Method of Silicon Application Affects Quality of Strawberry Daughter Plants during Cutting Propagation in Hydroponic Substrate System

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Abstract: The beneficial effects that silicon (Si) has on plant growth as well as resistance to biotic and abiotic stresses have been well documented for many crops in recent years. However, few studies focus on the effects of Si on plant growth during the propagation stage of strawberry (Fragaria × ananassa, Duchesne). This study was conducted to investigate the optimal method for Si application during the cutting propagation of strawberry in soilless cultivation. Strawberry mother plants were supplied with Si through foliar spray, runner spray, or root drench before the cutting propagation, then half of the daughter plants in each treatment received continued Si supply through foliar spray or through root drench after the cutting propagation. The results showed that the plant height, petiole length and diameter, leaf length and width, shoot fresh and dry weights, and root fresh and dry weights were significantly increased by Si root drench both before and after the cutting propagation. Moreover, plants absorbed more Si by drench than by spray, and the absorbed Si was only able to be transported from the root to the shoot, and from the mother plant to the daughter plant. Further research found that the chlorophyll fluorescence parameter of the maximum quantum efficiency of the photosystem II (Fv/Fm) and the activities of superoxide dismutase, ascorbate peroxidase, and guaiacol peroxidase were also enhanced while catalase did not change under a high temperature stress in strawberry treated with Si before and after cutting propagation by root drench. Thus, Si application by drenching the roots during the whole propagation period is recommended to increase the quality of the strawberry daughter plants in soilless cultivation.

Keywords: silicon; soilless; high temperature; chlorophyll fluorescence; antioxidant enzyme

1. Introduction

Strawberry (Fragaria × ananassa, Duchesne) is an economically important fruit crop contributing to human nutrition and agricultural output. Strawberry is cultivated on 6421 hectares and the annual yield is 233,291 tons in the Korea (Korean Statistical Information Service—KOSIS, 2019), which ranks sixth worldwide [1]. Thus, the economic value of strawberry is extremely high in Korea. Strawberry plants are mostly propagated through the daughter plants on the runners [2]. Growers start to prepare the mother plants in March to grow the runners and propagate the daughter plants by cutting or pinning in June. The propagated plants are usually kept in a greenhouse until they are transplanted into the soil or hydroponic systems in September. The temperature in greenhouses reaches up to 40 °C during the day in summer, which may lead to morphological and physiological changes due to the production of reactive oxygen species (ROS) caused by the high temperature stress [3]. Furthermore,
the photosynthesis and flower development are also inhibited under high temperature stresses [4–6]. Therefore, improving the quality of the propagated plants not only helps resist stresses, but also is beneficial to flowering and fruiting.

Silicon (Si) is considered to be “quasi-essential” due to the far-reaching benefits it confers on plants [7], which include enhanced growth, yield, photosynthesis, and response to abiotic and biotic stresses [8]. The beneficial role of Si has been extensively studied for crop plants, such as rice (Oryza sativa L.), barley (Hordeum vulgare L.), wheat (Triticum aestivum L.), and soybean (Glycine max L.) [9–13], whereas relatively fewer such studies have been reported for horticultural plants. Strawberry is a Si-accumulator species [14]. Application of Si improved the vegetative growth and fruit quality in strawberry [15,16]. Researchers also found that Si plays an important role in mitigating abiotic stresses like high temperature, high salinity, drought, and biotic stresses like powdery mildew in strawberry [3,17–23]. Moreover, two strawberry Si transporters named Lsi1 and Lsi2 were first identified in 2017 [24], which provided new evidence for Si uptake and promoted the studies of the internal mechanisms with which Si is transported in strawberry.

