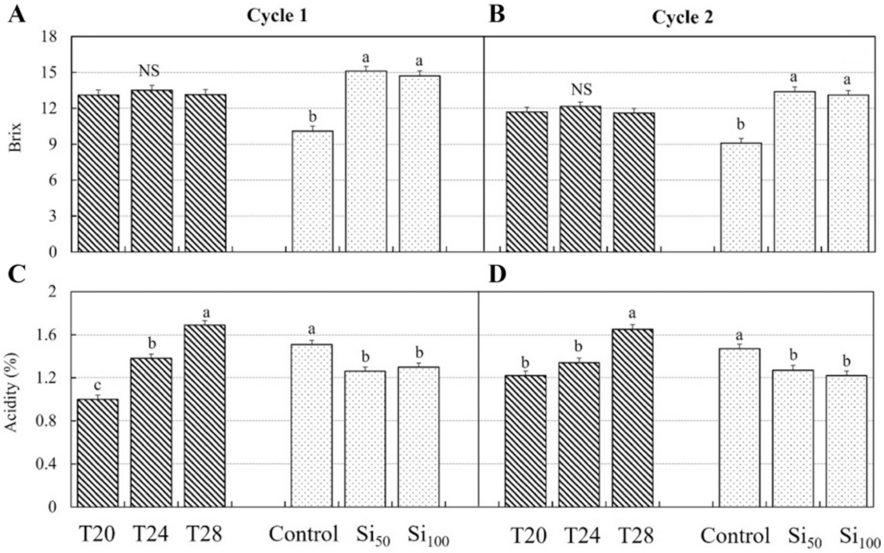

Fig. 4. Fruit brix (**A**, **B**) and acidity (**C**, **D**) of 'Cabrillo' strawberry plants grown under three temperature regimes (20 °C, T20; 24 °C, T24; and 28 °C, T28) and three potassium silicate foliar application treatments (0 $mg \cdot L^{-1}$, control; 50 $mg \cdot L^{-1}$, Si_{50}; and 100 $mg \cdot L^{-1}$, Si_{100}). Data were pooled across temperatures or potassium silicate doses. The left graphs correspond to cycle 1, and the right graphs correspond to cycle 2. Vertical error bars represent standard errors (*SE*s) (n = 5). Different letters indicate significant differences at $P \leq 0.05$ tested by Tukey's honestly significant difference. NS = no significant differences.

2016; Liang et al. 2015). Interestingly, CAs declined under high temperature, regardless of K_2SiO_3 treatment. This suggests that while Si mitigates physiological stress and sustains metabolic activity, it cannot fully prevent reductions in leaf expansion or canopy size caused by heat stress (Menzel 2021; Muneer et al. 2017). In other words, Si functions more as a stabilizer of physiological processes rather than a complete defense against growth suppression under heat stress.

Variations in growing conditions (light intensity, irrigation, and foliar application) across cycles alter floral traits and potassium silicate effects

In our study, cycle 1 was conducted under higher light intensity compared with that under cycle 2. High light intensity can cause stress in strawberry leaves, which often appear as reddish leaves (Xu et al. 2005). This happens because the plant produces more anthocyanins, which help protect the leaves by neutralizing harmful molecules such as reactive oxygen species (Neill and Gould 2003; van Gelderen 2020). In our case, the stress was mainly attributable to the short distance between the plants and the lamps, which led to reddish leaf tissue. In addition, under these conditions, plants treated with potassium silicate showed more reddish leaves than the control plants (Fig. 1A and Supplementary Fig. 1B). This may be because Si enhances the plant's natural defense response, including a greater accumulation of protective red pigments, which are anthocyanins (Habibi 2016). Moreover, Si accumulates in guard cells and the cuticle, making stomata more sensitive and reducing water loss through transpiration (Vandegeer et al. 2021). Under normal stress or drought, this protective stomatal response helps maintain water balance and photosynthesis. However, under high light intensity, Si-induced reduction in transpiration can also indicate less leaf cooling and CO_2 intake (Vandegeer et al. 2021; Wang et al. 2021), which possibly increases stress on photosystem II (PSII). The stress in PSII can further worsen leaf stress and trigger more anthocyanin buildup, making the reddish leaves more obvious in Si-treated plants.

In cycle 1, irrigation was applied through the substrate surface as needed. To minimize wetting the leaves while irrigating, we switched to subirrigation in cycle 2. However, because of a low-leaching fraction, salt gradually accumulated in the root zone, and leachate measurements confirmed an increase in EC up to 5.07 $dS \cdot m^{-1}$ within 6 weeks. This additional stress factor might lead to a distinct physiological environment compared with that in cycle 1.

