Drastic Differences in Silicon Concentrations between Roots and Leaves of 10 Different *Solanum lycopersicum* L. Varieties

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Abstract. Silicon (Si) absorption is highly variable among different plant types; however, few studies have examined variations among different cultivars within a single species. In this study, 10 different tomato cultivars, including determinants and indeterminants as well as hybrids and heirlooms, were hydroponically grown in the presence or absence of Si to determine the absorption and distribution of the nutrients in roots, stems, petioles, and leaves. A total elemental analysis revealed that Si concentrations significantly increased with Si treatment, and that root concentrations were significantly higher than those in leaves. Although a few species showed differences in carbon, nitrogen, and calcium concentrations in roots and leaves with Si treatment, many of the macronutrients and micronutrients were unaffected. These data suggest that tomato plants absorb Si within the macronutrient range and restrict its movement from roots to shoots.

Plants vary greatly in their leaf Si concentrations, with angiosperms ranging from 0.005% to 11% (Hodson et al., 2005). Compared with other essential nutrients, this concentration is well within the range of the micronutrients; in many species, Si concentrations in the leaves exceed those of macronutrients (Epstein and Bloom, 2005; Zellner et al., In press). Tomatoes (*Solanum lycopersicum* L.) have been referred to as Si excluders or nonaccumulators because previous studies showed that Si concentrations in the xylem sap of the upper portion of the plant were lower than those supplied in the nutrient solution (Heine et al., 2005; Mitani

and Ma, 2005; Takahashi and Miyake, 1977; and Takahashi et al., 1990). However, this suggests the restriction of Si movement, but not exclusion, because researchers have detected appreciable concentrations of the nutrient at slightly higher concentrations in the root than in the foliar tissue of tomato cultivar King Kong II (Heine et al., 2005). Other studies of foliar Si concentrations in tomato have shown lower values. For instance, Frantz et al. (2008) reported that tomato grown for 3 weeks with 1.0 mM potassium silicate accumulated 747 ppm Si in foliar tissue. Jarosz (2014) reported values of 500 ppm Si in leaves of ‘Cunero F1’ grown in the presence of 100 ppm modified colloidal silica solution and grown in the greenhouse for 8 months.

Tomatoes absorb Si and, more importantly, show beneficial responses to Si treatment. In the absence of Si, Miyake and Takahashi (1978) were able to show deficiency symptoms in ‘Bejiu’ and ‘Giant Fukuju’ that manifested as stunted growth with abnormal pollen and fruit development. The application of Si to tomato ‘Kada Gigante’ at increasing concentrations resulted in higher yields with less cracking (Marodin et al., 2014). More notable are the beneficial responses to environmental and abiotic stresses of tomato plants treated with Si. Silicon has been shown to protect tomatoes against blossom-end rot (Stamatakis et al., 2003). With Si supplementation, tomatoes were less susceptible to osmotic and salt stress (Ali

et al., 2018; Li et al., 2015; Romero-Aranda et al., 2006; Shi et al., 2016; Zhang et al., 2018). Researchers have observed protection against biotic disease in tomatoes supplemented with Si and inoculated with bacterial speck, bacterial wilt, *Fusarium* crown and root rot, powdery mildew, and *Pythium* root rot (Andrade et al., 2013; Dannon and Wydra, 2004; Garibaldi et al., 2011; Heine et al., 2006; Huang et al., 2011; Kirrika et al., 2013).

This study was designed to test for variable silicon absorption and allocation in different tomato cultivars and how those concentrations affected other macronutrient and micronutrient concentrations within roots, stems, petioles, and leaves. The 10 cultivars included the heirloom indeterminants ‘Beefsteak’, ‘Brandywine Red’, ‘German Pink’, and ‘Old German’, Heinz hybrids ‘H1015’ (early) and ‘H3406’ (late), indeterminant hybrid ‘Early Girl’, and determinant hybrids ‘Mega Bite’, ‘Micro Tom’, and ‘Sweet ‘N Neat’.

Materials and Methods

Solanum lycopersicum L. seeds for ‘Beef Steak’, ‘Brandywine Red’, ‘Early Girl’, ‘German Pink’, ‘H1015’, ‘H3406’, ‘Mega Bite’, ‘Micro Tom’, ‘Old German’, and ‘Sweet ‘N Neat’ were sown in CleanStart® Oasis Medium (No. 5005; Smithers-Oasis Company, Kent, OH), rinsed and saturated with tap water (Toledo, OH), and placed in a growth chamber set at 25 °C with 45% relative humidity. When plants developed three leaves, they were moved into the greenhouse (The University of Toledo, Toledo, OH), which was maintained between 25 and 32 °C throughout the course of this study. When plants developed two or three true leaves, a single plant was transplanted into a silver 4.7-L ring-free pail (01605 Promotional Pail; Encore Plastics Corp., Cambridge, OH). Each pail contained modified Hoagland’s solution with the following nutrient concentrations for the control solution: 2 mM KH₂PO₄; 2.5 mM KNO₃; 2.5 mM Ca(NO₃)₂; 1 mM MgSO₄; 71 μM Fe-DTPA (Sprint 330, BASF); 9 μM MnCl₂; 1.5 μM CuCl₂; 1.5 μM ZnCl₂; 45 μM H₃BO₃; 0.1 μM MoNa₂O₄; and 2 mM K₂SO₄; however, 2 mM K₂SiO₂ was used for the Si treatments (Frantz et al., 2005). There were four plants per treatment (n = 4), except for the control treatments, for the tomato cultivars: ‘Beefsteak’ (n = 3); ‘German Pink’ (n = 3); ‘H1015’ (n = 3); ‘Mega Bite’ (n = 2); and ‘Micro Tom’ (n = 3); the Si treatment was used for the tomato cultivar ‘Mega Bite’ (n = 3). Potassium silicate was made by adding KOH (P250-500; Fisher Scientific, Waltham, MA) at a concentration of 0.2 M to 18 MΩ H₂O and silicic acid (A288-500; Fisher Scientific) at a concentration of 0.1 M and mixing on a magnetic stirrer overnight. Potassium sulfate was added to the control solutions to ensure that equal concentrations of potassium were present in both treatments. The final concentration of sulfur differed between the Si and the control treatments by 1 mM and 3 mM, respectively. Final elemental concentrations were similar for both treatments with the exception of sulfur at 3 mM and 0 mM and Si at

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Table 1. Final nutrient concentrations in hydroponics solutions.

