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Silicon as a beneficial element for improving fruit quality and production in strawberry

Silicio como elemento benéfico para mejorar la calidad y producción en fresa

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ABSTRACT

Among fruit crops, strawberry (*Fragaria × ananassa* Duch.) is one of the most economically important species cultivated worldwide. In Colombia, production is mainly concentrated in the departments of Cundinamarca, Antioquia, Norte de Santander, Cauca, and Boyacá. Traditionally, macro- and micronutrient availability has been considered a key factor determining strawberry yield. However, in recent years, researchers have increasingly incorporated certain beneficial elements, particularly silicon (Si), into fertilization programs because of their positive effects on plant growth and productivity. Therefore, the objective of this study was to evaluate the effect of soil-applied silicon on fruit quality and yield of strawberry cv. 'Albion' under the environmental conditions of Tuta, Boyacá, Colombia. A completely randomized experimental design was used with four treatments consisting of increasing rates of calcium–magnesium silicate (0, 300, 600, and 900 kg ha^{-1} of $CaSiO_3{\cdot}MgSiO_3$). Fruit quality attributes, including fruit firmness, soluble solids (SS, °Brix), and titratable acidity (TA, % citric acid), as well as fruit yield per plant and leaf concentrations of calcium, magnesium, and silicon, were evaluated. Significant differences ($p \leq 0.05$) were observed for fruit quality, production per plant, and leaf nutrient and silicon concentrations. The application of 900 kg ha^{-1} of $CaSiO_3{\cdot}MgSiO_3$ significantly improved fruit quality attributes and yield, indicating that silicon, as a beneficial element, enhances fruit quality and production in strawberry plants.

Keywords: berries; crop production; fertilization; *Fragaria × ananassa* Duch; mineral nutrition; postharvest; silicate

RESUMEN

Entre los cultivos frutales, la fresa (*Fragaria × ananassa* Duch.) es una de las especies de mayor importancia económica cultivadas a nivel mundial. En Colombia, la producción se concentra principalmente en los departamentos de Cundinamarca, Antioquia, Norte de Santander, Cauca y Boyacá. Tradicionalmente, la disponibilidad de macro y micronutrientes se ha considerado un factor clave para determinar el rendimiento del cultivo de fresa. Sin embargo, en los últimos años, los investigadores han incorporado cada vez más ciertos elementos benéficos, particularmente el silicio (Si), en los programas de fertilización, debido a sus efectos positivos sobre el crecimiento y la productividad de las plantas. Por lo tanto, el objetivo de este estudio fue evaluar el efecto de la aplicación de silicio al suelo sobre la calidad y el rendimiento de los frutos de fresa cv. 'Albion', bajo las condiciones ambientales de Tuta, Boyacá, Colombia. Se utilizó un diseño experimental completamente al azar, con cuatro tratamientos correspondientes a dosis crecientes de silicato de calcio y magnesio (0, 300, 600 y 900 kg ha^{-1} de $CaSiO_3{\cdot}MgSiO_3$). Se evaluaron los atributos de calidad de los frutos, incluidos la firmeza, los sólidos solubles (SS, °Brix) y la acidez titulable (AT, % de ácido cítrico), así como el rendimiento de frutos por planta y las concentraciones foliares de calcio, magnesio y silicio. Se observaron diferencias significativas ($p \leq 0,05$) en la calidad de los frutos, la producción por planta y las concentraciones foliares de nutrientes y silicio. La aplicación de 900 kg ha^{-1} de $CaSiO_3{\cdot}MgSiO_3$ mejoró significativamente los atributos de calidad de los frutos y el rendimiento, lo que indica que el silicio, como elemento benéfico, mejora la calidad de los frutos y la producción en plantas de fresa.

Palabras clave: bayas; fertilización; *Fragaria × ananassa* Duch; nutrición mineral; poscosecha; producción de cultivos; silicato

INTRODUCTION

Strawberry (*Fragaria × ananassa* Duch.) is one of the most economically important fruit crops worldwide because of its high commercial value and broad consumer acceptance (Barbey *et al*., 2020). It belongs to the Rosaceae family, which includes numerous fruit and ornamental species of agricultural importance (Kumar *et al*., 2022). Although commonly regarded as a fruit, it is botanically classified as a pseudocarp because the edible portion develops primarily from the floral receptacle rather than exclusively from the ovary. The true fruits are the achenes located on its surface (Winkler *et al*., 2021). Owing to its desirable sensory attributes and nutritional value, strawberry is widely consumed both as fresh fruit and as a raw material for a variety of processed products, including jams, juices, ice cream, bakery products, and confectionery (Kim *et al*., 2021).

In Colombia, favorable climatic and geographic conditions enable year-round strawberry production, which is concentrated mainly in the departments of Cundinamarca, Antioquia, Norte de Santander, Cauca, and Boyacá (Medina-Bolívar *et al*., 2016; López-Valencia *et al*., 2017). Crop productivity depends on several factors, including agronomic management, resource availability, and the implementation of good agricultural practices (Botero Hoyos *et al*., 2022). Over the past decades, strawberry cultivation has expanded considerably in the country, surpassing other temperate fruit crops because of its continuous production cycle and high labor demand throughout the growing season, thereby making a substantial contribution to regional economic development (Galindo López *et al*., 2018).

Strawberry growth and development are influenced by environmental factors such as solar radiation, temperature, water availability, soil salinity, plant health status, and, particularly, mineral nutrition (Soppelsa *et al.*, 2019). Because of its shallow root system, strawberry is sensitive to fluctuations in nutrient availability; therefore, efficient nutrient management is essential to maximize vegetative growth, fruit yield, and fruit quality (Kaushalya Madhavi *et al.*, 2021). Traditionally, fertilization programs have focused on supplying essential macro- and micronutrients. However, increasing attention has recently been given to beneficial elements, which, although not essential for the life cycle of all plant species, promote plant growth, development, and tolerance to both biotic and abiotic stresses (Mittal *et al.*, 2023). Numerous studies have demonstrated that these elements are involved in key physiological processes, including photosynthesis, antioxidant defense regulation, hormone biosynthesis, and carbon metabolism, thereby enhancing plant growth and productivity in several crop species (Lo Piccolo *et al.*, 2021; Khan *et al.*, 2023; Singhal *et al.*, 2023). In this context, Pang *et al.* (2026) suggested that certain beneficial elements play a pivotal role in sustaining growth and productivity in specific crops. Among these, silicon (Si) has attracted considerable attention because it can increase crop biomass and yield by up to 39% (Yang *et al.*, 2024).

