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Silicon Supplements Affect Horticultural Traits of Greenhouse-produced Ornamental Sunflowers

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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 ($KSiO_3$) substrate incorporation or weekly substrate drenches, sodium silicate ($NaSiO_3$) 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.**

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; Dik 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, 2001). 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.

Materials and Methods

Plant material and silicon supplements. Ornamental sunflower, *Helianthus annuus* 'Ring of Fire' (Ernst Benary Samenzucht 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) peat:-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 ($NaSiO_3$) 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 $NaSiO_3$ 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^{-3} to the substrates used for the control, ashed rice husks, and sodium silicate foliar treatments, whereas a reduced rate of 3.5 kg·m^{-3} 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 polycarbonate-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_2O (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

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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 NS 2000 (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 PDIFF 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 silicomolybdous acid, colorimetric procedure (Taber et al., 2002).

Table 1. Effects of silicon (Si) supplementation on the morphology and development of *Helianthus annuus* 'Ring of Fire'.

	Si supplement		Ht.	Flower	Stem	Stem	Days to
Silicon source[z]	Conc.	mg Si/pot	(cm)	diam. (cm)	diam.[z] (mm)	diam.[y] (mm)	anthesis
None	0	0	102	11.8	13.2	6.1	47
	$g \cdot m^3$						
Rice husk ash	33	50	105	12.3	13.5	6.3	47
Substrate	66	100	108	12.0	13.5	6.3	47
Incorporation	100	150	106	12.6*	14.2*	6.9*	47
Hydrous $KSiO_3$	70	100	96	11.5	13.5	6.6	47
Substrate	140	200	112**	12.7*	15.0**	7.1**	48
Incorporation	280	400	102	12.2	13.9	7.6**	47
	$mg \cdot L^{-1}$						
$NaSiO_3$	50	▲	101	12.2	14.2*	6.9*	47
Five weekly	100	▲	101	12.6*	15.5**	7.1**	48
Foliar sprays	150	▲	103	12.1	14.8**	7.1**	46
$KSiO_3$	50	75	98	12.4	14.7**	7.1**	50**
Five weekly	100	150	105	12.1[a]	15.3**	7.1**	50**
Drenches	200	300	79**	10.3**[, b]	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.
[z]Basal stem diameter.
[y]Apical stem diameter.
$KSiO_3$ = potassium silicate; $NaSiO_3$ = sodium silicate.

Results and Discussion

The effect of Si supplements on sunflower height and flower diameter varied depending on Si source and concentration (Table 1). Incorporated hydrous $KSiO_3$ powder (140 $g \cdot m^{-3}$ 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 $mg \cdot L^{-1}$ 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 $g \cdot m^{-3}$ Si), $NaSiO_3$ (100 $mg \cdot L^{-1}$ Si), and hydrous $KSiO_3$ (140 $g \cdot m^{-3}$ 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 $mg \cdot L^{-1}$ 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 $g \cdot m^{-3}$), $KSiO_3$ substrate incorporation (140 $g \cdot m^{-3}$ Si), foliar $NaSiO_3$ applications (50, 100, and 150 $mg \cdot L^{-1}$ Si), and $KSiO_3$ drench (50 and 100 $mg \cdot L^{-1}$) increased both basal and apical stem diameters (Table 1). Substrate incorporation of hydrous $KSiO_3$ powder at 280 $g \cdot m^{-3}$ Si and $KSiO_3$ drenches of 200 $mg \cdot L^{-1}$ 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 $mg \cdot L^{-1}$ 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.

Fig. 1. Flower deformation observed in Helianthus annuus 'Ring of Fire' supplemented with weekly $KSiO_3$ substrate drenches of 200 $mg \cdot L^{-1}$ Si.

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 $g \cdot m^{-3}$ Si) and stem from $KSiO_3$ drench (50 $mg \cdot L^{-1}$ 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 $KiSO_3$ 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 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 $mg \cdot L^{-1}$ 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 $g \cdot m^{-3}$ 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 $\mu g \cdot g^{-1}$ (Dole and Wilkins, 1999). In our study, the control plants had a manganese concentration of 354 $\mu g \cdot g^{-1}$; 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

Table 2. Effects of silicon (Si) supplementation on plant tissue Si concentration of *Helianthus annuus* 'Ring of Fire'.