	Control	Si
S ²	3.0 mM	1.0 mM
Si	0 mM	2.0 mM
N	7.5 mM	
P	2.0 mM	
K	8.5 mM	
Ca	2.5 mM	
Mg	1.0 mM	
Fe	71 mM	
Mn	9.0 μM	
Cu	1.5 μM	
Zn	1.5 μM	
B	45 μM	
Mo	0.10 μM	
Cl	24 μM	

²Sulfur concentrations varied between the control and silicon treatments because of the use of potassium sulfate to maintain equal concentrations of potassium in the control and silicon-treated plants.

0 mM and 2 mM for the control and Si treatments, respectively (Table 1). Air was introduced to buckets through Tygon S3™ plastic tubing (14-171-104; Fisher Scientific) with a porous rod (F13635-0014; Bel-Art, Wayne, NJ) inserted at the submerged end. Nutrient solution was completely exchanged weekly.

Plants were maintained under these conditions until the first flowers were present (4–8 weeks, depending on the cultivar), at which time plants were harvested. Tissue from each cultivar was collected on the same day, weighed to determine the fresh weight, and divided into roots, leaves, petioles, and stems; the stems were measured to quantify shoot lengths. The tissue was washed in 0.1 N HCl three times, rinsed in 18 MΩ H₂O, placed into brown paper bags (#4 Kraft paper bags; Gordon Food Service, Aberdeen, MD) and dried at 55 °C in a drying oven (Blue M POM-1403C-1; Blue M Electric Co., Blue Island, IL) for at least 3 d. Dried tissue was weighed and ground in mortars with pestles and then placed into plastic snap cap vials (5 dr clear plastic; Thornton Plastics, Salt Lake City, UT). Inductively coupled plasma optical emission spectroscopy (ICP-OES) was performed for tissue to determine the total Si using KOH digestion (Frantz et al., 2008) and the total elemental concentrations using nitric digestion (Frantz et al., 2008; Frantz et al., 2011; Li et al., 2008). Elemental concentrations less than 1 ppm (mg Si/kg tissue) were reported as 0 ppm Si. This was a single exploratory study that was not repeated.

Statistical analysis was performed using R (R Core Team, 2016). Welch's *t* test was performed to determine differences in the stem lengths of 'Beefsteak' using the 't.test(y1,y2)' code. Analysis of variance (ANOVA) was used to analyze differences in nutrient concentrations of tomato cultivars. Tukey's honestly significant difference post hoc test was performed using the 'aov(DV~T*V)' code, where DV is the dependent variable, T is the treatment (control or Si), and V is the tomato cultivar. One-way ANOVA was also performed for

each cultivar to determine differences using 'aov(DV~T)'.

Results

During vegetative growth, 'Beefsteak' plants treated with Si were, on average, 5 cm taller than control-treated plants at 12 d and 6 cm taller at 32 d after transplanting (Table 2). Interestingly, compared with the control treatment, the Si treatment resulted in larger SD at both time points. No differences in stem length of the Si-treated and control-treated plants were observed for the other nine cultivars (Table 3). There were differences in the stem lengths of different cultivars, as expected.

The Si treatment had a positive effect on plant fresh weight and dry weight, with the exception of the petiole dry weight (Table 4). Overall, more Si-treated plants than control-treated plants had increased weight. Specifically, 'Beefsteak', 'German Pink', 'H1015', 'H3406', and 'Mega Bite' had increased dry root weights with Si treatment compared with those of controls. 'Beefsteak' and 'German Pink' with Si treatment had significantly higher dry weights of all the tissue tested, whereas 'H3406' had additional increases in the dry mass of leaves, roots, and stems, but not petioles, and 'H1015' Si-treated plants had higher stem weights than the controls.

The Si concentrations were significantly higher in all Si-treated plant tissue, compared to controls (Table 5). The highest Si concentrations were in the roots (range, 0.05% to 4.3% Si), followed by the leaves (0.06% to 3.7% Si), petioles (0.01% to 0.03% Si), and stems (0.009% to 0.02% Si). Based on the leaf Si concentrations, H1015, H3406, and heirloom cultivars had higher concentrations of Si, with 'Beefsteak', 'Early Girl', 'Micro Tom', and 'Sweet 'N Neat' having the lowest Si concentrations. Most interestingly, control plants still had concentrations of more than 35 ppm Si in root tissue, even with no inclusion of Si in the growing media. Many of the cultivars grown in these conditions had no detectable levels of Si in stems and petioles, and a few, including 'German Pink', 'H3406', and 'Sweet 'N Neat', had no detectable levels within the leaves.

Concentrations of macronutrients in the plants were more affected by the cultivar than by the Si treatment. In leaves, carbon (C), nitrogen (N), phosphorus (P), calcium (Ca), and magnesium (Mg) were not significantly different based on their treatment and cultivar (Table 6). The potassium (K) and sulfur (S) levels in leaves were significantly lower in Si-fed plants of five and seven of the 10 cultivars tested, respectively, compared with controls. Scattered throughout the data were individual Si-fed cultivars that were different from controls. For instance, the Ca level was higher in Si-fed 'Brandywine Red' and 'German Pink' than in controls, and the C level was higher in leaves of the Heinz cultivar and 'Mega Bite' Si-fed plants than in those of controls. In roots, there was no significant interaction for Si treatment and cultivar for N, P, Ca, Mg, and S,

Table 2. Stem lengths of tomato cultivar Beefsteak at 12 d and 32 d.

	Stem length (cm)			
	12 d		32 d	
Control	7.33 ^z	0.57	43.57	0.42
Si	12.60	3.25	49.38	7.66
	<i>P</i> = 0.045		<i>P</i> = 0.23	

^zAverage values of the stem length are reported with SD in italics for measurements at 12 d and 32 d during treatment. Welch's *t* test was performed on data with the *P* value indicated.

but differences were observed for C and K. 'Early Girl', 'German Pink', 'H1015', and 'H3406' had lower C concentrations in the roots of Si-fed plants compared to controls. 'Early Girl', 'German Pink', 'H3406', and 'Mega Bite' also had lower N in the root tissue of Si-fed plants compared to controls. The K levels were higher and lower in roots of Si-fed plants of 'Early Girl' and 'H3406', respectively.