In recent years, numerous studies have demonstrated that silicon fertilization enhances plant growth, photosynthetic efficiency, nutrient uptake, and productivity across a wide range of crops (Ghadirnezhad Shiade *et al*., 2026). Consequently, silicon has been recognized as a quasi-essential or beneficial element because of its multiple positive effects on plant metabolism and its ability to enhance tolerance to biotic and abiotic stresses (Thakral *et al*., 2024; Vinay *et al*., 2026). Historically, strawberry was classified as a non-silicon-accumulating species (Epstein, 2009). However, more recent studies have identified the silicon transporter genes Lsi1 and Lsi2 and reported silicon accumulation of up to 3% of plant dry matter (Ouellette *et al*., 2017). Likewise, Soppelsa *et al*. (2019) reported silicon accumulation in different strawberry organs, suggesting

that this species has a greater capacity for silicon uptake than previously assumed. Despite these advances, the incorporation of silicon into strawberry fertilization programs remains limited because of scarce information on its effects on fruit quality and yield under field conditions (Ouellette *et al*., 2017).

Therefore, the objective of this study was to evaluate the effect of soil-applied silicon, supplied as calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$), on fruit quality, leaf calcium, magnesium, and silicon concentrations, and fruit production per plant of strawberry (*Fragaria × ananassa* Duch.) cv. 'Albion' grown under open-field conditions in Tuta, Boyacá, Colombia.

MATERIALS AND METHODS

Location

The field experiment was conducted during the first semester of 2024 at San Pedro Farm, La Hacienda village, municipality of Tuta, Boyacá, Colombia (2,520 m a.s.l.; mean annual temperature, 15 °C). Laboratory analyses were performed at the Plant Physiology Laboratory, Universidad Pedagógica y Tecnológica de Colombia (UPTC), Tunja, Boyacá, Colombia.

Experimental design

A completely randomized design (CRD) was used, with four treatments and four replicates, for a total of 16 experimental units (EUs). Each experimental unit comprised 10 uniform, healthy runner plants of the strawberry cultivar 'Albion', selected because it is widely cultivated in the study area and, as a day-neutral cultivar, is well adapted to cold climatic conditions (Öztürk *et al.*, 2025).

The experiment was conducted under open-field conditions, with plants grown directly in the soil on raised beds covered with black polyethylene mulch. Treatments consisted of four application rates of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$): T1, untreated control (0 kg ha^{-1}); T2, 300 kg ha^{-1}; T3, 600 kg ha^{-1}; and T4, 900 kg ha^{-1}. Silicon was supplied by a commercial calcium–magnesium silicate fertilizer with the following guaranteed composition: 3% P_2O_5, 30% CaO, 13% MgO, and 20% SiO_2.

The application rates were determined from the results of the initial soil chemical analysis (Table 1). The fertilizer was applied in two equal splits, at planting and 60 days after planting (DAP), consistent with the agronomic management practices described by Galindo López *et al*. (2018).

Table 1. *Physicochemical properties of the soil used in the experiment*

Property	Value	Interpretation
pH	5.2	Strongly acidic
Organic matter (%)	7.33	High
P Bray II (ppm)	18.78	Low
Ca (cmol kg^{-1})	3.02	Medium
Mg (cmol kg^{-1})	1.07	Low
K (cmol kg^{-1})	1.02	High
Na (cmol kg^{-1})	0.06	Low
Electrical conductivity (dS m^{-1})	0.15	Non-saline
Soil texture	A:23 Ar:38 L: 39	Clay loam

Planting was carried out directly in the soil by placing runner plants at previously marked positions within the raised beds, where treatments had been applied beforehand. Plants were spaced 0.5 m between rows and 0.3 m within rows, resulting in a planting density of 66,666 plants ha^{-1}. Subsequently, standard agronomic management practices were implemented, including fertilization, pest and disease control, and other cultural operations required for crop establishment and development.

Response variables

At 130 days after transplanting (DAT), when fruit production had reached a stable stage, fruit yield and quality assessments were conducted. Fruit yield was recorded weekly over a one-month period (four consecutive harvests), and the cumulative monthly yield was expressed as g $plant^{-1}$.

In addition, fruits were classified by commercial quality. For this purpose, the equatorial diameter of each fruit was measured with a digital caliper. Fruits were classified as Grade 1 if the equatorial diameter exceeded 34 mm, or Grade 2 if it ranged from 30 to 33 mm, in accordance with the Colombian Technical Standard for Strawberry NTC 4103 (ICONTEC, 1997).

To evaluate fruit quality attributes, a sample of 10 fruits per experimental unit (40 fruits per treatment) was collected. Fruit firmness was measured with a PCE-PTR200 digital penetrometer (resolution: 0.05 N). Soluble solids (SS) were measured in °Brix with a digital refractometer (Hanna Instruments, Woonsocket, RI, USA; measurement range: 0–85 °Brix; accuracy: ±0.1 °Brix). Titratable acidity (TA) was determined following AOAC (2000). Briefly, 1 g of fruit juice was diluted with 50 mL of distilled water, and three drops of phenolphthalein were added as an indicator. The solution was titrated with sodium hydroxide (NaOH), and titratable acidity was calculated from the volume of NaOH consumed using Equation (1).

$$TA\ (\%) = (A*B*C)*100/D \quad \text{(e1)}$$

Where A = volume of NaOH consumed during titration (mL); B = normality of NaOH (0.1 N); C = equivalent weight of the predominant organic acid in strawberry fruit (citric acid = 0.065 g meq^{-1}); and D = sample weight (g).

To associate the observed responses with the supply of calcium, magnesium, and silicon provided by the treatments, leaf samples were collected at 130 days after transplanting (DAT) from the lower, middle, and upper thirds of the plant until approximately 80 g of dry tissue (equivalent to approximately 300 g of fresh tissue) was obtained. The samples were analyzed to determine calcium and magnesium concentrations by dry ashing at 600 °C, followed by acid digestion and quantification using visible spectrophotometry. Leaf silicon concentration was determined using the laboratory›s validated internal analytical method. All analyses were performed by Agrilab®, an accredited analytical laboratory located in Bogotá, Colombia.