Growers are recently trending toward planting strawberries in hydroponic systems filled with soilless media all around the world. It was reported that hydroponic cultivation increased the growth, productivity, and fruit quality through intensive and effective management [25,26]. The hydroponic systems also make the plants grow to an increased height, which benefits growers as the plants become easier to cultivate and the fruits less fatiguing to pick [27,28]. Moreover, the recyclable nutrient solution of hydroponic systems is economical and environmentally friendly [29]. The planting area of strawberry in hydroponic systems accounts for about 12% of all strawberry production in Korea. Generally, hydroponic cultivation of strawberry produced 26% more yield per plant with less unmarketable fruits compared to that of strawberry planted in soil in Korea, according to the data from the Rural Development Administration. In addition, most commercial strawberry plants are propagated in soilless plug trays [30].

Although Si is the second most abundant element in the soil [31], Si may not be as prevalent in soilless cultivation. This study was conducted to investigate the optimal method of Si application during strawberry cutting propagation in soilless substrates. To further identify the quality of the propagated plants after Si treatments, the chlorophyll fluorescence parameters and activities of antioxidant enzymes were also measured under a high temperature stress.

2. Materials and Methods

2.1. Plant Materials and Silicon Treatments

The runner plants of strawberry “Seolhyang” were purchased from a strawberry farm (Sugok-myeon, Jinju, Gyeongsangnam-do, Korea) and stuck in the BVB Medium (Bas Van Buuren Substrate, EN-12580, De Lier, Westland, The Netherlands) in 21-cell zigzag trays (21-Zigpot/21 cell tray, Daeseung, Jeonju, Korea) on 1 November 2019. The plants were then put on a propagation bench with a fogging system for rooting. The relative humidity inside the fogging tunnel was around 80%. Two weeks later, the plants were moved out from the fogging tunnel and cultured in a glasshouse at Gyeongsang National University, Jinju, Korea for two months. The plants were transplanted to a hydroponic cultivation system filled with the BVB Medium on 17 January 2020.

The application of Si from potassium silicate (K$_2$SiO$_3$) was started on 17 March 2020. Plants were treated with Si by spraying the runners of the mother plants (SR), spraying the leaves of the mother plants (SL), or drenching the roots of the mother plants (Dr) at a final Si concentration of 75 mg·L$^{-1}$ every day. Because of the strawberry mother plants were planted in the hydroponic gutters and the runners were hanging out of the gutters, thus, there was no possibility for moistening the roots with Si during spraying the runners. Cutting propagation for the similarly sized daughter plants was started on 20 May 2020, and samples of leaves from the mother and daughter plants were collected on the same day to detect the silicon content. Daughter plants were stuck in 21-cell zigzag trays with the
BVB Medium under a fogging system for two weeks to grow the roots. Then the daughter plants from each treatment were separated into two groups and supplied with 0 or 75 mg L$^{-1}$ of Si every day. The control group, whose mother plants were not supplied with Si, was separated into three groups; one group was supplied with distilled water by foliar spray and the other two were supplied with 75 mg L$^{-1}$ of Si through foliar spray or root drench, respectively. The treatments were designated as the control (supply 0 mg L$^{-1}$ Si before and after cutting propagation), C-S (supply 0 mg L$^{-1}$ Si before the cutting propagation and 75 mg L$^{-1}$ Si through spraying the leaves after the cutting propagation), C-D (supply 0 mg L$^{-1}$ Si before the cutting propagation and 75 mg L$^{-1}$ Si through root drench after the cutting propagation), SR-0 (supply 75 mg L$^{-1}$ Si on runners through spraying before the cutting propagation and 0 mg L$^{-1}$ Si after the cutting propagation), SR-S (supply 75 mg L$^{-1}$ Si on runners through spraying before the cutting propagation and spray 75 mg L$^{-1}$ Si on leaves after the cutting propagation), SL-0 (supply 75 mg L$^{-1}$ Si through spraying the leaves of the mother plants before the cutting propagation and 0 mg L$^{-1}$ Si after the cutting propagation), SL-S (supply 75 mg L$^{-1}$ Si through spraying the leaves of the mother plants before the cutting propagation and continuing to spray 75 mg L$^{-1}$ Si on leaves after the cutting propagation), D-0 (supply 75 mg L$^{-1}$ Si through root drench before the cutting propagation and 0 mg L$^{-1}$ Si after the cutting propagation), D-D (supply 75 mg L$^{-1}$ Si through root drench before and after the cutting propagation).