There were slight differences in macronutrient concentrations in the stems and petioles, with the petioles showing more differences with the Si treatment than with the control treatment (Table 7). Compared with the stem, the petioles showed stronger differences in nitrogen based on the treatment, cultivar, and the combination of cultivar and treatment. Both stems and petioles showed decreased N concentrations in Si-fed plants similar to those in the leaves and roots. Similar to roots and leaves, S levels were also significantly lower in the stems and petioles of five and six of the 10 plants, respectively. 'German Pink' and 'Sweet 'N Neat' only showed significantly lower S levels in the petioles of Si-fed plants, but not in the leaves, roots, or stems. The Ca and Mg levels were slightly higher in Si-fed plants than in control plants. There was no significant difference in

Table 3. Effect of silicon on the stem lengths of 'Beefsteak' (BS), 'Brandywine Red' (BWR), 'Early Girl' (EG), 'German Pink' (GP), Heinz 'H1015' (early) and 'H3406' (late), 'Mega Bite' (MB), 'Micro Tom' (MT), 'Old German' (OG), and 'Sweet 'N Neat' (SNN).

Cultivar	Stem length (cm)			
	Control		Si	
BS	43.57	efgh	49.38	def
BWR	61.55	bcd	64.05	bc
EG	57.13	cde	61.58	bcd
GP	72.97	ab	79.53	a
H1015	39.70	fghi	36.73	fghi
H3406	39.33	fghi	44.58	efg
MB	28.30	ghi	34.13	fghi
MT	4.00	j	4.00	j
OG	69.04	abc	73.48	ab
SNN	28.23	hi	26.78	i
	T		NS	
	C		***	
	T × C		NS	

The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with **P* < 0.05, ***P* < 0.01, or ****P* < 0.001. Differences with *P* > 0.05 are indicated as not significant (NS).

Table 4. Effects of silicon on fresh and dry weights of ‘Beefsteak’ (BS), ‘Brandywine Red’ (BWR), ‘Early Girl’ (EG), ‘German Pink’ (GP), Heinz ‘H1015’ (early) and ‘H3406’ (late), ‘Mega Bite’ (MB), ‘Micro Tom’ (MT), ‘Old German’ (OG) and ‘Sweet ‘N Neat’ (SNN).

Cultivar	Fresh wt (g)															
	Leaves				Roots				Stems				Petioles			
	Control		Si		Control		Si		Control		Si		Control		Si	
BS	54.40	efg	81.48	bc	26.77	fg	53.80	cde	56.83	bcdef	72.03	bc	49.87	cde	83.10	b
BWR	56.05	efg	67.90	cdef	40.15	def	60.23	abcd	61.40	bcdef	76.28	b	31.78	de	38.23	de
EG	105.05	a	102.75	ab	52.48	cde	58.45	bcde	65.68	bcd	75.35	b	106.28	a	113.93	a
GP	51.40	fg	75.43	cde	37.27	def	62.65	abcd	64.63	bcdef	62.65	a	26.93	ef	40.75	de
H1015	73.37	cdef	79.38	cd	68.43	abc	83.73	a	42.07	efg	51.90	cdef	53.54	cd	56.10	cd
H3406	68.68	cdef	77.48	cde	80.78	ab	66.73	abc	41.43	fg	53.60	cdef	39.65	de	51.68	cde
MB	63.10	cdefg	78.93	cde	31.15	efg	49.07	cdef	45.25	defg	57.27	bcdef	59.60	bcd	67.13	bc
MT	7.06	h	7.17	h	7.81	g	7.14	g	3.03	h	3.39	h	3.62	f	3.88	f
OG	58.50	defg	61.70	cdefg	54.35	cde	61.28	abcd	63.88	bcde	72.95	bc	37.15	de	50.38	cde
SNN	45.48	g	44.40	g	40.95	def	39.63	def	28.60	g	30.45	g	33.83	de	32.28	de
	C	**			T	***			T	***			T	***		
	T	***			C	***			C	***			C	***		
	C × T	*			T × C	***			T × C	*			T × C	*		

Cultivar	Dry wt (g)															
	Leaves				Roots				Stems				Petioles			
	Control		Si		Control		Si		Control		Si		Control		Si	
BS	5.29	efg	8.21	abcd	0.68	fg	1.22	ef	2.90	efg	3.90	bcdef	1.98	bcdef	3.93	ab
BWR	4.48	g	5.61	efg	1.47	efg	1.58	de	3.63	bcdefg	4.11	abcdef	1.61	def	1.95	cdef
EG	9.53	a	9.64	a	1.48	ef	1.73	de	3.57	cdefg	3.71	bcdef	4.95	a	5.01	a
GP	4.54	fg	6.72	bcdefg	1.17	ef	1.92	cde	3.25	defg	5.39	a	1.33	ef	2.08	bcdef
H1015	7.23	abcdef	8.28	abc	2.82	ab	3.52	a	4.07	abcdef	4.94	abc	4.07	ab	4.00	ab
H3406	6.26	cdefg	8.82	ab	2.50	bc	3.30	a	3.40	defg	4.46	abcde	3.48	abcd	3.83	abc
MB	5.40	efg	7.61	abcde	0.67	fg	1.77	cde	2.48	fg	3.50	cdefg	2.57	bcde	3.38	abcde
MT	0.65	h	0.66	h	0.17	g	0.16	g	0.17	h	0.17	h	0.19	f	0.20	f
OG	5.87	defg	6.07	cdefg	1.89	cde	2.25	bcd	5.03	ab	4.77	abcd	3.25	abcde	2.36	bcde
SNN	4.95	fg	4.93	fg	1.49	de	1.60	de	2.23	g	2.25	g	2.02	bcdef	1.78	def
	T	***			T	***			T	***			T	NS		
	C	***			C	***			C	***			C	***		
	T × C	**			T × C	*			T × C	**			T × C	NS		

Plants were grown hydroponically without (control) or with 2.0 mM silicon (Si). The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with **P* < 0.05, ***P* < 0.01, or ****P* < 0.001. Differences with *P* > 0.05 are indicated as not significant (NS). Differences between treatments for a single cultivar are underlined.

P concentrations in stems and petioles, and the C level was significantly higher in ‘Mega Bite’ petioles only.

Most of the micronutrients were unaffected by Si treatment. In the leaves and roots, manganese (Mn) levels were lower in Si-fed plants compared with control plants (Table 8). In roots only, the boron (B) level

was slightly higher, but the iron (Fe) and zinc (Zn) levels were slightly lower in Si-fed plants than in controls. In stems, the Zn levels were lower in all Si-fed plants except ‘Micro Tom’, which had a higher level, compared to control plants (Table 9). There were no other significant differences in micronutrient concentrations within the stems and petioles,

except for a decrease in Mn in ‘German Pink’ stems and an increase in Mn in ‘Old German’ petioles.

Discussion

Silicon supplementation produces differences in phenotypic observations, such as

Table 5. Effect of silicon (Si) treatment on Si concentrations in leaves, roots, stems, and petioles of tomatoes.