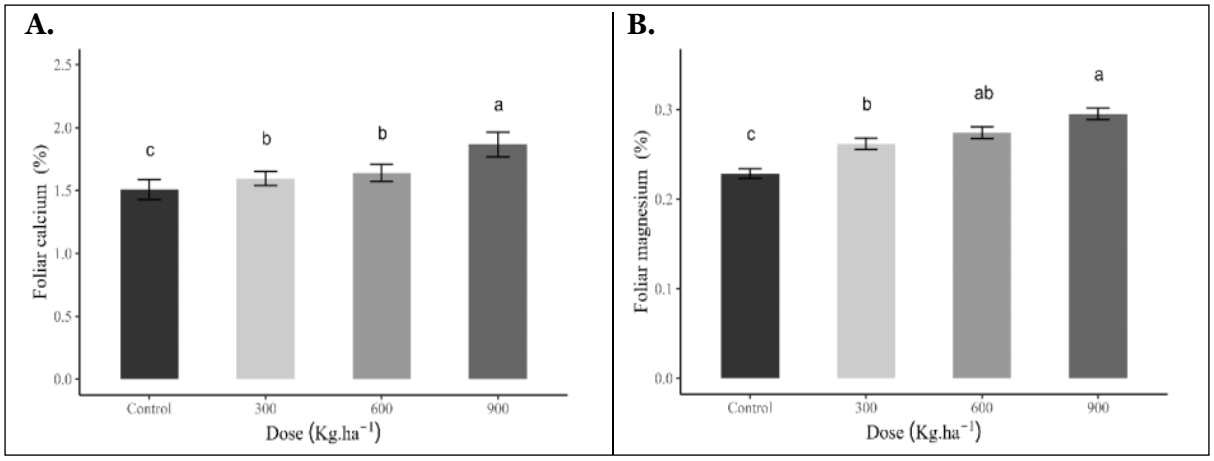
Data analysis

The data were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests, respectively. After confirming that the assumptions for parametric analysis were met, the data were analyzed using analysis of variance (ANOVA). Variables showing significant treatment effects were compared using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$ with the agricolae package. In addition, Pearson's correlation analysis was performed using the corrplot package. All statistical analyses were conducted using R software (R Core Team, 2022).

RESULTS

Leaf nutrient concentrations (Ca and Mg)

Leaf calcium concentration was significantly affected by the treatments ($p \leq 0.05$). The highest leaf Ca concentration was recorded in strawberry plants receiving 900 kg ha^{-1} of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$), reaching 1.86 ± 0.09%, whereas the untreated control exhibited a significantly lower value of 1.50 ± 0.08% (Figure 1A). Similarly, leaf magnesium concentration was significantly influenced by silicon application ($p \leq 0.05$). The highest Mg concentration (0.29 ± 0.006%) was observed in plants treated with 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$, whereas control plants showed a concentration of 0.22 ± 0.005% (Figure 1B).

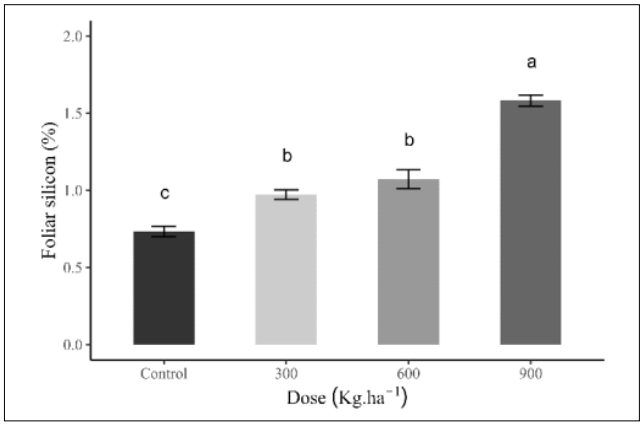


Note. Error bars represent the standard error of the mean (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$).

Figure 1. *Leaf concentrations of (A) calcium (Ca) and (B) magnesium (Mg) in strawberry (Fragaria × ananassa Duch.) cv. 'Albion' following soil application of different rates of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$).*

Leaf silicon concentration

Leaf silicon concentration was significantly affected by calcium–magnesium silicate application ($p \leq 0.05$). The highest Si concentration (1.58 ± 0.03%) was recorded in strawberry plants treated with 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$, whereas the untreated control exhibited a significantly lower concentration (0.73 ± 0.03%) (Figure 2). Overall, leaf Si concentration increased with increasing calcium–magnesium silicate application rate, indicating a dose-dependent accumulation of silicon in plant tissues.



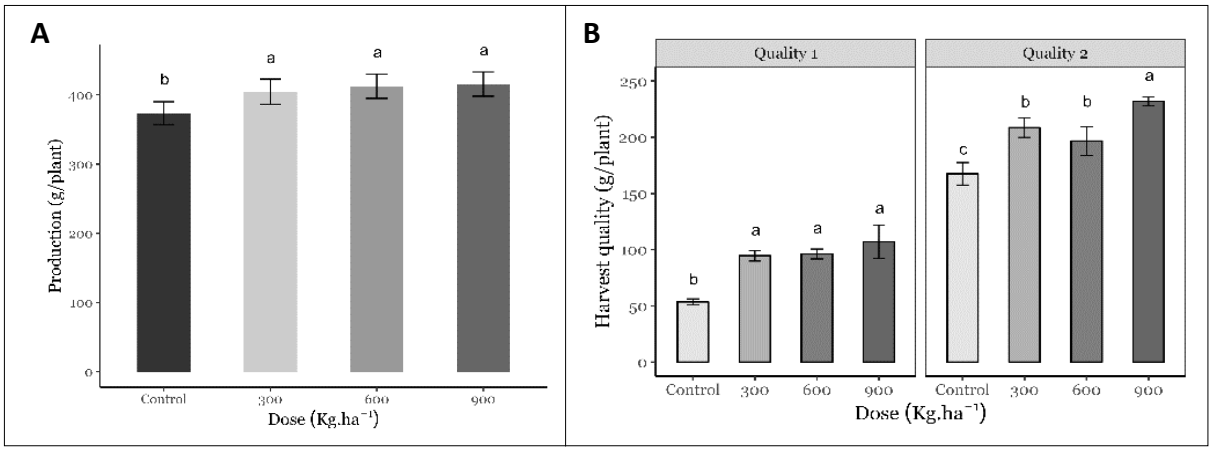
Note. Error bars represent the standard error of the mean (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$).

Figure 2. *Leaf silicon concentration in strawberry (Fragaria × ananassa Duch.) cv. 'Albion' plants following soil application of different rates of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$).*

Fruit production

Total fruit production was significantly affected by calcium–magnesium silicate application ($p \leq 0.05$). Strawberry plants treated with 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ had the highest fruit production, reaching 415.6 ± 17.6 g $plant^{-1}$ over the one-month sampling period, whereas untreated plants yielded 373.5 ± 16.5 g $plant^{-1}$ (Figure 3A). This corresponded to an 11.2% increase in total fruit yield compared with the untreated control.

