Effects of Silicon and Salinity on Fruit Yield and Quality of Tomato Grown Hydroponically

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Abstract

The effects of silicon added to the nutrient solution either at a standard electrical conductivity (EC) of 2.2 dS m⁻¹ or at an increased EC of 4.8 dS m⁻¹ on yield, nutritional status and fruit quality were investigated in a tomato crop grown in a closed hydroponic system. Si was added in form of a water-soluble potassium silicate compound at a reference concentration of 2.25 mM. The EC was raised either by NaCl or by extra addition of K, Ca, and Mg salts of nitrates and sulfates at rates resulting in the same K:Ca:Mg and NO₃:SO₄ ratios and NH₄, P, and micronutrient concentrations in all treatments. The average EC values in the drainage water were 3.7 and 3.4 dS m⁻¹ in the low EC treatments without and with Si supply, respectively, and 5.8, 5.7 and 5.8 dS m⁻¹ in the salinity treatments involving NaCl addition, NaCl and Si addition, and extra nutrients combined with Si addition, respectively. The increase of the EC up to 4.8 dS m⁻¹ by adding NaCl had no significant influence on the fruit yield of tomato, when Si was added to the saline nutrient solution. In contrast, the fruit yield per plant was significantly restricted at this level of salinity, when no Si was added to the NaCl-enriched nutrient solution, or when Si was included but salinity was induced by extra addition of major nutrients. In both cases, the yield depressions were exclusively due to a lower mean fruit weight. The β-carotene and lycopene contents of fruit were significantly increased by Si and nutrient-induced salinity. Both Si and EC enhanced the fruit firmness and the contents of total solid solutes and vitamin C in the tomato fruit. Moreover, the addition of Si significantly restricted the occurrence of blossom-end rot in tomato fruit when the plants were not exposed to salinity.

INTRODUCTION

Although silicon is not considered an essential element for plant nutrition, many authors report on beneficial effects when its supply to various cultivated plants is enhanced. In most cases, the favorable effects of Si on crop plants seem to originate from reinforcement of the cell walls due to deposition of Si in form of amorphous silica (SiO₂·nH₂O) and opal phytoliths (Inanaga and Okasaka, 1995; Epstein, 1999). For instance, Si increases the thickness and erectness of rice plants (Yoshida et al., 1969) and the roughness of wheat leaves and awns (Rafi and Epstein, 1997) thus improving light reception, which results in enhanced yield (Mitsui and Takatah, 1963). Moreover, the mechanical strength provided by Si to the plant tissues increases their resistance to several bacterial, fungi and insect diseases (Adatia and Besford, 1986; Menzies et al., 1991; Epstein, 1999) and decreases the occurrence of the physiological disorder “bent neck” in gerbera (Savvas et al., 2002). In other reports, Si was implicated to ameliorate the adverse effects of aluminium toxicity (Barcelo et al., 1993; Hammond et al., 1995), manganese toxicity (Horst and Marschner, 1978; Iwasaki et al., 2002), and salinity (Bradbury and Ahmad, 1990; Liang et al., 1996).

In commercial hydroponics, plants are grown on inert substrates and, therefore, their supply with Si depends mainly on the silicon concentration in the raw water used to prepare nutrient solution. Thus, if the Si concentration in the raw water is low, some plant species may benefit from extra addition of Si to the nutrient solution. On the other hand,
too high salt concentrations in the available irrigation water, and hence exposure of greenhouse crops to salinity, is a frequent problem worldwide (Sonneveld, 2000). Based on the above mentioned reports regarding the interactions between Si and salt, it seems likely that the supply of Si via the nutrient solution might alleviate the adverse effects of salinity on some soilless grown crop species. The objective of this study was to test whether tomato grown hydroponically either at a standard or at an increased salinity level responds positively to the supply of Si via the nutrient solution.