Cultivar	Si (ppm)															
	Leaves				Roots				Stems				Petioles			
	Control		Si		Control		Si		Control		Si		Control		Si	
Beefsteak	41.18	a	856.38	d	49.96	b	9857.02	cd	0.00	a	93.97	b	0.00	bc	140.22	c
Brandywine Red	3.32	a	2820.57	ab	242.65	ab	37674.65	a	0.00	a	171.33	a	0.00	c	276.54	a
Early Girl	33.30	a	1069.00	d	374.92	ab	16526.17	c	8.18	a	124.49	ab	5.66	a	167.73	bc
German Pink	0.00	a	1419.15	bcd	96.65	b	32338.66	ab	0.00	a	124.50	ab	0.00	c	212.22	abc
H1015 (early)	17.41	a	3708.15	a	637.61	a	37173.81	a	0.00	a	122.16	ab	5.10	ab	235.06	ab
H3406 (late)	0.00	a	2548.57	abc	442.66	ab	41413.05	a	0.00	a	89.46	b	0.00	c	160.98	bc
Mega Bite	1.06	a	1132.61	cd	35.98	b	18466.59	bc	0.00	a	133.02	ab	0.00	c	136.36	c
Micro Tom	2.48	a	630.55	d	49.66	b	529.64	d	15.26	a	115.64	ab	0.00	c	149.25	c
Old German	40.82	a	2867.96	bcd	242.98	ab	42947.87	a	0.00	a	166.79	a	0.00	c	263.24	a
Sweet ‘N Neat	0.00	a	1117.53	d	217.28	ab	10860.40	cd	2.40	a	93.94	b	0.00	c	134.66	c
	T	***			T	***			T	***			T	***		
	C	***			C	***			C	**			C	***		
	T × C	***			T × C	***			T × C	***			T × C	***		

All treatments were significantly different between Si treatments. Different letters in columns indicate a significant difference in Si concentrations between cultivars based on Tukey’s honestly significant difference test. The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with ***P* < 0.01 (**) or ****P* < 0.001. Values of 0.00 were <1 ppm of the element.

Table 6. Effects of silicon (Si) treatment on macronutrient concentrations in leaves and roots of 'Beefsteak' (BS), 'Brandywine Red' (BWR), 'Early Girl' (EG), 'German Pink' (GP), Heinz 'H1015' (early) and 'H3406' (late), 'Mega Bite' (MB), 'Micro Tom' (MT), 'Old German' (OG), and 'Sweet 'N Neat' (SNN).

Macronutrients (%)																												
Leaves																												
Cultivar	C		N (2.8–4.2)		P (0.30–0.46)		K (3.5–5.1)		Ca (1.6–3.2)		Mg (0.36–0.49)		S (0.25–1.28)															
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si														
BBS	38.62	abdef	5.11	bcd ^{efg}	4.67	defg	1.09	bcd ^{ef}	1.13	bcd ^e	3.91	ef	3.48	f	3.41	abcd	3.34	bcd	0.74	abcd	0.79	abcd	0.74	abcd	1.76	bc	1.01	ef
BWR	37.56	defg	4.63	efg	4.38	gh	0.78	fg	0.71	g	5.61	ab	5.29	bc	2.94	cdef	3.27	bcd ^e	0.67	defg	0.69	defg	0.73	bcd ^{ef}	1.91	b	1.12	def
EG	36.63	fg	5.45	abcd	5.29	bcd ^e	1.50	a	1.49	a	5.67	ab	5.31	bc	3.88	ab	4.00	a	0.89	abc	0.89	abc	0.79	abcd	1.94	b	1.14	def
GP	39.44	abcd	5.45	abcd	5.02	cdefg	1.17	bcd ^{efg}	1.02	bcd ^{efg}	5.67	ab	5.67	ab	2.31	g	2.65	fg	0.49	g	0.56	efg	0.56	efg	1.08	def	0.88	ef
H1015	36.73	fg	3.83	hi	3.36	ij	1.06	bcd ^{efg}	1.28	abc	6.39	ab	5.12	bcd	2.91	cdefg	3.06	cdef	0.92	a	0.93	a	0.93	a	2.63	a	1.23	def
H3406	36.43	g	3.38	ij	3.04	j	1.34	ab	1.27	abcd	5.42	abc	4.34	def	2.65	fg	2.74	efg	0.91	ab	0.87	abc	0.87	abc	2.19	ab	0.91	ef
MB	37.25	defg	5.56	abcd	5.26	bcd ^{ef}	1.02	bcd ^{efg}	0.85	efg	4.09	bcd	4.46	cde	3.60	abc	3.42	abcd	0.71	bcd ^{efg}	0.69	cdefg	0.69	cdefg	1.62	bcd	0.92	ef
MT	36.59	fg	5.99	ab	6.14	A	1.01	bcd ^{efg}	0.97	cdefg	5.82	bcd ^e	4.39	def	3.91	ab	3.93	a	0.84	abcde	0.74	abcde	0.98	ef	0.69	ef	0.69	f
OG	38.58	abdef	4.47	fgh	4.40	gh	0.94	defg	0.86	efg	4.97	bcd	4.35	def	2.66	fg	2.82	defg	0.74	abdef	0.66	defg	1.90	b	0.94	ef	0.94	ef
SSNN	39.81	ab	5.80	ab	5.69	abc	0.91	efg	0.84	efg	5.41	bc	5.30	bc	2.65	fg	2.85	defg	0.53	g	0.54	fg	1.24	cde	0.94	ef	0.94	ef
	T	***	T	***	*	*	T	***	NS	NS	T	***	***	***	T	***	***	***	T	***	NS	NS	T	***	T	***	***	***
	C	***	C	***	C	***	C	***	NS	NS	C	***	***	***	C	***	***	***	C	***	NS	NS	T	***	T	***	***	***
	T × C	NS	T × C	NS	T × C	NS	T × C	NS	NS	NS	T × C	NS	T × C	*	T × C	NS	T × C	NS	T × C	NS	NS	NS	T × C	T × C	T × C	T × C	NS	NS
Roots																												
Cultivar	C		N		P		K		Ca		Mg		S															
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si														
BS	38.61	cd	3.07	cde	0.99	b	1.01	b	4.94	abcd	4.30	abdef	0.85	ab	0.80	b	0.28	bcd	0.33	abc	0.53	abc	0.43	bc	0.53	abc	0.43	bc
BWR	42.34	abc	4.06	ab	1.25	ab	1.06	b	4.40	abdef	3.99	abdef	1.07	ab	1.17	ab	0.29	bcd	0.32	ab	0.74	a	0.54	abc	0.74	a	0.54	abc
EG	43.36	abc	3.66	abc	1.33	ab	0.90	ab	3.87	abdef	5.56	ab	1.72	ab	0.74	b	0.25	bcd	0.28	bcd	0.56	abc	0.53	abc	0.56	abc	0.53	abc
GP	39.86	bcd	4.51	a	1.31	ab	1.35	ab	6.04	a	5.67	ab	0.59	b	0.73	b	0.35	ab	0.46	a	0.66	ab	0.60	abc	0.66	ab	0.60	abc
H1015	45.14	ab	3.23	bcd ^e	0.83	b	0.76	b	3.12	def	2.47	ef	1.40	cd	1.27	ab	0.14	cd	0.16	cd	0.46	a	0.47	bc	0.59	abc	0.47	bc
H3406	45.84	a	3.21	cde	0.84	b	0.66	b	3.48	bcd ^{ef}	1.79	f	1.21	ab	1.29	ab	0.18	cd	0.13	d	0.67	ab	0.42	bc	0.67	ab	0.42	bc
MB	36.49	d	4.06	abcd	0.94	b	1.25	ab	4.50	abdef	6.15	a	0.77	b	0.98	ab	0.39	ab	0.36	ab	0.54	abc	0.51	abc	0.54	abc	0.51	abc
MT	NA		NA		0.78	b	0.72	b	4.88	abdef	4.19	abdef	2.36	b	0.70	b	0.31	abc	0.30	abcd	0.40	bc	0.30	c	0.40	bc	0.30	c
OG	40.52	abcd	3.94	abc	1.89	a	1.13	ab	4.30	abdef	3.33	cdef	0.62	a	1.01	ab	0.27	bcd	0.30	abcd	0.72	a	0.52	abc	0.72	a	0.52	abc
SSNN	40.55	abcd	3.99	abc	1.05	b	0.86	b	5.85	a	5.35	abcd	0.63	b	0.54	b	0.34	ab	0.36	ab	0.75	a	0.54	abc	0.75	a	0.54	abc
	T	***	T	***	T	*	*	*	T	NS	NS	NS	T	NS	T	*	*	*	T	*	T	***	T	***	T	***	***	***
	C	***	C	***	C	***	***	***	C	***	***	***	C	***	***	***	***	C	***	***	T	***	T	***	T	***	***	***
	T × C	*	T × C	NS	T × C	NS	T × C	NS	T × C	NS	T × C	*	T × C	NS	T × C	NS	T × C	NS	T × C	NS	T × C	NS	T × C	T × C	T × C	T × C	NS	NS