Commercial fruit quality was also significantly affected by the treatments ($p \leq 0.05$). Plants receiving 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ produced 106.8 ± 14.8 g $plant^{-1}$ of quality 1 fruit and 231.8 ± 3.8 g $plant^{-1}$ of quality 2 fruit. In contrast, untreated plants produced 53.6 ± 2.5 g $plant^{-1}$ and 167.4 ± 9.9 g $plant^{-1}$ of quality 1 and quality 2 fruit, respectively (Figure 3B). Compared with the control, the application of 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ increased the production per plant of quality 1 and quality 2 fruit by approximately 99% and 38%, respectively.



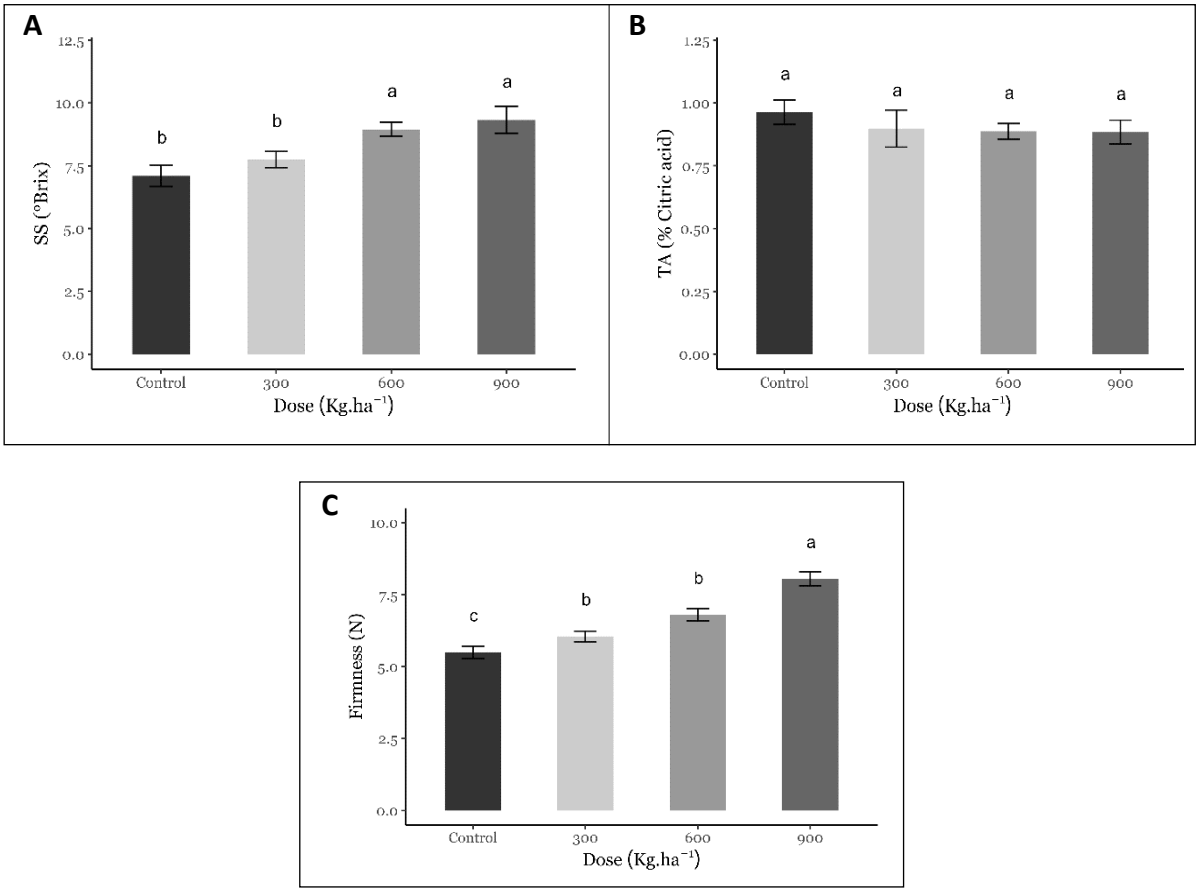
Note. Error bars represent the standard error of the mean (n = 4). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$).

Figure 3. *Effects of different application rates of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$) on (A) total fruit production and (B) fruit production by commercial grade in strawberry (Fragaria × ananassa Duch.) cv. 'Albion'*

Fruit quality: Fruit firmness, total soluble solids, and titratable acidity

Soluble solids (SS) were significantly affected by calcium–magnesium silicate application ($p \leq 0.05$). Plants treated with 600 and 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ produced fruits with SS values of 8.9 ± 0.3 and 9.3 ± 0.4 °Brix, respectively, whereas fruits from untreated plants exhibited a significantly lower value of 7.1 ± 0.4 °Brix (Figure 4A).

In contrast, titratable acidity (TA) was not significantly affected by the treatments ($p > 0.05$). The highest TA (0.96 ± 0.04% citric acid) was recorded in fruits from the untreated control, whereas the lowest (0.88 ± 0.06% citric acid) was observed in plants treated with 900 kg ha^{-1} of calcium–magnesium silicate (Figure 4B).



Note. Error bars represent the standard error of the mean (n = 4). Different letters indicate significant differences among treatments according to Tukey's honestly significant difference (HSD) test ($p \leq 0.05$).

Figure 4. *Effects of different application rates of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$) on (A) soluble solids (SS), (B) titratable acidity (TA), and (C) fruit firmness of strawberry (Fragaria × ananassa Duch.) cv. 'Albion'.*