	Si supplement		Tissue silicon concn. (% dry wt.)		
Si source[z]	Conc.	mg Si/pot	Leaf	Stem	Flower
None	0	0	0.43	0.28	0.32
	$g \cdot m^3$				
Rice husk ash	33	50	0.49	0.31**	0.38
Substrate	66	100	0.56*	0.31**	0.39*
Incorporation	100	150	0.67**	0.33**	0.44**
Hydrous $KSiO_3$	70	100	0.70**	0.34**	0.40*
Substrate	140	200	0.66**	0.33**	0.40*
Incorporation	280	400	0.65**	0.33**	0.43**
	$mg \cdot L^{-1}$				
$KSiO_3$	50	75	1.11**	0.29	0.43**
Five weekly	100	150	1.26**	0.37**	0.43**
Drenches	200	300	1.53**	0.42**	0.51**

Significant from the untreated control as determined by PDIFF at the 5% level (*) or 1% level (**).
[z]$NaSiO_3$ foliar applications were not analyzed because samples were not properly washed after sample collection.
$KSiO_3$ = potassium silicate.

Table 3. Effects of silicon (Si) supplementation on leaf macronutrient concentrations of *Helianthus annuus* 'Ring of Fire'.

	Supplemented Si		Macronutrients (% dry wt)					
Si source	Conc.	mg Si/pot	N	P	S	K	Mg	Ca
None	0	0	4.49	0.39	0.57	2.74	1.27	1.86
	$g \cdot m^3$							
Rice husk ash	33	50	4.70	0.41	0.54	3.10	1.21	1.71
Substrate	66	100	4.53	0.38	0.52	2.85	1.30	1.68
Incorporation	100	150	4.70	0.40	0.52	2.69	1.19	1.65
Substrate	140	200	4.91	0.40	0.46	4.08*	0.80**	1.55
Incorporation	280	400	4.58	0.38	0.49	4.65**	0.76**	1.39
	$mg \cdot L^{-1}$							
$KSiO_3$	50	75	4.42	0.43	0.48	2.86	1.11	1.64
Five weekly	100	150	4.21	0.38	0.49	2.83	1.05*	1.79
Drenches	200	300	4.32	0.37	0.45	3.95*	0.87**	1.62

Significant from the untreated control as determined by PDIFF at the 5% level (*) or 1% level (**).
$KSiO_3$ = potassium silicate.

Table 4. Effect of silicon (Si) supplements on leaf micronutrient concentration (%) of *Helianthus annuus* 'Ring of Fire'.

	Supplemented Si		Micronutrients and other trace elements ($\mu g \cdot g^{-1}$)							
Si source	Conc.	mg Si/pot	Al	B	Cu	Fe	Mn	Mo	Na	Zn
None	0	0	30	75	13.5	82	354	1.3	614	43
	$g \cdot m^3$									
Rice husk ash	33	50	35	76	13.8	79	262*	1.2	601	40
Substrate	66	100	32	71	14.4	71	248*	1.0	780	40
Incorporation	100	150	32	80	16.3	78	327	2.2	770	45
Hydrous $KSiO_3$	70	100	28	80	17.6*	85	274*	1.2	565	43
Substrate	140	200	31	79	18.2*	82	303	2.5*	603	42
Incorporation	280	400	30	68	17.4*	87	183**	1.9	395	47
	$mg \cdot L^{-1}$									
$KSiO_3$	50	75	32	65	14.4	74	310	2.6*	600	44
Five weekly	100	150	30	74	12.2	75	324	2.7*	641	46
Drenches	200	300	34	81	12.4	72	280*	2.5*	515	49

Significant from the untreated control as determined by PDIFF at the 5% level (*) or 1% level (**).
$KSiO_3$ = potassium silicate.

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 $KSiO_3$.

Literature Cited

Cherif, M., N. Benhamou, J.G. Menzies, and R.R. Belanger. 1992. Silicon induced resistance in cucumber plants against *Pythium ultimum*. Physiol. Mol. Plant Pathol. 41:411–425.

