Silicon Supplements Affect Horticultural Traits of Greenhouse-produced Ornamental Sunflowers

Sophia Kamenidou and Todd J. Cavins
Department of Horticulture and Landscape Architecture, Oklahoma State University, Stillwater, OK 74078-6027

Stephen Marek
Department of Entomology and Plant Pathology, Oklahoma State University, Stillwater, OK 74078-6027

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Abstract. In greenhouse production, most floricultural crops are cultivated in soilless substrates, which often supply limited amounts of plant-available silicon (Si). The goal of this study was to determine the effects of Si supplementation on greenhouse-produced ornamental sunflower (Helianthus annuus L. ‘Ring of Fire’). Potassium silicate (KSiO$_3$)$_2$ substrate incorporation or weekly substrate drenches, sodium silicate (Na$_2$SiO$_3$) foliar applications, and rice husk ash substrate incorporation were used as Si supplements. Silicon content of Si-treated plants increased compared with untreated controls. Depending on the source and concentration of silicon supplied, several horticultural traits were improved as a result of Si supplementation. Thick, straight stems, increased flower and stem diameters, and increased height were observed in some of the treatments, upgrading sunflower quality compared with untreated controls. However, growth abnormalities were observed when concentrations of 100 and 200 mg L$^{-1}$ Si were supplied as KSiO$_3$ substrate drenches. In these treatments, plants appeared stunted with deformed flowers and were delayed in flowering. Consequently, Si supplementation effects on greenhouse-produced sunflowers can vary from beneficial to detrimental depending on the applied source and concentration.

Materials and Methods

Plant material and silicon supplements. Ornamental sunflower, Helianthus annuus ‘Ring of Fire’ (Ernst Benary Samenzeitung GmbH, Hann. Muenden, Germany), was selected for this study because of its importance to the cut flower industry and uniformity of growth. Sunflower seeds were sown into 0606 (2.7 L/36 plants) bedding plant flats using a soilless commercial substrate (BM2, St. Modeste, Quebec, Canada) and seedlings were transplanted into 20.3-cm diameter (1.8 L) containers when four to six true leaves were present to ensure growth uniformity of replicates before Si applications.

The substrate was 4:1 (by volume) perlite with 875 g m$^{-3}$ MicroMax (The Scotts Co., Marysville, OH). The sources, concentrations, and method of application of Si were: rice husk ash substrate incorporation (33, 66, and 100 g m$^{-3}$ Si), potassium silicate (KSiO$_3$) hydrous powder substrate incorporation (70, 140, and 280 g m$^{-3}$ Si), five weekly sodium silicate (Na$_2$SiO$_3$) foliar applications (50, 100, and 150 mg L$^{-1}$ Si), and five weekly KSiO$_3$ substrate drenches (50, 100, and 200 mg L$^{-1}$ Si). The rice husk ash was a natural byproduct with high Si content (RiceLand Industries, Jonesboro, AR) and all KSiO$_3$ and Na$_2$SiO$_3$ were from PQ Corporation (Valley Forge, PA). Two rates of limestone were used to equilibrate pH levels among treatments. Dolomitic limestone was added at 5 kg m$^{-2}$ to the substrates used for the control, ashed rice husks, and sodium silicate foliar treatments, whereas a reduced rate of 3.5 kg m$^{-2}$ was added to substrates used for the potassium silicate drenches and substrate incorporation as a result of the alkaline pH of the KSiO$_3$ solution. These two rates of dolomitic limestone are commonly used in greenhouse production (R. Vetanovetz, Sun Gro Horticulture, personal communication). Plants were grown in poly-carbonate-covered greenhouses with night/day set temperatures of 15/18 °C and fertilized with 150 mg L$^{-1}$ N from 20N–4.4P–16.6K complete fertilizer (The Scotts Co.) that also contained WET FOOT “L,” a wetting agent at 33 mL L$^{-1}$ H$_2$O (Parkway Research Corp., Houston, TX). Data collection, elemental and statistical analyses. Data collected included weekly pH and electrical conductivity values, days to anthesis (first flower) from transplant into final containers, height, flower diameter, and dry weights for the main stem and the first fully expanded flower for each replicate. Two stem diameters were measured by caliper, one at the base of the main stem (basal stem