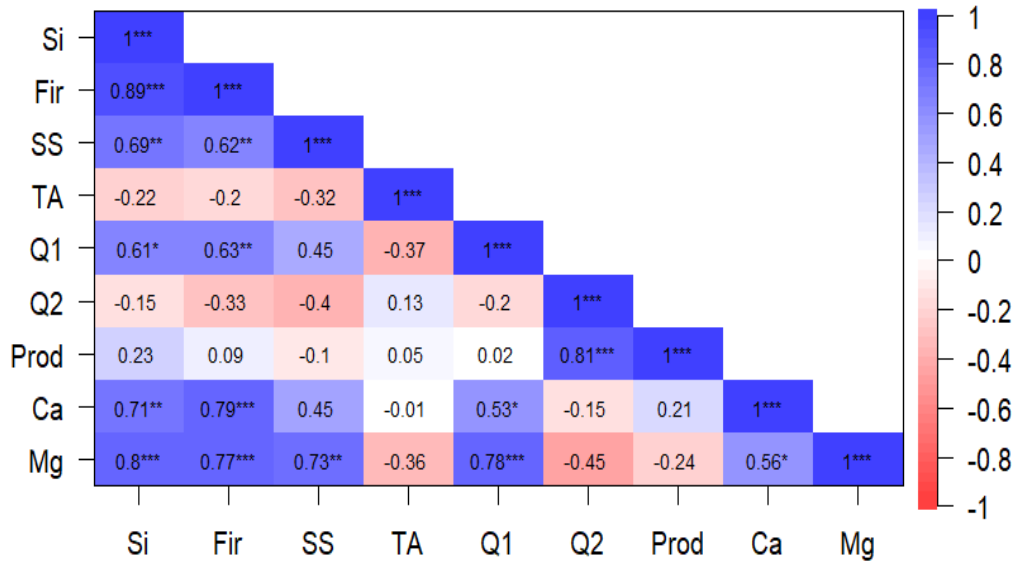
Fruit firmness was significantly affected by calcium–magnesium silicate application ($p \leq 0.05$). The highest firmness value (8.05 ± 0.2 N) was recorded in fruits harvested from plants treated with 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$, whereas fruits from the untreated control exhibited a significantly lower firmness of 5.5 ± 0.2 N (Figure 4C).

Correlation analysis

Pearson's correlation analysis revealed significant linear relationships among the evaluated variables. Leaf silicon concentration was strongly and positively correlated with fruit firmness ($r = 0.89$, $p < 0.001$), leaf magnesium concentration ($r = 0.80$, $p < 0.001$), leaf

calcium concentration (r = 0.71, p < 0.001), soluble solids (SS) (r = 0.69, p < 0.001), and quality 1 fruit yield (r = 0.61, p < 0.001) (Figure 5). These findings suggest that increased silicon accumulation in leaf tissues was closely associated with enhanced mineral nutrition, improved fruit quality, and greater production of premium-grade fruit.

In contrast, titratable acidity (TA) was negatively correlated with most of the evaluated variables, indicating that the beneficial physiological and nutritional effects of silicon fertilization were associated with lower fruit acidity. This trend may improve the maturity index (TSS/TA ratio), an important indicator of strawberry flavor and consumer acceptance.



Note. Si: leaf silicon concentration; Fir: fruit firmness; SS: soluble solids; TA: titratable acidity; Q1: Quality 1; Q2: Quality 2; Pro: total fruit production; Ca: leaf calcium concentration; and Mg: leaf magnesium concentration.

Figure 5. *Pearson's correlation matrix showing the relationships among yield, fruit quality, and leaf nutrient concentrations in strawberry (Fragaria × ananassa Duch.) cv. 'Albion' subjected to different application rates of calcium–magnesium silicate ($CaSiO_3$·$MgSiO_3$).*

DISCUSSION

Leaf concentrations of calcium, magnesium, and silicon

The application of calcium–magnesium silicate ($CaSiO_3$·$MgSiO_3$) significantly increased leaf silicon (Si) concentration in strawberry cv. 'Albion' (Figure 2). Similar results were reported by Dehghanipoodeh *et al*. (2018), who demonstrated that root application of soluble silicon increased Si accumulation in strawberry plants and improved vegetative growth, leaf area, and photosynthetic rate. These findings indicate that, despite strawberry's traditional classification as a low silicon accumulator, this species can absorb and accumulate appreciable amounts of Si when supplied under appropriate agronomic conditions.

One of the primary physiological benefits of increased silicon accumulation is enhanced mineral nutrient uptake. Hajiboland *et al*. (2018) reported that higher Si concentrations in strawberry tissues improve the acquisition of essential nutrients, while Park *et al*. (2018) and Soppelsa *et al*. (2019) demonstrated that silicon fertilization increases the accumulation of macronutrients, particularly calcium (Ca) and magnesium (Mg), in the aerial tissues of strawberry plants. Consistent with these findings, plants

receiving 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ in the present study exhibited significantly higher leaf Ca and Mg concentrations than the untreated control (Figure 1A-B).

The increase in leaf calcium concentration is particularly relevant because calcium plays a fundamental structural role in fruit development and postharvest quality. Calcium forms cross-links between pectic polysaccharides by binding to free carboxyl groups, producing calcium pectate, which reinforces the cell wall, improves tissue integrity, and increases fruit firmness (Soares *et al*., 2025; Udomkun *et al*., 2014). Likewise, magnesium is essential for photosynthetic metabolism because it is the central atom of the chlorophyll molecule and is involved in phloem loading and the translocation of photoassimilates from source to sink organs. Consequently, adequate Mg nutrition enhances carbon assimilation and the allocation of assimilates to developing fruits, thereby improving fruit growth and quality (Gerendás & Führs, 2013). Collectively, these results suggest that calcium–magnesium silicate fertilization, by promoting increased silicon accumulation, not only enhances Si uptake but also improves calcium and magnesium nutrition, thereby contributing to physiological processes associated with fruit development and quality in strawberry plants.

Fruit production

Silicon is widely recognized for promoting both vegetative growth and reproductive development, thereby enhancing fruit yield and quality in horticultural crops (Xu, Zhang *et al*., 2023). Recent studies have demonstrated that strawberry plants actively absorb silicon through the Lsi1 and Lsi2 transporter proteins, allowing this species to accumulate sufficient Si to be considered a silicon accumulator under adequate Si supply (Li *et al*., 2020). Consequently, silicon fertilization not only enhances the mechanical strength of plant tissues but also stimulates several physiological and metabolic processes involved in plant growth and productivity. The findings of the present study are consistent with these reports. Soil application of 900 kg ha^{-1} of calcium–magnesium silicate ($CaSiO_3 \cdot MgSiO_3$) significantly increased both total fruit production and the production of quality 1 fruits compared with the untreated control (Figure 3A-B). These results indicate that silicon fertilization can improve not only the quantity but also the commercial quality of strawberry production.