Datnoff, L.E., T.A. Nell, R.T. Leonard, and B.A. Rutherford. 2006. Effect of silicon on powdery mildew development on miniature potted rose. Phytopathology 96:S28. (abstr.).

Dik, A.J., M.A. Verhaar, and R.R. Belanger. 1998. Comparison of three biological control agents against cucumber powdery mildew (*Sphaerotheca fuliginea*) in semi-commercial-scale glasshouse trials. Eur. J. Plant Pathol. 104:413–423.

Dole, J.M. and H.F. Wilkins. 1999. Floriculture: Principles and species. Prentice Hall, Upper Saddle River, NJ.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proc. Natl. Acad. Sci. USA 91:11–17.

Locke, C., M. Omer, A.K. Widrig, and C.R. Krause. 2006. Delay of expression of powdery mildew on zinnia grown hydroponically in Hoagland's solution fortified with silicon. Phytopathology 96:S70. (abstr.).

Lu, G. and J. Cao. 2001. Effects of silicon on earliness and photosynthetic characteristics of melon. Acta Hort. Sciencia. 28:421–424.

Ma, J.F., Y. Miyake, and E. Takahashi. 2001. Silicon as a beneficial element for crop plants, p. 17–39. In: L.E. Datnoff, G.H. Snyder, and G.H. Korndörfer (eds.). 2001. Silicon in agriculture. Elsevier, Amsterdam, The Netherlands.

Ma, J.F. and E. Takahashi. 2002. Soil, fertilizer, and plant silicon research in Japan. Elsevier, Amsterdam, The Netherlands.

Ma, J.F., K. Tamai, N. Yamaji, N. Mitani, S. Konishi, M. Katsuhara, M. Ishiguro, Y. Murata, and M. Yano. 2006. A silicon transporter in rice. Nature 440:688–691.

Ma, J.F. and N. Yamaji. 2006. Silicon uptake and accumulation in higher plants. Trends Plant Sci. 11:392–397.

Marschner, H. 2003. Mineral nutrition of higher plants. 2nd ed. Academic Press, Amsterdam, The Netherlands.

McAvoy, R.J. and B.B. Bernard. 1996. Silica sprays reduce the incidence and severity of bract necrosis in poinsettia. HortScience 31: 1146–1149.

Menzies, J.G., D.L. Ehret, A.D.M. Glass, T. Helmer, C. Koch, and F. Seywerd. 1991. Effects of soluble silicon on the parasitic fitness of *Sphaerotheca fuliginea* on *Cucumis sativus*. Phytopathology 81:84–88.

Novozamsky, I., R. Van Eck, and V.J.G. Houba. 1984. A rapid determination of silicon in plant material. Commun. Soil Sci. Plant Anal. 15: 205–212.

Rogalla, H. and V. Romheld. 2002. Role of apoplast in silicon-mediated manganese tolerance of *Cucumis sativus* L. Plant Cell Environ. 25:540–555.

Sangster, A.G., M.J. Hodson, and H.J. Tubb. Silicon deposition in higher plants, p. 85–113. In: L.E. Datnoff, G.H. Snyder, and G.H. Korndörfer (eds.). 2001. Silicon in agriculture. Elsevier, Amsterdam, The Netherlands.

Savvas, D., G. Manos, A. Kotsiras, and S. Souvaliotis. 2002. Effects of silicon and nutrient-induced salinity on yield, flower quality and nutrient uptake of gerbera grown in a closed hydroponic system. J. Appl. Bot. 76:153–158.

Taber, H.G., D. Shogren, and G. Lu. 2002. Extraction of silicon from plant tissue with dilute HCl and HF and measurement by modified inductive coupled argon plasma procedures. Commun. Soil Sci. Plant Anal. 33:1661–1670.

Voogt, W. and C. Sonneveld. 2001. Silicon in horticultural crops grown in soilless culture, p. 115–131. In: L.E. Datnoff, G.H. Snyder, and G.H. Korndörfer (eds.). 2001. Silicon in agriculture. Elsevier, Amsterdam, The Netherlands.