Silicon (Si) is not considered an essential nutrient for most plants with the exception of some Equisitaceae members and generally is not incorporated in commercially available fertilizers (Epstein, 1994). Nowadays in Japan, Si is considered an agronomically essential element because the beneficial effects of Si, including enhanced growth and quality, photosynthesis stimulation, transpiration reduction, and increased plant resistance to abiotic and biotic stresses, are well-established in several agricultural crops (Ma and Takahashi, 2002).

The positive effects of Si observed in agronomic crops have generated interest for research with horticultural crops as well. The reported effects vary and depend strongly on plant species. Several researchers have noted a relationship between Si and disease suppression of horticultural crops like cucumber (Cucumis sativus L.), miniature roses (Rosa sp.), and zinnia (Zinnia elegans Jacq.) (Cherif et al., 1992; Datnoff et al., 2006; Dick et al., 1998; Locke et al., 2006; Menzies et al., 1991). Silicon-supplemented melon (Cucumis melo L.) contained higher chlorophyll levels and reduced transpiration rates compared with untreated plants (Lu and Cao, 1991). Silicon sprays significantly reduced the occurrence and severity of bract necrosis of poinsettia (Euphorbia pulcherrima Willd. ex. Klotzsch), a physiological disorder caused by calcium deficiency. This effect was attributed to reduced evapotranspiration (McAvoy and Bernard, 1996). Silicon supplementation of hydroponically cultured gerbera resulted in a higher percentage of flowers grading as Class I and significantly thicker flower stems (Savvas et al., 2002).

Silicon is a predominant element in mineral soils. However, in greenhouse floriculture production, most plants are cultivated using soilless substrates in which Si availability is limited (Voogt and Sonneveld, 2001). The majority of studies with horticultural crops generally emphasized either disease management or physiological differences between Si-treated and untreated plants. There is limited evidence that Si supplementation affects the aesthetic qualities of ornamental crops. The objectives of this work were to determine the effects of different Si sources, concentrations, and methods of application on the horticultural traits of greenhouse-produced ornamental sunflowers. Silicon supplements were evaluated based on Si concentrations accumulated in plant tissues; visual quality characteristics such as height, stem, and flower diameter; and days to anthesis after transplanting.
diameter) and the second one below the top flower (apical stem diameter). Tissues sampled were recently mature leaves, stem, and the first fully expanded flower. For the silicon plant tissue analysis, each treatment was analyzed in triplicate and included leaf, stem, and flower samples from each treatment plus the untreated control. Plant tissues from NaSiO$_3$ foliar application treatments were not submitted to elemental analysis since surface accumulation of silicon-biased measurements and did not represent silicon deposition within the tissues. For all the other elements, analyses were performed on leaf tissues. Leaf samples were analyzed for nitrogen by dry combustion using the NS2000 (Leco, St. Joseph, MI) and by inductively coupled plasma spectrometry (ICAP 9000 OE2; Jarrell Ash Corp., Franklin, MA) for P, K, Ca, Mg, B, Cu, Fe, Mn, Zn, Mo, Na, and Al. In this study, four Si sources at three different rates each were used resulting in 12 Si treatments plus Si untreated controls with 20 plants/replicates per treatment. The data were analyzed using the one-way analysis of variance procedure of SAS statistical analysis software (SAS Institute, Cary, NC). Least square means were determined using the LSMEANS statement in PROC GLM. Mean separation were determined using the PDFF statement in PROC GLM.

**Silicon extraction and analysis.** A modified Si extraction procedure was used (Novozamsky et al., 1984) for leaf, flower, and stem samples. Extracted silicon was quantified using a blue silicomolybdic acid, colorimetric procedure (Taber et al., 2002).