MATERIALS AND METHODS

Tomato plants were grown in bags filled with perlite in an unheated glasshouse at the Mediterranean Agronomic Institute of Chania. The plants were supplied with nutrient solution having a standard (2.2 dS m\(^{-1}\)) or a high (4.8 dS m\(^{-1}\)) total salt concentration and a low (0.2 mM) or a high (2.25 mM) reference Si concentration. When no Si was applied, the increase of the electrical conductivity (EC) to 4.8 dS m\(^{-1}\) was achieved by adding appropriate amounts of NaCl to the standard nutrient solution. However, when Si was also included, two salinity treatments were established by injecting either NaCl or extra salts of K, Ca and Mg with sulfates and nitrates at the same K:Ca:Mg and NO\(_3\):SO\(_4\) ratios as in the standard EC treatments. The concentration of 0.2 mM Si originated exclusively from the raw water, while the increase to 2.25 mM Si was attained by adding a liquid potassium silicate compound (Sonneveld, 2000) from a separate stock solution tank. The five nutrient solution treatments were applied by means of a computer-controlled system as described in a previous paper (Savvas and Adamidis, 1999). At each irrigation, the entire volume of drainage water collected after the previous nutrient solution application was automatically recycled according to Savvas and Manos (1999). The target mean ionic concentrations in each nutrient solution treatment, which were attained by replenishing the reused drainage with nutrients according to the concept of a reference composition (Savvas, 2002), are given in Table 1. The pH of the supplied nutrient solution was set at 5.6 in all treatments.

The plants were planted on November 1, 2001 and arranged into twenty experimental units at a plant density of 2.4 plants per m\(^2\). Thus, there were four replications of each treatment with 16 experimental plants per replication. Harvesting of commercially ripe fruits was commenced on 21 March and terminated on 13 July 2002. During the whole growing period, the harvested fruits from all treatments were counted, weighed and graded.

To determine the influence of Si and salinity on the uptake of nutrients, 4 young, fully expanded leaves were sampled from each experimental unit on May, 22. The leaves were collected immediately above the trust bearing the most recently set fruits. Moreover, on June 12, samples of fruits at commercial ripening were collected from each experimental unit. The above samples were dried at 65 °C to constant weight, ground, and used to determine the fruit firmness and the K, Ca, Mg, P, Na, and Cl concentrations. Moreover, a sub-sample was obtained from each fruit sample, which was used for the determination of β-carotene, lycopene, lutein, vitamin C and total solute solids contents.

The concentrations of K, Ca, Mg, P, and Na from the plant tissue samples were measured by inductively-coupled plasma spectroscopy (Isaac and Johnson, 1998) using a PS 1000 AT, Leeman Labs Inc spectrometer, after dry ashing at 550°C for 5 h and extraction with 2 N HCl (Miller, 1998). Leaf Cl concentrations were measured by an ion specific electrode after a water extraction of the dried and ground material (Liu, 1998).

The extraction of β-carotene, lycopene and lutein was performed by weighing 5 g of homogenized tomato fruit tissue, adding 2 g of silica gel 60 and 10 ml methanol, concentrating the mixture to dryness on a rotary evaporator, then adding 10 ml acetone plus 10 ml tetrahydrofuran Z.A., treating it with ultra sound, concentrating it again to dryness, adding ethyl acetate and distilled water to separate the pigments from the sugars, using sodium sulfate to dry over the organic phase, concentrating the mixture to dryness on a rotary evaporator, and taking up the residue using 10 ml ethyl acetate. Subsequently, the concentrations of β-carotene, lycopene and lutein were determined by means of HPLC.
analysis on a RP18 Lichrospher 100 (Merck) 250X4 (5 µ) column and DAD detection. Eluent (A) was acetonitrile : water (9:1) containing 0.1% triethylamine and (B) ethyl acetate and the flow rate was 1 ml min⁻¹. The elution program used was as follows: from 100% A to 0% A in 25 min (total run time 35 min). The temperature of the column was kept at 40 °C and monitoring was performed at 450nm (β-carotene), 447nm (lutein), and 471 (lycopene). The total solute solids were determined by means of a digital refractometer (Palette-Atago PR-100). Vitamin C was determined according to the 2,6-dichloroindophenol titrimetric method. The fruit firmness was measured on both sides of 3 randomly selected fruits per replication by means of a penetrometer Bishop FT model 011.

The data were subjected to ANOVA and all possible comparisons between the five treatment means were carried out by employing Duncan’s MRT (P = 0.05).

RESULTS
As shown in Table 2, the increased supply of Si enhanced the Ca concentration of both the leaf and the fruit, when no salinity was applied. However, when the EC was increased up to 4.8 dS m⁻¹, no significant effect of Si on Ca uptake could be established. Unlike the NaCl-salinity, the nutrient-induced salinity reduced significantly the leaf Ca concentration in comparison with the control. The translocation of Na and Cl to the leaf and Na to the fruit of tomato was significantly reduced when plants were exposed to NaCl salinity combined with enhanced Si supply in comparison with plants exposed to NaCl salinity without addition of Si.