2.2. Measurements of the Growth Parameters

The growth parameters of the daughter plants, such as the plant height, petiole length and diameter, leaf length and width, and fresh and dry weights of the shoot and root, were collected after a 45-day treatment of the cutting propagation. The dry weights of the shoot and root were measured after one week of drying in an oven (FO-450M, Jeio Technology Co. Ltd., Daejeon, Korea) at 60 °C. Diameters of the petiole were measured using a Vernier caliper (CD-20CPX, Mitutoyo Korea Co., Gunpo, Korea). The dried leaves and roots were further used to determine the Si content.

2.3. Determination of the Si Content

The Si content was measured according to the method of Zhang et al. [32]. Dried leaves and roots of plants from each treatment were ground using a stainless mill (Cytclotec, Model 1093, Tector, Hoganas, Sweden). Afterwards, 0.3 g samples were ashed in a Nabertherm muffle furnace (Model LV 5/11/B180, Lilienthal, Bremen, Germany) at 525 °C for 4 h. The ash was dissolved in 5 mL of 25% HCl, followed by dilution with 10 mL of room-temperature distilled water and 15 mL of hot distilled water. The filtered solutions were then measured three times using an inductively coupled plasma (ICP) spectrometer (Optima 4300DV/5300DV, Perkin Elmer, Germany).

2.4. High Temperature Stress Treatment

The daughter plants were transplanted into 10-cm pots filled with the BVB Medium before being subjected to high temperature stress. Two weeks later, strawberry daughter plants of the same size were selected from each treatment and placed in plant growth chambers at 42 °C or 23 °C for 1 week. Each treatment consisted of 3 replicates with 3 plants for each replicate. The plants were randomly placed in the growth chambers. Samples were collected at the end of the treatment and frozen in liquid nitrogen before storage in a −80 °C refrigerator.

2.5. Chlorophyll Fluorescence Parameters

The chlorophyll fluorescence parameters were measured every 24 h using a portable fluorometer (FluorPen FP110, Photon Systems Instruments, Drásov, Czech Republic).
2.6. Activities of Antioxidant Enzymes

Fresh frozen leaf samples were ground and homogenized in a 50 mM sodium phosphate buffer (pH 7.0) containing 1 mM EDTA, 0.05% triton X, and 1 mM polyvinylpyroloilone. The mixtures were then centrifuged at 13,000× g rpm for 15 min at 4 °C. Later, the supernatants were used for the assay of the antioxidant enzyme activities. The activities of superoxide dismutase (SOD), ascorbate peroxidase (APX), guaiacol peroxidase (GPX), and catalase (CAT) were measured with a UV spectrophotometer (Libra S22, Biochrom Ltd., Cambridge, UK) based on the methods of Manivannan et al. [33].

2.7. Statistical Analysis

The SAS statistical software, release 8.2 (SAS Inst., Cary, NC, USA) was used for the statistical analysis according to the analysis of variance (ANOVA) and Duncan’s multiple range test at a significance level of \( p = 0.05 \). F-test was also calculated based on Fisher’s least significant difference test at a threshold of \( p = 0.05 \). Pearson’s correlation coefficient was calculated by SPSS 17.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Growth and Development of Strawberry Daughter Plants as Affected by Si

The morphology of the daughter plants is shown in Figure 1. Strawberry plants treated with Si were bigger compared to those in the control, especially for the plants supplied with Si both before and after the cutting propagation, and more roots were produced in these treatments as well. All the growth parameters were significantly increased in D-D (Table 1). The shoot fresh and dry weights were also promoted in the other treatments except for C-S and SR-0. Although the root fresh and dry weights were significantly increased after the Si supply, the length of the longest root did not vary significantly among the differently treated strawberry plants. The results of the F-test revealed that the application methods before and after the cutting propagation significantly affected the plant height, leaf length, leaf width, shoot fresh and dry weights, and root fresh weight; Si application after the propagation also affected the petiole diameter and root dry weight. There was no interaction for Si application before and after cutting propagation, except for shoot fresh weight.