**Results and Discussion**

The effect of Si supplements on sunflower height and flower diameter varied depending on Si source and concentration (Table 1). Incorporation of hydrous KSiO$_3$ powder (140 g m$^{-3}$ Si) resulted in taller plants than the control. On the contrary, a decrease in plant height and flower diameter was observed when the substrate was drenched with KSiO$_3$ (200 mg L$^{-1}$ Si). All other Si treatments were similar in height to the untreated controls. The mechanism of Si supplementation’s effect on height is unclear, but Si has been previously reported to increase stem number and shorten stems (Voogt and Sonneveld, 2001). Some of the Si treatments affected flower diameter of sunflower compared with the untreated control. Flower diameters increased 0.8, 0.8, and 0.9 cm with rice husk ash (100 g m$^{-3}$ Si), NaSiO$_3$ (100 mg L$^{-1}$ Si), and hydrous KSiO$_3$ (140 g m$^{-3}$ Si), respectively. Although not measured in our study, Si application has been found to reduce evapotranspiration (Lu and Cao, 2001; McAvoy and Bernard, 1996), which could have contributed to increased turgor pressure within the flower, resulting in cell swelling and thus larger flower diameters. Conversely, a decrease in flower diameter was observed in plants drenched weekly with KSiO$_3$ (200 mg L$^{-1}$ Si), indicating the horticultural benefits of Si are dependent on the form and concentration of the Si applied.

Several combinations of Si source and concentration increased stem diameter (Table 1). Rice husk ash substrate incorporation (100 g m$^{-3}$), KSiO$_3$ substrate incorporation (140 g m$^{-3}$ Si), foliar NaSiO$_3$ applications (50, 100, and 150 mg L$^{-1}$ Si), and KSiO$_3$ drench (50 and 100 mg L$^{-1}$) increased both basal and apical stem diameters (Table 1). Substrate incorporation of hydrous KSiO$_3$ powder at 280 g m$^{-3}$ Si and KSiO$_3$ drenches of 200 mg L$^{-1}$ Si increased apical stem diameters only. As noted previously, reduced evapotranspiration may have contributed to the increased cell turgor pressure. Additionally, deposition of Si could have also contributed to increased thickness and mechanical strength of stems (Epstein, 1994). Delayed flowering, occurring 3 to 5 d after the controls, was observed in plants treated with weekly KSiO$_3$ substrate drenches. No other treatments affected days to anthesis. Deformed flower heads were also observed in plants supplemented with weekly KSiO$_3$ substrate drenches of 100 and 200 mg L$^{-1}$ Si (Fig. 1). It is unclear how these Si treatments delayed anthesis, but it may have been the result of an overall slowing of growth of the whole plant. The flower deformations may have been the result of Si-related mechanical strengthening, which decreased the plasticity of the cell walls of the floral meristems, resulting in uneven tissue expansion.

Many of the beneficial effects of Si on agricultural crops are associated with silica gel deposition on leaves and stems, resulting in reduced transpiration and increased stem strength (Ma et al., 2001). Similarly, Si uptake and deposition in sunflower tissue may be responsible for the improved quality observed in some of the Si treatments of this study. Thus, the Si concentrations deposited in tissues were determined.

Silicon is absorbed from the soil solution as silicic acid and is actively transported in rice while passively transported in other species (Ma et al., 2006). Afterward, silicic acid moves up the transpiration stream until it polymerizes under the cuticle near stomata where it accumulates as silica gel (Ma and Yamaji, 2006). In general, dicotyledonous plants do not accumulate high amounts of Si compared with monocotyledonous plants. However, sunflower has been reported to accumulate and deposit Si (Sangster et al., 2001). In our study, Si accumulated to the highest concentrations, on a dry weight basis, in the leaves, followed by the flowers, and then the stems of sunflower (Table 2). This Si accumulation pattern corresponds to the likely evapotranspiration rates of each of these tissues.