Both Si and salinity had a profound effect on β-carotene, lycopene and TSS contents in the fruit (Table 3). In particular, both silicon and nutrient-induced salinity enhanced significantly the β-carotene and lycopene contents, while the NaCl-induced salinity tended to suppress them. The TSS content was significantly increased by both Si and salinity, irrespective of salinity source. The lutein content tended to be enhanced by both Si and salt exposure, regardless of salinity source, but due to the high variation of the measured values no significance could be established. The vitamin C content and the fruit firmness were enhanced by both addition of Si to standard nutrient solution and salinity. However, the addition of Si to saline nutrient solution had no effect on the vitamin C content and the firmness of the fruit. The salinity source had no effect on the vitamin C content but enhanced further the fruit firmness.

The increase of the EC up to 4.8 dS m⁻¹ by adding NaCl had no significant influence on the fruit yield of tomato, when Si was added to the saline nutrient solution (Table 4). In contrast, the fruit yield was significantly restricted by this level of salinity when no Si was added to the NaCl-enriched nutrient solution, or when Si was included but salinity was induced by increasing the concentrations of major nutrients. In both cases, the yield depressions were exclusively due to a lower mean fruit weight. Nevertheless, the addition of Si to the nutrient solution had no significant effect on yield and yield components within each EC level.

The addition of Si significantly restricted the occurrence of blossom-end rot in tomato fruit, when the plants were not exposed to salinity (Table 4). However, the diminishing effect of Si on the incidence of BER was insignificant when Si was added in the NaCl-enriched nutrient solution. The exposure of plants to salinity resulted in a significantly higher number of fruits per plant suffering from blossom-end rot, and this effect was more marked when the high salt concentration was induced by addition of extra nutrients, despite the presence of Si in that nutrient solution. The number of fruits per plant graded Class I was significantly restricted by salinity. The inclusion of Si to the nutrient solution and the salinity source did not exert any significant effect on the number of fruits graded Class I.

DISCUSSION
The presented results indicate that silicon may restrict the uptake of undesirable Na and Cl ions when the tomato is exposed to NaCl-salinity. A similar response was
observed also in barley (Liang, 1999). However, in our study, the depressing effect of Si on the uptake of Na by tomato was rather mild, while in case of rice and barley, the suppression of the tissue Na concentration due to the presence of Si in the growing medium was profound. The mechanisms underlying this effect have not been fully elucidated (Epstein, 1999). Yoshida (1965) ascribed this effect to the formation of a silica-cellulose layer beneath the cuticle layer of leaves, which reduces transpiration. If this is true, transpiration may be differently influenced by this silica-cellulose layer in various plant species due to anatomical dissimilarities in leaves, thus resulting in quantitative differences in the response of Na uptake to the supply of Si. Nevertheless, the reduction of Na and Cl concentrations observed in the present study when the NaCl-salinity was combined with Si supply were insufficient for a significant enhancement of the yield of tomato as compared to that obtained at the same level of NaCl-salinity without Si addition.

Enhancement of Ca uptake due to the addition of Si in the supplied nutrient solution has been reported also by Liang et al. (1996) and Savvas et al. (2002). Nevertheless, a decreased shoot Ca concentration under conditions of an enhanced Si supply has been also reported (Ma and Takahashi, 1993). It is well known that blossom-end rot (BER) is a physiological disorder originating from an insufficient supply of Ca to the distal part of the fruit (Adams, 2002). In our study, the inclusion of Si in standard nutrient solution for tomato enhanced significantly the Ca concentrations in both the leaf and the fruit of tomato, thus restricting concomitantly the incidence of blossom-end rot. However, a similar effect of Si on Ca translocation to leaf and fruit and to the occurrence of BER could not be established when the plants were exposed to salinity. Nevertheless, the Ca concentrations tended to be higher and the incidence of BER less frequent with NaCl-salinity rather than nutrient-induced salt stress of the same level. The physiological mechanisms underlying the effects of Si on the uptake and translocation of Ca by plants are not clear. Differences in the modulation of cell walls due to deposition of Si (Inanaga and Okasaka, 1995; Epstein 1999) may enhance the indiffusible anion sites, which adsorb Ca, thus imposing an elevated Ca content in the plant tissues. Nevertheless, the possible relationship between Si supply and Ca uptake by plants requires further investigation.