![Figure 1](image_url)
Table 1. Growth of strawberry daughter plants under different treatments.

| Applications before Cutting (A) | Applications after Cutting (B) | Plant Height (cm) | Petiole | Leaf | Shoot | Root |
|--------------------------------|--------------------------------|-------------------|---------|------|-------|------|
|                                |                                |                   | Length (cm) | Diameter (mm) | Length (cm) | Width (cm) | Fresh Weight (g) | Dry Weight (g) | Fresh Weight (g) | Dry Weight (g) | Length (cm) |
| Control                        |                                |                   | 20.83 ab | 3.31 c   | 9.32 cd | 7.67 bc | 14.69 f   | 2.61 d   | 4.23 d   | 0.37 d   | 24.98 a    |
| S                              |                                |                   | 19.12 b  | 3.41 bc  | 9.65 bc | 8.13 b  | 14.69 f   | 3.39 c   | 5.31 bc  | 0.56 bc  | 25.11 a    |
| D                              |                                |                   | 34.00 ab | 2.71 ab  | 10.18 bc| 8.33 b  | 23.15 b   | 4.29 b   | 6.71 ab  | 0.69 ab  | 25.10 a    |
| SR                             |                                |                   | 30.98 bc | 32.77 abc| 22.55 a | 3.30 c  | 9.13 d    | 7.35 c   | 16.64 ef | 3.38 c   | 5.25 bc  | 25.98 a    |
| S                              |                                |                   | 30.02 c  | 34.07 ab | 22.70 a | 3.41 bc | 9.68 bcd  | 7.82 b   | 20.88 bc | 4.40 b   | 6.25 b   | 25.85 a    |
| SL                             |                                |                   | 34.00 ab | 34.58 ab | 22.70 a | 3.58 bc | 10.33 b   | 8.12 b   | 19.57 cd | 3.76 bc  | 6.84 ab  | 26.97 a    |
| S                              |                                |                   | 30.02 c  | 34.58 ab | 23.15 b | 3.89 a  | 11.30 a   | 9.59 b   | 27.54 a  | 5.41 a   | 8.02 a   | 25.86 a    |
| Dr                             |                                |                   | 36.70 a  | 34.58 ab | 21.13 ab| 3.31 c  | 10.07 bc  | 8.02 b   | 17.70 de | 3.38 c   | 5.58 bc  | 0.57 bc  | 25.86 a    |
| D                              |                                |                   | 36.70 a  | 34.58 ab | 23.83 a | 3.89 a  | 11.30 a   | 9.58 b   | 27.54 a  | 5.41 a   | 8.02 a   | 25.77 a    |

\[^2\] Lowercase letters indicate significant differences calculated by Duncan’s multiple range test at \(p \leq 0.05\); \[^7\] NS, *, **, and *** represent non-significant or significant at \(p \leq 0.05, 0.01,\) and \(0.001,\) respectively. SR, spraying the runners; SL, spraying the leaves; Dr, drenching the roots; S, spraying the leaves; D, drenching the roots.
3.2. The Si Content in Strawberry

Leaf samples were collected before the cutting propagation, when daughter plants have not been detached from with their mother plants, to investigate the Si transport between the mother and daughter plants. Both spraying the leaves and drenching the roots of the mother plants promoted the Si content in mother and daughter plants (Figure 2A). However, spraying Si on runners only increased the Si content in daughter plants. The contents of Si in leaves and roots after the cutting propagation were also measured (Figure 2B). Foliar Si spray on strawberry plants after the cutting propagation promoted the Si content in leaves. However, the Si contents in the roots did not show any difference compared with those in the control after the foliar spray. Drenching the roots (C-D and D-D) promoted the Si contents in both the leaves and the roots. Furthermore, the Si contents were maintained at the same level as that in the control for the strawberry that were only treated with Si before the cutting propagation.