Plants were grown hydroponically without (control) or with 2.0 mM Si. Different letters in columns indicate a significant difference in nutrient concentrations of the same cultivar. The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with * $P < 0.05$, ** $P < 0.01$, or *** $P < 0.001$. Differences with $P > 0.05$ are indicated as not significant (NS). Differences between treatment for a single cultivar are underlined. Expected ranges of the macronutrients in leaves are indicated in parentheses next to the appropriate element (Bryson et al., 2014).

Table 7. Effects of silicon (Si) treatment on macronutrient concentrations in stems and petioles of 'Beefsteak' (BS), 'Brandywine Red' (BWR), 'Early Girl' (EG), 'German Pink' (GP), Heinz 'H1015' (early) and 'H3406' (late), 'Mega Bite' (MB), 'Micro Tom' (MT), 'Old German' (OG), and 'Sweet 'N Neat' (SNN).

Macronutrients (%)																		
Stems																		
Cultivar	C		N		P		K		Ca		Mg		S					
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si				
BBS	29.27	cde	32.08	bcd	0.81	abc	9.28	bcd	8.10	defgh	1.35	cde	0.43	bcd	0.48	bc	0.32	bcdef
BWR	32.22	bcd	32.35	bcd	0.60	de	8.21	defgh	8.28	defg	1.01	ef	0.24	g	0.32	efg	0.24	fg
EG	29.20	de	28.07	e	4.48	a	10.48	abc	10.66	ab	1.47	cd	0.54	ab	0.60	a	0.35	abcde
GP	33.95	bcd	34.34	bcd	0.58	de	8.80	cde	8.58	def	0.99	ef	0.23	g	0.29	fg	0.21	g
H1014	35.95	abc	35.90	abc	0.71	cd	6.28	hi	6.12	i	0.89	f	0.38	c-f	0.44	bcd	0.25	efg
H3406	40.49	a	36.67	ab	0.74	cd	6.96	fghi	6.92	ghi	0.89	f	0.33	defg	0.41	cde	0.24	fg
MB	31.95	bcd	33.63	bcd	0.84	abc	8.21	defgh	7.31	efghi	1.10	ef	0.47	bc	0.43	bcd	0.26	efg
MT	NA	NA	NA	NA	0.71	cd	11.16	ab	11.45	a	2.12	ab	0.46	bcd	0.40	abc	0.28	cdefg
OG	34.56	bcd	34.62	bcd	0.68	cd	7.31	efghi	7.12	efghi	0.83	f	0.26	fg	0.37	cdef	0.26	efg
SNN	33.57	bcd	33.18	bcd	0.73	cd	7.02	fghi	7.41	efghi	1.10	ef	0.26	fg	0.26	fg	0.20	g
	T	NS	T	***	T	*	T	NS	NS	NS	T	***	T	***	T	***	***	***
	C	***	C	***	C	***	C	***	***	***	C	***	C	***	C	***	***	***
	T × C	NS	T × C	*	T × C	NS	T × C	NS	NS	NS	T × C	NS	T × C	NS	T × C	NS	NS	NS
Petioles																		
Cultivar	C		N		P		K		Ca		Mg		S					
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si				
BBS	25.23	ef	28.14	cdef	5.58	bc	4.34	bcd	0.74	abcde	0.78	abcde	0.57	abc	0.58	abc	0.37	abcd
BWR	30.26	abcd	28.58	bcd	3.34	efg	3.23	efg	0.58	e	0.68	cde	0.31	e	0.48	bcd	0.44	abc
EG	24.79	f	25.07	ef	5.89	b	4.93	bcd	0.90	ab	0.96	a	0.69	a	0.71	a	0.48	a
GP	29.34	abcde	30.15	abcd	3.64	defg	2.52	fgh	0.63	de	0.63	de	0.33	de	0.50	bcd	0.31	def
H1015	33.19	a	32.93	a	1.89	gh	1.43	h	0.85	abc	0.80	abcd	0.40	cde	0.58	abc	0.45	abc
H3406	33.44	a	33.49	a	1.54	h	1.61	h	0.83	abc	0.77	abcde	0.36	de	0.51	bcd	0.34	bcd
MB	18.21	g	26.57	def	8.04	a	4.62	bcd	0.74	abcde	0.68	cde	0.68	ab	0.73	a	0.34	bcd
MT	NA	NA	NA	NA	0.79	abcde	0.78	abcde	1.99	abc	0.34	bcd	0.68	ab	0.73	a	0.34	bcd
OG	32.32	ab	31.45	abc	2.48	fgh	2.67	fgh	1.95	abcd	0.38	cde	0.38	cde	0.41	cde	0.29	def
SNN	28.19	bcd	27.92	cdef	4.38	bcd	4.05	cdef	1.05	ef	0.34	de	0.34	de	0.50	bcd	0.45	ab
	T	NS	T	***	T	***	T	NS	T	NS	T	NS	T	NS	T	NS	0.32	cdef
	C	***	C	***	C	***	C	***	C	***	C	***	C	***	C	***	***	***
	T × C	***	T × C	***	T × C	NS	T × C	NS	T × C	*	T × C	NS	T × C	NS	T × C	NS	T × C	**