Similar responses have been reported in previous studies. Jarosz *et al*. (2025) found that root application of orthosilicic acid significantly increased fruit yield, fruit weight, and fruit diameter in strawberries. Likewise, Nada (2020) reported that foliar application of increasing doses of potassium silicate enhanced both total and marketable fruit yield. In the present study, plants treated with 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ exhibited an 11.2% increase in total fruit yield and approximately a 99% increase in quality 1 fruit yield relative to untreated plants (Figure 3A-B). The particularly large increase in premium-grade fruits suggests that silicon fertilization improves fruit development beyond simply increasing fruit number. The yield improvement observed in this study may be explained by several physiological mechanisms. Peris-Felipo *et al*. (2020) reported that silicon application increased pollen fertility during the flowering stage of strawberry plants, resulting in improved fruit set and, consequently, higher fruit production. Furthermore, silicon has been shown to enhance photosynthetic performance, nutrient uptake, water-use efficiency, and tolerance to environmental stresses, thereby increasing assimilate production and allocation to reproductive organs (Xu, Zou *et al*., 2023). These physiological responses likely contributed to the greater fruit yield and higher proportion of marketable fruits observed following calcium–magnesium silicate application in the present study.

Fruit quality

The increase in leaf silicon concentration observed in the present study confirms that the applied calcium–magnesium silicate effectively supplied plant-available silicon (Figure 2). Similarly, Somma *et al.* (2025) reported that silicon applied as potassium

metasilicate (K_2SiO_3) was readily absorbed and translocated throughout strawberry plants, with the highest Si concentrations detected in roots and leaves, followed by fruits and stems. Moreover, silicon accumulation in the edible receptacle showed a clear dose-dependent response, indicating that increasing silicon availability enhanced its deposition in fruit tissues.

Although silicon concentration was not directly quantified in strawberry fruit in the present study, fruits harvested from plants receiving increasing rates of calcium–magnesium silicate showed superior quality attributes, including greater firmness, higher soluble solids (SS), and a slight reduction in titratable acidity (Figures 4A–C). These findings suggest that enhanced silicon nutrition improved fruit quality through physiological and structural mechanisms linked to fruit development and ripening.

Total soluble solids are among the most important quality attributes that determine strawberry flavor and consumer acceptance because they reflect the accumulation of soluble sugars during fruit ripening (Soares *et al*., 2025). In the present study, silicon fertilization significantly increased SS, which may be associated with enhanced carbohydrate metabolism and greater translocation of photoassimilates to developing fruits. Hajiboland *et al*. (2018) likewise reported increased sugar accumulation in strawberry fruits following silicon application. Similarly, Xu *et al*. (2024) demonstrated that silicon increased the concentrations of total soluble sugars, glucose, and fructose in strawberry fruits, while simultaneously enhancing leaf glucose concentration, indicating improved carbon assimilation and partitioning.

Fruit firmness is largely determined by the integrity and architecture of the cell wall, which is composed primarily of cellulose, hemicelluloses, pectins, and lignin, all of which contribute to the mechanical strength of fruit tissues (Waldron *et al*., 2003; Pan *et al*., 2021). Strawberries are characterized by rapid softening during ripening, resulting in considerable postharvest losses due to their highly perishable nature (Figueroa *et al*., 2010; López-Valencia *et al*., 2017). Therefore, management strategies that delay fruit softening are essential for maintaining postharvest quality (Pan *et al*., 2021).

The significant increase in fruit firmness after applying 900 kg ha^{-1} of $CaSiO_3 \cdot MgSiO_3$ may be explained by silicon's structural role in reinforcing cell walls and preserving tissue integrity. In addition, silicon has been reported to delay fruit softening by reducing the activity of cell wall-degrading enzymes, including xylanase, cellulase, and polygalacturonase, thereby slowing the degradation of structural polysaccharides during ripening (Abidi *et al*., 2023). These findings are consistent with those of Meena *et al*. (2014), who concluded that silicon fertilization improves fruit quality and extends postharvest shelf life in horticultural crops. Furthermore, the increased leaf calcium concentration observed in the present study may have acted synergistically with silicon to reinforce cell wall stability through the formation of calcium pectate, thereby contributing to the higher fruit firmness recorded in silicon-treated plants.

Overall, these results indicate that calcium–magnesium silicate application not only increased silicon accumulation in strawberry plants but also improved fruit quality by enhancing sugar accumulation and maintaining fruit firmness, two attributes essential for consumer acceptance and postharvest performance.

CONCLUSIONS

This study demonstrated that soil application of calcium–magnesium silicate, particularly at 900 kg ha^{-1}, significantly increased leaf silicon accumulation and improved the nutritional status of strawberry plants by raising calcium and magnesium concentrations. These nutritional improvements were associated with higher fruit yield and better fruit quality, particularly through greater fruit firmness and higher total soluble solids. From an agronomic perspective, soil application of calcium–magnesium

silicate is a practical, cost-effective, and environmentally sustainable strategy that can be readily integrated into existing fertilization programs to improve both the productivity and market quality of strawberry crops. Future research should evaluate the long-term effects of silicon fertilization under different environmental conditions and across a wider range of strawberry cultivars. In addition, further studies are needed to elucidate the physiological and molecular mechanisms underlying the beneficial effects of silicon on nutrient uptake, fruit development, and postharvest quality.

AUTHOR CONTRIBUTIONS

Conceptualization, E.H.P-S., and D.F.T-H.; Methodology, E.H.P-S.; Formal Analysis, E.H.P-S., D.F.T-H., and M.A.T-H.; Investigation, E.H.P-S., D.F.T-H., and M.A.T-H.; Writing—Original Draft Preparation, E.H.P-S., D.F.T-H., and M.A.T-H.; Writing—Review & Editing, E.H.P-S., and D.F.T-H.; Visualization, E.H.P-S.; Supervision, E.H.P-S. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

Abidi, W., Akrimi, R., Hajlaoui, H., Rejeb, H., & Gogorcena, Y. (2023). Foliar fertilization of potassium silicon improved postharvest fruit quality of peach and nectarine (*Prunus persica* (L.) Batsch) Cultivars. *Agriculture*, *13*(1), 195. https://doi.org/10.3390/agriculture13010195

The Association of Official Analytical Chemists – AOAC. (2000) *Official Methods of Analysis*. 17th Ed, Gaithersburg, MD, USA.