![Figure 2.](image)

**Figure 2.** The Si content in different tissues of strawberry plants after being treated with Si. (A), Si content in leaves of mother or daughter plants before cutting propagation; (B), Si content in leaves or roots after cutting propagation. Lowercase letters indicate significant differences calculated by Duncan’s multiple range test at \( p \leq 0.05 \). Vertical bars indicate the standard error (n = 3). The letters before the hyphen indicate Si being applied before the cutting propagation, while the letters after the hyphen represent Si being supplied after the cutting propagation. C, control; SR, spraying the runners; SL, spraying the leaves; Dr, drenching the roots; D, drenching the roots; 0, spraying distilled water; S, spraying the leaves.

3.3. Change of the Chlorophyll Fluorescence Parameters

The chlorophyll fluorescence parameters of the photosystem II (PS II) began to show differences among the treatments after a 1-week in a 42 °C growth chamber. The leaves in the control and SL-0 turned distinctly yellow under high temperature stress (Figure 3A). The chlorophyll fluorescence parameters of the maximum/potential quantum efficiency of PS II (Fv/Fm) and the maximum primary yield of PS II photochemistry (Fv/F0) were significantly decreased among different treatments except for C-D and D-D under high temperature stress compared to plants in 23 °C. However, the values of Fv/Fm were significantly increased in C-S, C-D, and D-D, while they were decreased in SL-0 compared to that of the control under high temperature stress (Figure 3B). The values of Fv/F0 also decreased in SL-0 compared with that of the other treatments under high temperature stress (Figure 3C).
3.4. Antioxidant Enzyme Activities

The activities of the antioxidant enzymes in leaves under a high temperature stress or normal temperature for 1 week were analyzed. The activities of SOD, APX, and GPX were significantly decreased while CAT did not change under high temperature stress compared with unstressed plants (Figure 4). However, the activities of SOD and APX in SR-0, SR-S, and D-D were significantly promoted compared with those in the control under high temperature stress (Figure 4A,B). The activities of GPX were higher in D-0 and D-D under 42 °C (Figure 4C). There were no significant differences for the activities of CAT in plants treated with or without Si under the high temperature (Figure 4D).
Figure 4. The activities of superoxide dismutase (SOD) (A), ascorbate peroxidase (APX) (B), guaiacol peroxidase (GPX) (C), and catalase (CAT) (D) as affected by a high temperature in the different treatments. Lowercase letters indicate significant differences calculated by Duncan’s multiple range test at $p \leq 0.05$. Vertical bars indicate the standard error ($n = 3$). The letters before the hyphen indicate Si being applied before the cutting propagation, while the letters after the hyphen represent Si being supplied after the cutting propagation. C, control; SR, spraying the runners; SL, spraying the leaves; D, drenching the roots; 0, spraying distilled water; S, spraying the leaves.

3.5. Correlation Analysis

Pearson’s correlation analysis revealed a significant positive correlation of Si contents in leaves and roots with plant height, petiole diameter, leaf length and width, shoot fresh and dry weight, root fresh and dry weight, Fv/Fm, and Fv/F0 (Table 2). The activities of antioxidant enzymes did not correlate with other parameters (data not shown).
Table 2. Correlation analysis between different parameters measured in this study.