Plants were grown hydroponically without (control) or with 2.0 mM Si. The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with * $P < 0.05$, ** $P < 0.01$, or *** $P < 0.001$. Differences with $P > 0.05$ are indicated as not significant (NS). Differences between treatment for a single cultivar are underlined.

Table 8. Effects of silicon (Si) treatment on micronutrient concentrations in leaves and roots of 'Beefsteak' (BS), 'Brandywine Red' (BWR), 'Early Girl' (EG), 'German Pink' (GP), Heinz 'H1015' (early) and 'H3406' (late), 'Mega Bite' (MB), 'Micro Tom' (MT), 'Old German' (OG), and 'Sweet 'N Neat' (SNN).

Micronutrients (ppm)																							
Leaves																							
Cultivar	B (45–76)			Cu (5–10)			Fe (84–112)			Mn (55–165)			Mo (2.9–5.8)			Zn (25–39)							
	Control	Si		Control	Si		Control	Si		Control	Si		Control	Si		Control	Si						
BBS	48.79	gh	56.73	13.66	a	11.00	a	147.29	d	162.96	cd	116.76	bcde	81.41	e	2.44	def	2.45	def	21.59	ef	18.75	f
BWR	114.11	cd	102.19	31.52	a	10.13	a	174.57	cd	169.73	cd	129.59	bcd	116.63	b-e	1.74	ef	2.32	ef	37.55	ab	31.47	abcd
EG	84.32	def	78.25	13.33	a	13.60	a	194.04	bcd	207.36	bcd	129.71	bcd	105.69	bcd	3.71	bcd	4.06	abc	26.15	cdef	29.31	bcd
GP	53.01	fgh	74.37	26.11	a	31.48	a	165.29	cd	147.60	d	100.57	cde	92.82	de	1.17	f	1.71	ef	26.96	cdef	26.65	cdef
H1015	158.31	a	152.61	5.63	a	5.97	a	275.38	ab	285.84	a	131.52	bcd	122.70	bcd	2.21	ef	2.58	de	24.26	def	26.31	cdef
H3406	125.63	abc	120.88	6.68	a	10.73	a	226.45	abc	268.05	ab	106.50	cde	98.31	cde	2.15	ef	2.40	ef	18.98	f	20.07	f
MB	56.14	fgh	74.52	14.66	a	10.53	a	157.52	cd	157.52	cd	151.65	b	99.84	cde	3.14	cde	2.55	def	24.29	cdef	22.52	def
MT	47.95	gh	44.95	21.23	a	18.87	a	144.53	d	133.18	d	232.29	a	221.14	a	4.37	abc	4.53	abc	25.81	cdef	29.56	bcd
OG	132.35	abc	111.83	16.01	a	7.16	a	235.37	abc	208.22	abcd	111.14	bcde	103.76	cde	2.07	ef	2.34	ef	39.46	a	34.04	abc
SSNN	64.96	fgh	65.41	13.09	a	11.62	a	189.38	cd	181.33	cd	124.69	bcd	133.40	bc	5.07	a	4.77	ab	30.74	abcde	30.00	bcde
	T		NS	T		NS		T		NS		T		**		T		NS		T		NS	
	V		***	C		NS		C		***		C		***		C		NS		C		NS	
	T × V		NS	T × C		NS		T × C		NS		T × C		*		T × C		NS		T × C		NS	
Roots																							
Cultivar	B			Cu			Fe			Mn			Mo			Zn							
	Control	Si		Control	Si		Control	Si		Control	Si		Control	Si		Control	Si						
BBS	11.02	efg	15.08	12.95	ab	16.02	ab	644.46	cde	425.45	de	674.09	bc	493.45	cd	1.58	bc	1.75	bc	35.23	bcd	29.14	bcd
BWR	16.57	cdef	15.80	273.71	a	49.00	ab	1450.73	ab	1037.36	abcd	349.94	cdef	266.70	def	1.48	bc	1.20	bc	47.54	bc	30.57	bcd
EG	39.08	a	46.23	24.24	ab	15.51	ab	960.54	bcde	636.59	cde	943.40	cd	628.30	c	1.00	cde	1.64	bc	25.47	cd	20.69	cd
GP	13.84	defg	22.40	22.10	ab	12.17	ab	1166.00	abc	895.21	bcde	469.65	cde	283.54	def	1.54	bc	1.75	bc	58.82	b	36.56	bcd
H1015	13.47	defg	15.38	36.07	ab	18.21	ab	546.92	cde	721.35	cde	155.46	ef	128.32	f	2.94	a	2.29	ab	16.35	cd	14.61	bcd
H3406	11.26	efg	12.09	21.39	ab	20.43	ab	569.78	cde	703.77	cde	144.20	ef	146.67	ef	2.88	a	2.92	a	15.94	cd	10.45	cd
MB	19.54	cdef	35.74	24.26	ab	9.52	b	1152.50	abcd	333.89	e	1272.44	a	391.93	cdef	1.75	bc	2.12	abc	47.57	d	23.53	bc
MT	0.00	gh	4.22	12.18	ab	9.92	ab	423.06	de	238.19	e	362.89	cdef	392.98	cdef	3.28	a	2.43	ab	101.66	cd	61.67	a
OG	16.49	cdef	17.19	24.41	ab	22.65	ab	1581.01	a	1407.74	ab	275.34	def	161.15	ef	2.12	ab	1.75	bc	27.26	bcd	21.34	cd
SSNN	26.76	bc	25.34	18.65	ab	11.65	b	941.97	bcde	753.14	cde	598.70	c	427.27	c	2.29	ab	2.06	abc	44.37	bc	40.69	bc
	T		**	T		NS		T		***		T		***		T		NS		T		***	
	C		***	C		NS		C		***		C		***		C		NS		C		***	
	T × C		*	T × C		NS		T × C		*		T × C		***		T × C		NS		T × C		NS	