Despite these differences, the overall trends in response to K_2SiO_3 were similar between the two cycles for traits such as time to first flower, number of flowers, single fruit fresh weight, soluble solids (°Brix), and acidity. Notably, in the Pearson's correlation matrix, brix showed a positive correlation with the percentage of reddish leaves. However, in cycle 2, our results followed a similar increasing trend in brix as observed in cycle 1, suggesting that the increase in soluble solids was indeed attributable to foliar application of K_2SiO_3, not to the reddish leaves. Moreover, fruit set and marketable fruit yield diverged between the cycles. In cycle 1, potassium silicate significantly influenced fruit set and marketable yield under the three temperatures, whereas in cycle 2 these effects were not significant. This suggests that the combined stresses of elevated EC and high temperature in cycle 2 limit the effectiveness of potassium silicate. In addition, salinity is known to reduce fruit set and increase flower and fruit abortion (Parida and Das 2005); under these conditions, even if flower production was stimulated, the possibility of successful fruit set was diminished. Consequently, marketable fruit yield was not improved in cycle 2 by K_2SiO_3 applications.

Flower and fruit quality traits were improved by K_2SiO_3 foliar applications

Temperature exerted a strong influence on reproductive development of strawberries in both cycles of this study. As temperature increased, flowering occurred earlier, and foliar Si application further reduced the time to flower, with the effect being most evident at T28. This result is consistent with the known effect of higher temperatures on accelerating the developmental rate of strawberries (Ledesma and Sugiyama 2005).

However, fruit set showed the opposite trend. At T28 in cycle 1, fruit numbers declined sharply despite similar flower numbers across all temperatures. High temperature is known to impair pollen viability and stigmatic receptivity, leading to poor fertilization and malformed or aborted berries (Ledesma and Sugiyama 2005). Under these conditions, foliar K_2SiO_3 improved fruit set significantly compared with the control, indicating that Si-based fertilizer alleviated part of the reproductive stress. Reproductive enhancement is supported by Si because it has been shown to stabilize membranes, reduce oxidative stress, and maintain photosynthesis under heat stress (Ma and Yamaji 2015; Younis et al. 2020).

In cycle 2, when light intensity was lower and sub-irrigation caused root zone salinity, the effect of K_2SiO_3 was less evident. Strawberry is highly salt-sensitive, and even moderate increases in root zone EC restrict yield (Ferreira et al. 2019). Under such stress, the positive effects of foliar K_2SiO_3 were insufficient to counteract reduced fruit set. Although flower numbers remained unaffected by temperature, the higher Si dose consistently increased flower production compared with Si_{50} in both cycles. This suggests that Si enhanced the assimilate status and possibly hormonal balance to support floral development, although the benefit did not always translate to more marketable fruit under stress. Marketable yield was highest at T24 in cycle 1, supporting the established optimum temperature range for strawberry fruit development. At T28, reduced fruit set and higher incidence of malformation lowered marketable yield despite the presence of many flowers.

Fruit quality was also strongly influenced by Si. In both cycles, Si increased the soluble solids content (°Brix) and reduced acidity. These effects are consistent with those of previous studies that showed that Si enhances carbohydrate accumulation in fruits through improved source–sink function under stress (Savvas et al. 2009). In both cycles, the brix increased and acidity decreased with increasing temperature, in agreement with earlier studies that found that that warmer ripening conditions reduce the sugar–acid balance in strawberry (Kumakura and Shishido 1994; Muley et al. 2022).

Conclusion

Foliar application of potassium silicate significantly influenced strawberry growth, SPAD index (relative chlorophyll content), and fruit quality under elevated temperatures. At 28 °C, potassium silicate increased shoot biomass, CD, and the SPAD index, indicating stronger growth and improved potential photosynthetic capacity under stress. Foliar spray with potassium silicate also improved flower productivity in cycle 1 and enhanced fruit quality in both cycles with higher soluble solids and lower acidity. However, foliar Si application did not affect root biomass and increased the reddish leaves under high light conditions. In cycle 2, high salinity in the root zone (EC = 5.07 $dS \cdot m^{-1}$) reduced the benefits of Si application. These results highlight the positive effects of potassium silicate for sustaining growth and fruit quality of strawberries under heat stress. Future work should test different application methods such as drenching or incorporating Si in nutrient solutions. Additionally, the physiological mechanisms behind improved fruit set under stress should be investigated.

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