| Correlation Coefficient | Petiole Length | Petiole Diameter | Leaf Length | Leaf Width | Shoot Fresh Weight | Shoot Dry Weight | Root Fresh Weight | Root Dry Weight | Root Length | Si Content in Leaves | Si Content in Roots | Fv/Fm | Fv/F0 |
|-------------------------|----------------|------------------|-------------|------------|-------------------|------------------|-------------------|-----------------|-------------|---------------------|---------------------|-------|-------|
| Plant height            | 0.94 **        | 0.32 *           | 0.48 **     | 0.26       | 0.59 **           | 0.56 **          | 0.58 **           | 0.38 **         | 0.1         | 0.39 **             | 0.29 *              | 0.04  | -0.05|
| Petiole length          | 0.19           | 0.21             | 0.49 **     | 0.04       | 0.48 **           | 0.49 **          | 0.49 **           | 0.32 *          | 0.08        | 0.25                | 0.14                | -0.01 | -0.08|
| Petiole diameter        | 0.50 **        | 0.42 **          | 0.60 **     | 0.42 **    | 0.48 **           | 0.49 **          | 0.45 **           | -0.08           | 0.61 **     | 0.56 **             | 0.24                | 0.16  |       |
| Leaf length             | 0.84 **        | 0.53 **          | 0.48 **     | 0.53 **    | 0.46 **           | 0.26             | 0.09              | 0.57 **          | 0.59 **     | 0.09                | 0.08                |       |       |
| Leaf width              | 0.43 **        | 0.45 **          | 0.36 **     | 0.45 **    | 0.36 **           | 0.26             | 0.08              | 0.60 **          | 0.60 **     | 0.07                | 0.09                |       |       |
| Shoot fresh weight      | 0.88 **        | 0.81 **          | 0.64 **     | 0.81 **    | 0.04              | 0.78 **          | 0.66 **           | 0.12             | 0.02        |                    |                     |       |       |
| Shoot dry weight        | 0.87 **        | 0.81 **          | 0.06        | 0.81 **    | 0.71 **           | 0.57 **          | 0.25              | 0.17             |            |                    |                     |       |       |
| Root fresh weight       | 0.75 **        | 0.13             | 0.58 **     | 0.13       | 0.58 **           | 0.50 **          | 0.50 **           | 0.25             | 0.13        |                    |                     |       |       |
| Root dry weight         | 0.04           | 0.05             | 0.93 **     | 0.05       | 0.45 **           | 0.31 *           | 0.19              | 0.12             |            |                    |                     |       |       |
| Root length             | 0.05           | 0.25             | 0.32 *      | 0.05       | 0.55              | 0.31 *           | 0.27              | 0.65             |            |                    |                     |       |       |
| Si content in leaf      | 0.93 **        | 0.32 *           | 0.31 *      | 0.93 **    | 0.32 *            | 0.31 *           | 0.27              | 0.65             |            |                    |                     |       |       |
| Si content in root      | 0.29 *         | 0.27 *           | 0.65 **     | 0.29 *     | 0.27 *            | 0.65 **          | 0.27              | 0.65             |            |                    |                     |       |       |

**; * p < 0.01, 0.05, respectively. Fv/Fm, the maximum quantum efficiency of the photosystem II; Fv/F0, the maximum primary yield of photosystem II photochemistry.
4. Discussion

The effects of Si on the growth and development vary from plant to plant. It either increases or decreases the plant height, stem diameter, fresh and dry weights, flower diameter, and leaf thickness for some floricultural crops [34]. In this study, the fresh and dry weights of the shoots and roots were significantly increased after the strawberry plants were supplied with Si both before and after the cutting propagation by drenching the roots. Foliar spray also increased the weights of the shoots and roots in some treatments. Few studies have compared the morphological responses to Si by foliar spray and root drench. However, researchers found that plants absorbed more Si through root drench than through foliar spray [35,36]. Our results also showed that root drench resulted in a higher Si accumulation in the leaves than foliar spray did (Figure 2B). Thus, the treatment D-D, which resulted in the highest level of Si in the strawberry plants, significantly increased the plant height, petiole diameter, leaf length, and fresh and dry weights of the shoots and roots. Furthermore, the growth stage of the plants at which Si is supplied also affects the plant growth. Researchers found the Si supply during the reproductive stage was more important for plant growth [37,38]. Our results showed that all the growth parameters except for petiole and root length were significantly correlated with Si content in leaves and roots (Table 2). Thus, strawberry plants treated with Si during the whole propagation process were stronger than plants only treated with Si before or after the cutting propagation during this stage.