Plants were grown hydroponically without (control) or with 2.0 mM Si. The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C), with **P* < 0.05, ***P* < 0.01, or ****P* < 0.001. Differences with *P* > 0.05 are indicated as not significant (NS). Differences between treatment for a single cultivar are underlined. Expected ranges of the micronutrients in leaves are indicated in parentheses next to the appropriate element (Bryson et al., 2014).

Table 9. Effect of silicon treatment on micronutrient concentrations in stems and petioles of tomato cultivars 'Beefsteak' (BS), 'Brandywine Red' (BWR), 'Early Girl' (EG), 'German Pink' (GP), Heinz 'H1015' (early) and 'H3406' (late), 'Mega Bite' (MB), 'Micro Tom' (MT), 'Old German' (OG), and 'Sweet 'N Neat' (SNN).

Micronutrients (ppm)																								
Stems																								
Cultivar	B		Cu		Fe		Mn		Mo		Zn													
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si												
BBS	13.34	d	12.90	d	24.99	a	6.51	a	35.11	c	41.90	c	29.87	bcd	26.53	cdef	1.22	cd	1.20	cd	23.28	def	14.60	defgh
BWR	20.07	bc	21.70	b	4.56	a	7.38	a	39.93	c	34.76	c	26.01	defg	21.92	fgh	0.67	cdef	0.77	cdef	20.96	def	13.51	efgh
EG	36.42	a	32.77	a	15.61	a	14.80	a	44.21	c	47.97	c	36.95	bc	33.90	bcd	0.98	cdef	0.95	cdef	21.16	def	18.66	defgh
GP	14.54	cd	15.75	cd	7.18	a	2.71	a	43.55	c	45.72	c	28.66	bcd	20.53	fgh	0.55	def	0.70	cdef	24.65	cde	14.49	defgh
H1014	15.24	cd	17.49	bcd	3.45	a	5.10	a	44.76	c	48.71	c	18.74	gh	18.74	gh	0.22	f	0.37	ef	7.20	gh	7.92	gh
H3406	15.33	cd	15.71	cd	19.14	a	8.03	a	44.72	c	53.85	bc	15.16	h	13.11	h	0.61	cdef	0.59	def	6.99	h	6.53	h
MB	14.20	cd	17.64	bcd	7.58	a	4.75	a	38.31	c	44.74	c	33.44	b-g	23.92	e-h	1.36	bc	1.12	cd	27.82	cd	10.84	fgh
MT	6.63	e	5.42	e	6.69	a	6.38	a	140.96	a	91.05	b	63.40	a	71.22	a	3.17	a	2.03	b	54.57	b	69.26	a
OG	15.97	bcd	17.54	bcd	9.56	a	12.44	a	40.68	c	37.51	c	20.12	gh	23.40	efgh	0.67	cdef	0.87	cdef	9.82	gh	9.04	gh
SSNN	16.22	bcd	15.24	cd	6.05	a	4.75	a	42.33	c	39.24	c	37.97	b	36.30	bcd	1.32	c	1.24	c	35.44	c	35.97	c
	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	*	*	
	C	***	***	***	C	NS	NS	NS	C	***	***	***	C	***	***	***	C	***	***	***	C	***	***	***
	T × C	NS	NS	NS	T × C	NS	NS	NS	T × C	NS	*	*	T × C	NS	*	*	T × C	NS	**	**	T × C	NS	NS	NS
Petioles																								
Cultivar	B		Cu		Fe		Mn		Mo		Zn													
	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si	Control	Si												
BBS	16.81	f	17.04	f	6.70	a	4.77	a	39.02	bcd	41.67	bcd	38.83	cdef	26.63	fghi	1.04	ab	0.92	ab	16.09	bc	9.15	bc
BWR	28.84	bcd	30.91	abc	7.54	a	16.13	a	27.85	cd	28.08	cd	30.47	efgh	26.49	fghi	0.62	bc	0.66	bc	10.25	bc	7.24	c
EG	35.50	a	33.37	ab	21.00	a	7.18	a	54.32	b	55.48	b	47.78	bcd	42.48	cde	0.64	bc	1.52	a	19.97	bc	16.73	bc
GP	21.96	ef	24.17	de	25.03	a	21.36	a	47.42	bcd	42.07	bcd	42.56	cde	33.84	defg	0.41	bc	0.59	bc	14.35	bc	7.80	c
H1015	24.13	de	24.72	cde	4.48	a	5.64	a	35.82	bcd	34.05	bcd	19.44	ghi	19.00	hi	0.18	bc	0.10	c	6.65	c	6.77	c
H3406	21.77	ef	22.69	def	15.77	a	2.90	a	37.31	bcd	40.76	bcd	13.33	i	12.53	i	0.50	bc	0.41	bc	6.91	c	16.61	bc
MB	19.91	ef	25.58	cde	5.32	a	3.87	a	38.62	bcd	37.93	bcd	51.77	abc	33.55	d-h	1.18	ab	1.09	ab	24.58	abc	10.62	bc
MT	13.18	fg	5.52	g	5.72	NA	3.71	a	98.12	NA	88.38	a	67.80	NA	69.64	a	2.06	NA	1.57	a	33.82	NA	44.80	a
OG	24.46	de	24.42	de	3.01	a	16.18	a	25.93	d	27.38	cd	21.63	ghi	26.95	efghi	0.87	abc	0.84	abc	7.83	c	6.63	c
SSNN	25.69	cde	25.75	cde	12.77	a	4.24	a	49.08	bc	46.83	bcd	47.51	bcd	54.31	abc	1.61	a	1.50	a	38.58	a	37.32	a
	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS	T	NS	NS	NS
	C	***	***	***	C	NS	NS	NS	C	***	***	***	C	***	***	***	C	***	***	***	C	***	***	***
	T × C	*	*	*	T × C	NS	NS	NS	T × C	NS	NS	NS	T × C	NS	**	**	T × C	NS	*	*	T × C	NS	NS	NS