The NaCl-salinity restricted the β-carotene and lycopene concentrations in tomato fruit. In a previous study, De Pascale et al. (2001) found an increasing effect of moderate salinity levels up to 4 dS m⁻¹ in the root zone on total carotenoid and lycopene contents in tomato fruit. A similar response was reported also by Petersen et al. (1998). However, when salinity was higher than 4 dS m⁻¹ in the rhizosphere, the total carotenoid and lycopene contents progressively declined (De Pascale et al., 2001). In our study, the average EC values in the root environment of the plants not treated and treated with salinity were 3.4-3.7 and 5.7-5.8 dS m⁻¹, respectively. Hence, the reduction of β-carotene and lycopene concentrations caused by NaCl salinity in our study is consistent with the results of De Pascale et al. (2001). Nevertheless, the lutein content was not affected by the salinity level tested in our study. In contrast, lutein exhibited an increasing tendency. These results indicate that lutein responds differently to salinity in comparison with β-carotene and lycopene. The enhancing effects of salinity on the vitamin C and the soluble solid contents as well as on the firmness of fruit are in agreement with reports of other investigators (Petersen et al., 1998; De Pascale et al., 2001). Petersen et al. (1998) attributed the enhancing contents of vitamin C and total soluble solids in tomato fruit with increased salinity to concentration effects originating from reduced fruit water content due to adaptation of the plant to salinity. Nevertheless, in terms of consumer quality, the relevant criterion is the composition of the fresh fruit.

The present study clearly indicated that an enhanced Si supply to tomato increases markedly the β-carotene and lycopene contents, irrespective of salinity status in the root zone. It is not clear how Si can influence the carotenoid content of the tomato fruit. Carotenoids are antioxidant compounds whose nutritional value is highly respected (Khachik et al., 1992), and therefore, a high concentration of these pigments in the tomato fruit increases their internal quality. De Pascale et al. (2001) proposed the exposure of
tomato to a moderate salt stress as a means to improve carotenoids content in the fruit. The combination of a moderate salt stress with an enhanced Si supply may be an even more effective means to achieve this goal. Nevertheless, further research is required to confirm these results in various tomato cultivars under varying growing conditions.

**Literature Cited**


Rafi, M.M. and Epstein, E. 1997. Silicon deprivation causes physical abnormalities in...

### Tables

**Table 1.** Different target mean ionic concentrations (mM) in the five nutrient solution treatments. The corresponding NH$_4$, P, and micronutrient concentrations were identical in all treatments (1 mM NH$_4$, 1.3 mM P, 15, 10, 4, 0.75, 20 and 0.5 µM Fe, Mn, Zn, Cu, B, and Mo, respectively).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>NO$_3$</th>
<th>SO$_4$</th>
<th>Cl</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 dS m$^{-1}$; No Si</td>
<td>7.20</td>
<td>4.00</td>
<td>1.75</td>
<td>0.45</td>
<td>14.00</td>
<td>2.00</td>
<td>0.45</td>
<td>0.20</td>
</tr>
<tr>
<td>2.2 dS m$^{-1}$; Yes Si</td>
<td>7.20</td>
<td>4.00</td>
<td>1.75</td>
<td>0.45</td>
<td>14.00</td>
<td>2.00</td>
<td>0.45</td>
<td>2.25</td>
</tr>
<tr>
<td>4.8$^1$ dS m$^{-1}$; No Si</td>
<td>7.20</td>
<td>4.00</td>
<td>1.75</td>
<td>22.50</td>
<td>14.00</td>
<td>2.00</td>
<td>22.50</td>
<td>0.20</td>
</tr>
<tr>
<td>4.8$^1$ dS m$^{-1}$; Yes Si</td>
<td>7.20</td>
<td>4.00</td>
<td>1.75</td>
<td>22.50</td>
<td>14.00</td>
<td>2.00</td>
<td>22.50</td>
<td>2.25</td>
</tr>
<tr>
<td>4.8$^2$ dS m$^{-1}$; Yes Si</td>
<td>17.05</td>
<td>9.45</td>
<td>4.15</td>
<td>0.45</td>
<td>33.85</td>
<td>4.85</td>
<td>0.45</td>
<td>2.25</td>
</tr>
</tbody>
</table>

$^1$: NaCl-salinity  $^2$: Nutrient-induced salinity

**Table 2.** Effects of Si supply, EC of the irrigation nutrient solution, and source of salinity on the Ca, Na and Cl concentration in leaf and fruit of tomato grown hydroponically. In each column, values followed by the same letter do not differ significantly at P = 0.05 according to Duncan’s MRT.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Leaf (mg g$^{-1}$ dry weight)</th>
<th>Fruit (mg g$^{-1}$ dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca</td>
<td>Na</td>
</tr>
<tr>
<td>2.2 dS m$^{-1}$; No Si</td>
<td>19.6 b</td>
<td>0.67 c</td>
</tr>
<tr>
<td>2.2 dS m$^{-1}$; Yes Si</td>
<td>21.3 a</td>
<td>0.57 c</td>
</tr>
<tr>
<td>4.8$^1$ dS m$^{-1}$; No Si</td>
<td>19.1 bc</td>
<td>2.15 a</td>
</tr>
<tr>
<td>4.8$^1$ dS m$^{-1}$; Yes Si</td>
<td>20.1 ab</td>
<td>1.85 b</td>
</tr>
<tr>
<td>4.8$^2$ dS m$^{-1}$; Yes Si</td>
<td>17.6 c</td>
<td>0.57 c</td>
</tr>
</tbody>
</table>