The Si transport in strawberry was unidirectional; from the root to the shoot, and from the mother plant to the daughter plant. The Si content in leaves was significantly increased after Si was supplied by drenching the roots, even higher than that in the roots. However, the Si content in the roots did not increase after a foliar spray of Si. These results suggest that Si can only be transported from the root to the leaf. A model to decipher the Si uptake, transport, and distribution system in higher plants, which involves uptake and radial transport in the root, xylem and inter-vascular transport, xylem unloading, and deposition in leaves has been developed based on the cooperation of Si influx channels and efflux transporters in recent years [39]. Researchers found that more than 90% of the Si uptake by the roots was translocated to the shoot [40]. Leaves also have the capacity to absorb Si. The mechanism of Si uptake by leaves has not been clear until now. Some researchers suggested that leaves could absorb silicic acid directly and/or stimulate the plant to absorb more nutrients including Si from the soil [41]. Since the Si content in the roots did not increase after foliar Si spray, we considered that strawberry leaves absorb the Si directly instead of stimulating the plants to absorb Si from the soil, and the Si absorbed by leaves was not transported to the roots. More research is needed to understand the mechanism with which Si is absorbed and transported after foliar Si applications. Moreover, the Si can only be transported from mother plants to daughter plants. Both foliar spray and root drench of mother plants significantly promoted the Si accumulation in daughter plants, while spraying the runner plants did not increase the Si content in the mother plants. It is logical that mother plants nurture daughter plants, but whether or not there are any transporters involved in this process still remains unknown.

The beneficial effects of Si on photosynthesis have been well reported for various abiotic stresses. Chlorophyll fluorescence parameters provide useful information about the activity of PSII. Both Fv/Fm and Fv/F0 are related to the photosynthetic efficiency of plant leaves [42]. In this study, the value of Fv/Fm was increased in D-D, C-S, and C-D compared with that of the control under a high temperature stress, while the Fv/F0 did not show any differences among the treatments except for SL-0. However, the correlation analysis revealed that both Fv/Fm and Fv/F0 were significantly correlated with Si content in leaves and roots, which indicates that Si may alleviate heat stresses to some extent. The effects of high temperatures on the photosynthesis varies according to the plant species and temperature. Maize (Zea mays L.) leaves subjected to a high temperature in the dark showed a decrease in photosynthesis at temperatures above 35 °C, whereas in potato (Solanum tuberosum L.), the Fv/Fm was significantly decreased only at temperatures above 42 °C [43]. Thus, researchers suggested that a heat-sensitive component of the photosynthetic apparatus may be located downstream of the PSII and before the
carbon cycle \[44\]. This theory may explain the little change of Fv/F0 among the treatments in this study. Few studies have reported the change of the chlorophyll fluorescence parameters under a high temperature in strawberry until now \[45\]. Far more research is needed to fully understand photosynthesis under high temperatures in strawberry plants.

High temperature causes abundant production of ROS such as superoxide radicals (O$_2^{•−}$) and hydrogen peroxide (H$_2$O$_2$), which is deleterious to plants \[46\]. The SOD enzyme that is the first line of defense can convert O$_2^{•−}$ to H$_2$O$_2$ and oxygen, and the H$_2$O$_2$ is further eliminated by APX, GPX, and CAT \[47,48\]. The activities of SOD, APX, and GPX were enhanced in D-D, suggesting D-D may lead to less injury under a high temperature stress. Moreover, the increased activities of SOD and APX in SR-0 and SR-S indicate that those two treatments may also relieve the damage caused by high temperature stresses to some extent.

5. Conclusions

Our results suggested that Si increased plant growth during the cutting propagation, and also that the D-D treatment was the best for improving the growth of the daughter plants. Most Si absorbed by the roots were translocated to the leaves, while the Si absorbed by leaves was not transported to the roots. Moreover, the Si was only transported from the mother plant to the daughter plant. Furthermore, plants in the D-D treatment also suffered from less injury caused by high temperature, because photosynthesis was less affected by the high temperature and the activities of SOD, APX, and GPX were also increased to scavenge the overproduction of the ROS.

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