Plants were grown hydroponically without (control) or with 2.0 mM Si. The 2 × 10 factorial analysis indicates a significant difference for treatment (T), tomato cultivar (C), or treatment and cultivar (T × C) with **P* < 0.05, ***P* < 0.01, or ****P* < 0.001. Differences with a *P* > 0.05 are indicated as not significant (ns). Differences between treatment for a single cultivar are underlined.

chlorophyll content, plant height, stem thickness/diameter, and tissue mass (Frazao et al., 2020; Kamenidou et al., 2008; Mattson and Leatherwood, 2010; Silva et al., 2012; Song et al., 2014). During this study, we observed that 'Beefsteak' had longer stem lengths and a larger SD after Si treatment than after control treatment. However, differences in plant height were not observed for any of the other cultivars tested. This could suggest that plant growth of this cultivar was an indirect response to Si treatment. Other environmental or genetic factors, in addition to Si, may have been responsible for phenotypic changes observed during other studies.

Tomatoes are known to accumulate lower foliar concentrations of Si compared with grains and other dicots, such as cucumber, sunflower, and zinnia (Frantz et al., 2010; Hodson et al., 2005). Previous studies showed similar Si concentrations in roots and leaves of the tomato cultivar 'King Kong II' (Heine et al., 2005). During this study, the highest Si concentrations were observed in the roots of Si-fed plants; their levels exceeded the macronutrient concentrations in many of the cultivars. Root Si concentrations were higher than leaf Si concentrations in all cultivars except for 'Micro Tom'. During the study involving 'King Kong II', plants were grown for less than 2 weeks in 1.0 mM Si; however, during this study, plants were grown for 4 to 8 weeks with 2.0 mM Si, thereby allowing more time for more accumulation in plant tissue. The high concentration of Si in roots compared with that in leaves suggests that tomatoes restrict the movement of Si into aboveground tissue of some cultivars. However, this restriction does not suggest exclusion because the Si concentrations in leaves were higher than the Fe concentrations (Tables 4–8). These data showed that tomato plants accumulate Si and partition the element into different organs, with roots and leaves appearing as Si sinks. Unlike other nutrients amended in excess, there were no observable toxicity symptoms in the plants as the Si levels significantly increased. This suggests that the plants likely have cellular mechanisms for movement and use in root and leaf tissues.

The Si concentrations in petioles were significantly higher than those in stems, possibly suggesting that this tissue is a larger sink for the nutrient as it moves into the leaves. Both tissues, however, had small fractions of total Si compared with roots and shoots. Because sap analyses using petiole tissue are becoming more frequent for nutrient analysis, the quantification technique needs to be sensitive enough to detect Si in these ranges.

Interestingly, Si concentrations in tissue varied widely with cultivar. 'Micro Tom' had the lowest Si concentrations when compared with the other nine varieties in this study, and it had a higher concentration in leaves than in roots, which was opposite of what was observed for the other species tested. This cultivar is a small, determinate plant that has been used for genomic information. This could suggest that different uptake/partitioning

strategies for this plant are involved, and that the use of 'Micro Tom', in contrast to Heinz, may provide insight regarding Si regulation. Additionally, Heinz and heirloom cultivars accumulated the highest concentration of Si within tissue. This suggests that they have a larger draw on the silicic acid pool in the media and would require a higher dose of Si in the growing media.

The first criterion for nutrient essentiality in plants states that in the absence of the nutrient or element in question, a plant cannot complete its lifecycle (Arnon and Stout, 1939). Previous studies reported the use of copper stills to produce mineral-free water. During this study, ultra-purified water was used with laboratory-grade chemicals, but there were still detectable concentrations of Si in the roots. The source of Si contamination in this study was unknown. This exemplifies the problem of testing Si essentiality in plants using criteria developed in 1939, requiring that the nutrient be absent from the growing media (Arnon and Stout, 1939). Epstein and Bloom (2005) recognized this limitation and revised the criterion stating that a nutrient is essential if depletion of the element in question from the growing media leads to reduced plant performance. It may be time to reconsider that the essentiality of Si in plants is strongly supported by this adapted definition when considering the role of this element in plant health.

There were few differences in the nutrient compositions of the tomato cultivars between Si-fed and control plants. Differences in K and S concentrations were not too surprising because control plants were fed with K₂SO₄ to provide equal concentrations of K in the growing media, and this difference was more likely caused by the nutrient solution than by a direct effect of Si absorption by the plant. The amount of nutrients provided in the hydroponics system, including Si, were supplied at a rate at which no nutrient would be limiting to the growth of the plants. This is likely why only slight differences were observed for a few of the nutrients of Si-fed and control plants.

This is not the first study to show differences in Si accumulation among different cultivars. Several studies of rice have shown distinct differences in Si accumulation in different cultivars (Deren et al., 1992; Ma et al., 1992). Arsenault-Labrecque et al. (2012) reported that Si concentrations ranged from 0.4% to 1.3% in different soybean cultivars. Most recently, reports of varying Si contents in eight petunia cultivars were reported (Boldt and Altland, 2021). It is likely that as more plant cultivars are tested, this list will continue to grow.

Because of our knowledge of the benefits of Si against stress and the high demand that is placed on tomato plants during hydroponic production, the incorporation of Si into fertilizer programs is warranted. During this study, a high Si concentration was incorporated in a deep-water hydroponic system. Based on these data, it could be suggested that a higher concentration of Si is needed when growing certain heirlooms than when growing hybrids and determinates. A few studies have

examined the effects of Si on hydroponic tomato production. Costan et al. (2020) showed an increase in fruit firmness and vitamin C content. Foliar sprays comprising a combination of Si and B increased the shelf life, vitamin C, and firmness of tomato fruit (Islam et al., 2018). Barreto et al. (2016) showed that Si in hydroponic tomato production can also protect against ammonium toxicity. During hydroponic production, fertilization programs tend to be closely monitored, but research regarding how Si may alter the balance of other nutrients is lacking.

During this study, ample amounts of essential nutrients, including Si, were provided so that no nutrient was limiting to the growth of the 10 tomato cultivars. To understand the role of Si in a balanced nutrient plan for tomatoes, further studies of the effects or interactions of varying Si concentrations and low or limiting amounts of other nutrients, including N, P, and Ca, should be performed. In conclusion, tomatoes accumulate Si at macronutrient concentrations in leaves and do not exclude Si from the media; however, the movement of Si into foliar tissue is restricted when it and other nutrients are supplied in significant ranges.

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