Barbey, C., Hogshead, M., Schwartz, A. E., Mourad, N., Verma, S., Lee, S., Whitaker, V. M., & Folta, K. M. (2020). The genetics of differential gene expression related to fruit traits in strawberry (*Fragaria×ananassa*). *Frontiers in Genetics*, *10*, 1–15. https://doi.org/10.3389/fgene.2019.01317

Botero Hoyos, A., Garzón Cortés, G. del P., & González Siabato, N. G. (2022). Oportunidades para crear valor y sostenibilidad en la producción de fresa. *Revista EIA*, *19*(38), 1–20. https://doi.org/10.24050/reia.v19i38.1578

Dehghanipoodeh, S., Ghobadi, C., Baninasab, B., Gheysari, M., & Shiranibidabadi, S. (2018). Effect of silicon on growth and development of strawberry under water deficit conditions. *Horticultural Plant Journal*, *4*(6), 226–232. https://doi.org/10.1016/j.hpj.2018.09.004

Epstein, E. (2009). Silicon: Its manifold roles in plants. *Annals of Applied Biology*, *155*(2), 155–160. https://doi.org/10.1111/j.1744-7348.2009.00343.x

Figueroa, C. R., Rosli, H. G., Civello, P. M., Martínez, G. A., Herrera, R., & Moya-León, M. A. (2010). Changes in cell wall

polysaccharides and cell wall degrading enzymes during ripening of Fragaria chiloensis and *Fragaria×ananassa* fruits. *Scientia Horticulturae*, *124*(4), 454–462. https://doi.org/10.1016/j.scienta.2010.02.003

Galindo López, F., Pinzón Sandoval, E. H., Quintana Blanco, W. A., Serrano, P. A., & Galán, M. (2018). Evaluación de un termofosfato en el crecimiento y producción de fresa (Fragaria x ananassa Duch.) cv. 'Albión'. *Revista U.D.C.A Actualidad & Divulgación Científica*, *21*(1), 61–69. https://doi.org/10.31910/rudca.v21.n1.2018.663

Gerendás, J., & Führs, H. (2013). The significance of magnesium for crop quality. *Plant and Soil*, *368*(1–2), 101–128. https://doi.org/10.1007/s11104-012-1555-2

Ghadirnezhad Shiade, S. R., de Mello Prado, R., Fathi, A., & Carvalho, R. F. (2026). Silicon at the frontline: enhancing plant multistress tolerance. *Journal of Soil Science and Plant Nutrition*, *26*(1), 3089–3111. https://doi.org/10.1007/s42729-026-03052-8

Hajiboland, R., Moradtalab, N., Eshaghi, Z., & Feizy, J. (2018). Effect of silicon supplementation on growth and metabolism of strawberry plants at three developmental stages. *New Zealand Journal of Crop and Horticultural Science*, *46*(2), 144–161. https://doi.org/10.1080/01140671.2017.1373680

Instituto Colombiano de Normas Técnicas y Certificación - ICONTEC. (1997). *Frutas frescas. Fresa variedad Chandler. Especificaciones. Norma Técnica Colombiana ntc 4103*. ICONTEC.

Jarosz, Z., Dzida, K., Zydlik, Z., Jarosz, M., Kamiński, S., & Pitura, K. (2025). Effect of foliar and root silicon supply on yielding and gray mold incidence in strawberry pot cultivation. *Agriculture*, *15*(4), 401. https://doi.org/10.3390/agriculture15040401

Kaushalya Madhavi, B. G., Khan, F., Bhujel, A., Jaihuni, M., Kim, N. E., Moon, B. E., & Kim, H. T. (2021). Influence of different growing media on the growth and development of strawberry plants. *Heliyon*, *7*(6), e07170. https://doi.org/10.1016/j.heliyon.2021.e07170

Khan, M. I. R., Khan, N. A., Sofo, A., & Siddique, K. H. M. (2023). Beneficial elements in plants: developing resilience under stressful environments. *Plant and Soil*, *486*(1–2), 1–5. https://doi.org/10.1007/s11104-023-06056-w

Kim, A. N., Lee, K. Y., Jeong, E. J., Cha, S. W., Kim, B. G., Kerr, W. L., & Choi, S. G. (2021). Effect of vacuum–grinding on the stability of anthocyanins, ascorbic acid, and oxidative enzyme activity of strawberry. *Lwt*, *136*(P1), 110304. https://doi.org/10.1016/j.lwt.2020.110304

Kumar, L., Ramakanth, D., Akhila, K., & Gaikwad, K. K. (2022). Edible films and coatings for food packaging applications: a review. *Environmental Chemistry Letters*, *20*(1), 875–900. https://doi.org/10.1007/s10311-021-01339-z

Li, Y., Xiao, J., Hu, J., & Jeong, B. R. (2020). Method of silicon application affects quality of strawberry daughter plants during cutting propagation in hydroponic substrate system. *Agronomy*, *10*(11), 1753. https://doi.org/10.3390/agronomy10111753

Lo Piccolo, E., Ceccanti, C., Guidi, L., & Landi, M. (2021). Role of beneficial elements in plants: Implications for the photosynthetic process. *Photosynthetica*, *59*(2), 349–360. https://doi.org/10.32615/ps.2021.032

López-Valencia, D., Sánchez-Gómez, M., Acuña-Caita, J. F., & Fischer, G. (2017). Propiedades fisicoquímicas en frutos de siete variedades de fresa (*Fragaria x ananassa Duch*.) durante su maduración. *Ciencia y Tecnología Agropecuaria*, *19*(1), 147–162. https://doi.org/10.21930/rcta.vol19_num1_art:528

Medina-Bolívar, J. S., Pinzón-Sandoval, E. H., & Cely, G. E. (2016). Efecto de sustratos orgánicos en plantas de fresa (Fragaria sp.) cv 'albion' bajo condiciones de campo. *Ciencia y Agricultura*, *13*(2), 19–28. https://doi.org/10.19053/01228420.v13.n2.2016.5548

Meena, V. D., Dotaniya, M. L., Coumar, V., Rajendiran, S., Ajay, Kundu, S., & Subba Rao, A. (2014). A case for silicon fertilization to improve crop yields in tropical soils. *Proceedings of the National Academy of Sciences India Section B - Biological Sciences*, *84*(3), 505–518. https://doi.org/10.1007/s40011-013-0270-y

Mittal, U., Kumar, V., Kukreja, S., Singh, B., Pandey, N. K., & Goutam, U. (2023). Role of beneficial elements in developing resilience to abiotic and biotic stresses in plants: present status and future prospects. *Journal of Plant Growth Regulation*, *42*(6), 3789–3813. https://doi.org/10.1007/s00344-022-10840-w

Nada, M. (2020). Effect of foliar application with potassium silicate and glycine betaine on growth and early yield quality of strawberry plants. *Journal of Plant Production*, *11*(12), 1295–1302. https://doi.org/10.21608/jpp.2020.149800

Ouellette, S., Goyette, M. H., Labbé, C., Laur, J., Gaudreau, L., Gosselin, A., Dorais, M., Deshmukh, R. K., & Bélanger, R. R. (2017). Silicon transporters and effects of silicon amendments in strawberry under high tunnel and field conditions. *Frontiers in Plant Science*, *8*, 1–11. https://doi.org/10.3389/fpls.2017.00949