Silicon treatments increased tissue Si concentrations relative to the control in all tissues, except for leaf and flower from rice husk ash (33 g m$^{-3}$ Si) and stem from KSiO$_3$ drench (50 mg L$^{-1}$ Si) treatments, although qualitative effects were observed (Table 2). In the unsupplemented control plants, leaves contained 0.43% Si, whereas Si-treated plants contained 0.49% to 1.53% Si with KSiO$_3$ drenches increasing Si content the greatest followed by KSiO$_3$ media incorporation and then rice hull ash media incorporation indicating sunflower readily took up Si from the substrate and distributed the Si across the plant tissue (Table 2). Table 1. Effects of silicon (Si) supplementation on the morphology and development of Helianthus annuus ‘Ring of Fire’.

![Fig. 1. Flower deformation observed in Helianthus annuus ‘Ring of Fire’ supplemented with weekly KSiO3 substrate drenches of 200 mg L$^{-1}$ Si.](image)

| Si supplement | Conc. mg Si/pot | Ht. (cm) | Flower diam. (cm) | Stem diam. 1st (mm) | Stem diam. 2nd (mm) | Days to anthesis |
|--------------|----------------|---------|------------------|---------------------|---------------------|-----------------|
| None         | 0              | 102     | 11.8             | 13.2                | 6.1                 | 47              |
| Rice husk ash| 33             | 105     | 12.3             | 13.5                | 6.3                 | 47              |
| Substrate    | 66             | 108     | 12.0             | 13.5                | 6.3                 | 47              |
| Incorporation| 100            | 106     | 12.6*            | 14.2*               | 6.9*                | 47              |
| Hydrous KSiO3| 70             | 96      | 11.5             | 13.5                | 6.6                 | 47              |
| Substrate    | 140            | 112**   | 12.7*            | 15.0**              | 7.1**               | 48              |
| Incorporation| 280            | 102     | 12.2             | 13.9                | 7.6**               | 47              |
| NaSiO3       | 50             | ▲1      | 101              | 12.2               | 14.2*               | 6.9*            |
| Foliar sprays| 150            | ▲1      | 121              | 14.8*               | 7.1**               | 46              |
| KSiO3        | 50             | 98      | 12.4             | 14.7**              | 7.1**               | 50**            |
| Five weekly  | 100            | 105     | 12.1*            | 15.3*               | 7.1**               | 50**            |
| Drenches     | 200            | 79**    | 10.3**           | 13.9                | 8.4**               | 52**            |

Significant from the untreated control as determined by PDIFF at the 5% level (*) or 1% level (**). ▲ Plants were sprayed until runoff; thus, the exact amount applied per plant cannot be calculated.

*Basal stem diameter.

**Apical stem diameter.

KSiO$_3$ = potassium silicate; NaSiO$_3$ = sodium silicate.
throughout its tissues, although only sparingly in the stem. It is unclear if foliar-applied Si similarly increased Si tissue content, because the Si content of NaSiO$_3$-sprayed plants was not determined.

Treatments resulting in leaf Si concentrations from 0.6% to 1.1% corresponded to plants with thicker stems and slightly larger flowers (Tables 1 and 2). However, treatments increasing leaf Si concentrations above 1.2% (100 and 200 mg Si/L KSiO$_3$ drenches) were associated with flower deformations and stunted growth, resulting in unmarketable flowers. Silicon has not been previously reported to cause detrimental effects in excess levels, so the indirect effects of Si supplements on soil pH and other plant nutrients were investigated as potential causes of these symptoms.