$^1$: NaCl-salinity  $^2$: Nutrient-induced salinity

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Table 3. Effects of Si supply, EC of nutrient solution, and salinity source on β-carotene, lycopene, lutein, total solute solids (TSS), and vitamin C concentrations in fresh fruit, as well as on fruit firmness in tomato grown hydroponically. In each column, values followed by the same letter do not differ significantly at P = 0.05 according to Duncan’s MRT.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>β-Carotene (µg g⁻¹ fresh weight)</th>
<th>Lycopene (µg g⁻¹ fresh weight)</th>
<th>Lutein (µg g⁻¹ fresh weight)</th>
<th>Vit. C (g)</th>
<th>TSS (% in fresh wt.)</th>
<th>Firmness (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 dS m⁻¹; No Si</td>
<td>1.46 bc</td>
<td>3.42 cd</td>
<td>1.64 a</td>
<td>35 a</td>
<td>4.7 c</td>
<td>8.2 c</td>
</tr>
<tr>
<td>2.2 dS m⁻¹; Yes Si</td>
<td>2.35 a</td>
<td>7.07 b</td>
<td>2.26 a</td>
<td>83 b</td>
<td>5.5 ab</td>
<td>10.2 b</td>
</tr>
<tr>
<td>4.8¹ dS m⁻¹; No Si</td>
<td>1.14 c</td>
<td>2.43 d</td>
<td>2.85 a</td>
<td>68 b</td>
<td>5.4 b</td>
<td>10.9 b</td>
</tr>
<tr>
<td>4.8¹ dS m⁻¹; Yes Si</td>
<td>1.75 b</td>
<td>4.49 c</td>
<td>3.09 a</td>
<td>68 b</td>
<td>5.7 a</td>
<td>10.8 b</td>
</tr>
<tr>
<td>4.8² dS m⁻¹; Yes Si</td>
<td>2.44 a</td>
<td>11.00 a</td>
<td>3.82 a</td>
<td>72 b</td>
<td>6.0 a</td>
<td>12.2 a</td>
</tr>
</tbody>
</table>

¹: NaCl-salinity          ²: Nutrient-induced salinity

Table 4. Effects of Si supply, EC of the irrigation nutrient solution, and source of salinity on fruit yield, yield components, incidence of blossom-end rot (BER) and fruit quality in tomato grown hydroponically. In each column, values followed by the same letter do not differ significantly at P = 0.05 according to Duncan’s MRT.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Kg of fruit per plant</th>
<th>No of fruits per plant</th>
<th>Mean fruit weight (g)</th>
<th>Fruits with BER per plant</th>
<th>Fruits graded Class I</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 dS m⁻¹; No Si</td>
<td>5.58 ab</td>
<td>49.7 abc</td>
<td>113 ab</td>
<td>10.0 b</td>
<td>1.83 a</td>
</tr>
<tr>
<td>2.2 dS m⁻¹; Yes Si</td>
<td>5.78 a</td>
<td>47.1 c</td>
<td>122 a</td>
<td>6.8 a</td>
<td>2.08 a</td>
</tr>
<tr>
<td>4.8¹ dS m⁻¹; No Si</td>
<td>5.01 cd</td>
<td>47.7 bc</td>
<td>104 b</td>
<td>12.1 b</td>
<td>1.39 b</td>
</tr>
<tr>
<td>4.8¹ dS m⁻¹; Yes Si</td>
<td>5.18 bc</td>
<td>51.3 ab</td>
<td>100 b</td>
<td>10.9 b</td>
<td>1.33 b</td>
</tr>
<tr>
<td>4.8² dS m⁻¹; Yes Si</td>
<td>4.63 d</td>
<td>52.7 a</td>
<td>87 c</td>
<td>16.1 c</td>
<td>1.02 b</td>
</tr>
</tbody>
</table>

¹: NaCl-salinity          ²: Nutrient-induced salinity