Öztürk, S., Karakoyun, M., Karaer, M., & Gültaş, H. (2025). The effect of Fe3O4 nanoparticle applications on seedling development in water-stressed strawberry (*Fragaria × ananassa* 'Albion') Plants. *Applied Fruit Science*, *67*(2), 73. https://doi.org/10.1007/s10341-025-01299-6

Pan, Y. W., Cheng, J. H., & Sun, D. W. (2021). Inhibition of fruit softening by cold plasma treatments: affecting

factors and applications. *Critical Reviews in Food Science and Nutrition*, *61*(12), 1935–1946. https://doi.org/10.1080/10408398.2020.1776210

Pang, Z., Nikolic, N., Nikolic, M., Lux, A., & Liang, Y. (2026). Where is plant beneficial element research heading? *Journal of Integrative Agriculture*, *25*(3), 829–846. https://doi.org/10.1016/j.jia.2025.05.008

Park, Y., Muneer, S., Kim, S., Hwang, S., & Jeong, B. (2018). Silicon application during vegetative propagation affects photosynthetic protein expression in strawberry. *Horticulture, Environment, and Biotechnology*, *59*(2), 167–177. https://doi.org/10.1007/s13580-018-0022-2

Peris-Felipo, F. J., Benavent-Gil, Y., & Hernández-Apaolaza, L. (2020). Silicon beneficial effects on yield, fruit quality and shelf-life of strawberries grown in different culture substrates under different iron status. *Plant Physiology and Biochemistry*, *152*, 23–31. https://doi.org/10.1016/j.plaphy.2020.04.026

R Core Team. (2022). *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.* https://www.r-project.org/

Singhal, R. K., Fahad, S., Kumar, P., Choyal, P., Javed, T., Jinger, D., Singh, P., Saha, D., Md, P., Bose, B., Akash, H., Gupta, N. K., Sodani, R., Dev, D., Suthar, D. L., Liu, K., Harrison, M. T., Saud, S., Shah, A. N., & Nawaz, T. (2023). Beneficial elements: New players in improving nutrient use efficiency and abiotic stress tolerance. *Plant Growth Regulation*, *100*(2), 237–265. https://doi.org/10.1007/s10725-022-00843-8

Soares, A. C., de Jesus, M. S., Sargent, S. A., Brecht, J. K., de Oliveira Junior, L. F. G., & Carnelossi, M. A. G. (2025). Quality maintenance and increased firmness of fresh-cut strawberries using vacuum infusion of calcium lactate and pectin methylesterase. *Journal of Food Science*, *90*(11), e70658. https://doi.org/10.1111/1750-3841.70658

Somma, A., Bonelli, L., D'Imperio, M., Montesano, F. F., Blando, F., Santamaria, P., Serio, F., & Gonnella, M. (2025). Silicon partitioning and accumulation in agronomic biofortification of strawberry (Fragaria × ananassa) cv. Sabrosa grown in soilless system. *Scientia Horticulturae*, *350*, 114322. https://doi.org/10.1016/j.scienta.2025.114322

Soppelsa, S., Kelderer, M., Casera, C., Bassi, M., Robatscher, P., Matteazzi, A., & Andreotti, C. (2019). Foliar applications of biostimulants promote growth, yield and fruit quality of strawberry plants grown under nutrient limitation. *Agronomy*, *9*(9), 483. https://doi.org/10.3390/agronomy9090483

Thakral, V., Raturi, G., Sudhakaran, S., Mandlik, R., Sharma, Y., Shivaraj, S. M., Tripathi, D. K., Sonah, H., & Deshmukh, R. (2024). Silicon, a quasi-essential element: Availability in soil, fertilizer regime, optimum dosage, and uptake in plants. *Plant Physiology and Biochemistry*, *208*, 108459. https://doi.org/10.1016/j.plaphy.2024.108459

Udomkun, P., Mahayothee, B., Nagle, M., & Müller, J. (2014). Effects of calcium chloride and calcium lactate applications with osmotic pretreatment on physicochemical aspects and consumer acceptances of dried papaya. *International Journal of Food Science & Technology*, *49*(4), 1122–1131. https://doi.org/10.1111/ijfs.12408

Vinay, K. T., B. K., S., Manohara, K. K., Suganthy, M., Indu Rani, C., Ashokkumar, G., & Jothimani, P. (2026). Biostimulatory effects of silicon on vegetable crop growth, productivity, and stress resilience: A review. *South African Journal of Botany*, *192*, 432–445. https://doi.org/10.1016/j.sajb.2026.03.032

Waldron, K. W., Parker, M. L., & Smith, A. C. (2003). Plant cell walls and food quality. *Comprehensive Reviews in Food Science and Food Safety*, *2*(4), 128–146. https://doi.org/10.1111/j.1541-4337.2003.tb00019.x

Winkler, A., Hurtado, G., & Knoche, M. (2021). Xylem, phloem and transpiration flows in developing strawberries. *Scientia Horticulturae*, *288*, 110305. https://doi.org/10.1016/j.scienta.2021.110305

Xu, X., Lei, X., Zou, G., Liao, S., Sun, N., Sun, Y., & Li, Y. (2024). Deficit irrigation and silicate spray applied since blooming period improved strawberry fruit quality without reducing fruit size. *Horticulture, Environment, and Biotechnology*, *65*(1), 57–69. https://doi.org/10.1007/s13580-023-00553-8

Xu, X., Zhang, Y., Li, Y., Liao, S., Sun, Y., & Liu, F. (2023). Supplemental light and silicon improved strawberry fruit size and sugars concentration under both full and deficit irrigation. *Scientia Horticulturae*, *313*, 111912. https://doi.org/10.1016/j.scienta.2023.111912

Xu, X., Zou, G., Li, Y., Sun, Y., & Liu, F. (2023). Silicon application improves strawberry plant antioxidation ability and fruit nutrition under both full and deficit irrigation. *Scientia Horticulturae*, *309*, 111684. https://doi.org/10.1016/j.scienta.2022.111684

Yang, X., Ni, Y., Li, Z., Yue, K., Wang, J., Li, Z., Yang, X., & Song, Z. (2024). Silicon in paddy fields: Benefits for rice production and the potential of rice phytoliths for biogeochemical carbon sequestration. *Science of the Total Environment*, *929*, 172497. https://doi.org/10.1016/j.scitotenv.2024.172497