Because Si sources vary in solubility with concentration of OH$^-$, and consequently with pH, uniform pH was maintained across the treatments (Voogt and Sonneveld, 2001). The media pH values ranged between 6.3 and 6.5 among all treatments, indicating that the observed growth abnormalities in the KSiO$_3$ drenches were not likely to have been the result of a pH imbalance caused by Si supplementation. Previous studies used additional calcium carbonate in controls and low rates of Si applied as wollastonite (CaSiO$_3$) in greenhouse-produced potted miniature roses (Datnoff et al., 2006). In our study, the use of dolomitic limestone proved efficient to equilibrate pH across all the different treatments.

The possibility that excessive Si caused the deficiency or toxicity of other elements was also investigated. Tissue macronutrient analyses indicated no differences in leaf N, P, S, and Ca concentrations between Si treatments and controls. Hydrous KSiO$_3$ substrate incorporation and KSiO$_3$ weekly substrate drench (200 mg L$^{-1}$ Si) increased leaf K concentrations (Table 3). The additional amount of potassium supplied by those two forms may have decreased magnesium leaf concentrations in these Si treatments (Table 3), because Mg$^{2+}$ uptake can be antagonized by K$^+$ (Marschner, 2003). However, the observed growth abnormalities could not be attributed to either potassium toxicity or magnesium deficiency because the deformations were observed only with KSiO$_3$ substrate drenches and not with KSiO$_3$ substrate incorporation that resulted in similar leaf concentrations for both macronutrients. Additionally, the observed symptoms (e.g., stunting, floral deformation) were not typical of magnesium deficiency.

Leaf micronutrient and trace element concentrations also were analyzed and did not differ across all treatments for Al, B, Fe, Na, and Zn (Table 4) compared with the control. However, leaf copper concentrations increased with the KSiO$_3$ substrate incorporation, whereas leaf molybdenum concentrations increased with KSiO$_3$ weekly drenches and the 140 g m$^{-3}$ Si KSiO$_3$ substrate incorporation (Table 4). Leaf manganese concentration decreased in several of the tested Si treatments (Table 4). Supplementation with Si is reported to alleviate manganese toxicity in both agricultural and horticultural crops (Ma et al., 2001; Marschner, 2003; Rogalla and Romheld, 2002). Recommended leaf manganese concentration for potted sunflowers during flowering stage is 67 to 77 µg g$^{-1}$ (Dole and Wilkins, 1999). In our study, the Control plants had a manganese concentration of 354 µg g$^{-1}$; however, no manganese toxicity symptoms were observed.

As a result of the experimental design, the interactions among Si source, concentration, and application method were not analyzed, and thus, comparisons among Si treatments were not possible. Rather, the goal of this study was to determine the horticultural effects of Si on greenhouse-produced sunflowers previously tested on other crops. Only the effects observed in Si-supplemented plants were compared with untreated controls.

Based on this study, the effects of Si supplements on greenhouse-produced sunflowers can vary from beneficial to detrimental depending on the applied source and concentration. Si sources vary in solubility with concentration of OH$^-$, and consequently with pH, uniform pH was maintained across the treatments (Voogt and Sonneveld, 2001). The media pH values ranged between 6.3 and 6.5 among all treatments, indicating that the observed growth abnormalities in the KSiO$_3$ drenches were not likely to have been the result of a pH imbalance caused by Si supplementation. Previous studies used additional calcium carbonate in controls and low rates of Si applied as wollastonite (CaSiO$_3$) in greenhouse-produced potted miniature roses (Datnoff et al., 2006). In our study, the use of dolomitic limestone proved efficient to equilibrate pH across all the different treatments.

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Based on this study, the effects of Si supplements on greenhouse-produced sunflowers can vary from beneficial to detrimental depending on the applied source and concentration.
concentration. The most beneficial Si forms and concentrations for sunflower greenhouse production were 100 g m$^{-3}$ Si supplied as rice husk ash, 140 g m$^{-3}$ Si supplied as hydrous KSiO$_3$ incorporated into the substrate, 100 mg L$^{-1}$ Si supplied as NaSiO$_3$ weekly foliar application, and 50 mg L$^{-1}$ Si supplied as weekly substrate drenches of KSiO$_3$.

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