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Extraction and accumulation of silicon in tomato grown under different water regimes and application forms

Extração e acúmulo do silício em tomate cultivado sob diferentes reposições hídricas e formas de aplicação

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ABSTRACT

The application of silicon (Si) in plants benefits the performance of several species. However, the dynamics of the element, mainly in non-accumulating species such as tomatoes, are rarely analyzed. This study investigated the dynamics of Si in tomato plants cultivated under different forms of application and water conditions. The experiment was carried out in a completely randomized design with four replications, using a factorial scheme 2 x 4: two water conditions (60 and 100% of the evapotranspiration of the crop - ETc), and four forms of silicon application (without application, full dose applied at soil, split dose applied at soil, and foliar application). Si content in the soil and in the different plant organs were analyzed. Si content in the soil increased after the crop cycle depending on the application form (full or split doses). The dynamics of Si accumulation and extraction by tomato are influenced by the application form (higher in soil application) and water management, with fruits and leaves having the higher values. Si application, mainly in the soil, increased the rate of Si accumulation and extraction by tomatoes cultivated in different water conditions.

Index terms: Mineral nutrition; *Solanum lycopersicum* L.; subtropical environment; water management.

RESUMO

A aplicação de silício em plantas ocasiona benefícios no desempenho de diversas espécies. Entretanto, a dinâmica do elemento, principalmente em plantas de espécies não acumuladoras como o tomate, é pouco analisada. O estudo teve como objetivo analisar a dinâmica do silício no cultivo do tomate em diferentes condições hídricas e formas de aplicação do elemento. O experimento foi conduzido em delineamento inteiramente casualizado com quatro repetições, adotando esquema fatorial 2 x 4: duas condições de reposição hídrica (60 e 100% da evapotranspiração da cultura - ETc), quatro formas de aplicação de silício (sem aplicação, aplicação no solo de dose total, aplicação no solo de dose parcelada e aplicação foliar). Foi analisado o teor de silício no solo e nos componentes vegetais do tomateiro. O teor de silício no solo após o cultivo foi elevado em função da aplicação do elemento, em dose total ou parcelada. A dinâmica de acúmulo e extração do silício pelo tomateiro é influenciada pelo manejo hídrico e pela forma de aplicação do elemento, sendo as maiores taxas no fruto e na folha. A aplicação do elemento, principalmente no solo, elevou a taxa de acúmulo e extração do silício pelo tomateiro cultivado em diferentes condições de reposição hídrica.

Termos de indexação: Nutrição mineral; *Solanum lycopersicum* L.; ambiente subtropical; manejo da água.

INTRODUCTION

Silicon (Si) is an element present in large proportions on the planet, whose availability to plants is influenced by soil formation, mineralogical and chemical characteristics, climatic conditions in the production environment, and agricultural management (Mandlik et al., 2020; Katz et al., 2021; Schaller et al., 2021). Although it is not considered an essential element for plants, Si application can benefit the development and yield of crop species (Yan et al., 2018; Leroy et al., 2019; El-Saadony et al., 2021; Mitani-Ueno; Ma, 2021).

Plants are characterized as non-accumulator, intermediate, and accumulator according to their capacity of accumulating Si in their dry mass (Hoffmann et al., 2020; Katz et al., 2021; Souri et al., 2021). However, fertilization with Si also increases the yield of non-accumulator species

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(Lozano et al., 2018; Nascimento et al., 2020; Camargo; Keeping, 2021; Nocchi et al., 2021; Wenneck et al., 2021). The exogenous application becomes efficient considering that the soils, mainly weathered, have low natural concentrations of Si, and its availability is still influenced by the sources used and interactions with the soil and the plant (Leroy et al., 2019; Souri et al., 2021; Wenneck; Saath; Rezende, 2022).

In melon, the application of Si in the soil at doses up to 200 kg ha^{-1} improved the fruit maturation index under adequate water replacement (Lozano et al, 2018), while doses between 52 and 104 kg ha^{-1} of soluble Si showed better results in terms of yield (Nascimento et al., 2020). In cotton, a higher foliar dose improved the quality of the harvested fiber (Nocchi et al., 2021). In cauliflower, the application of Si in the soil up to 150 kg ha^{-1} increased inflorescence yield under normal water supply and moderate water deficit (Wenneck et al., 2021). In tomato, Chakma et al. (2021) obtained superior results at a dose of 300 kg ha^{-1}.

Tomato (*Solanum lycopersicum* L.) is classified as a Si non-accumulator plant, having less than 0.5% of Si in its dry mass (Hoffmann et al., 2020). However, studies developed by Zhou et al. (2019); Zhang et al. (2019); Moraes et al. (2020), and Chakma et al. (2021) demonstrate that the crop is responsive to the application of Si, which mitigates stress.

Although Si is efficient in the agricultural context, several knowledge gaps exist mainly related to its transport mechanisms in different species, interaction with the soil, and the induced changes that improve plant productivity, especially in non-accumulating species such as tomato (Marxen et al., 2016; Bhat et al., 2021; Katz et al., 2021; Souri et al., 2021). This study aimed to analyze the dynamics of Si applied in various forms in tomatoes grown under different water regimes.

MATERIAL AND METHODS

Study site and soil used

The experiment was carried out at the Technical Irrigation Center of the State University of Maringá in the municipality of Maringá, Paraná (PR), Brazil (23° 25' S, 51° 57' W, and 542 m altitude). The climate in the region is characterized as Cfa (subtropical humid with hot summers and without a defined dry season), with temperature between 22.1 and 22 °C, solar radiation between 14.5 and 15 MJ m^{-2} day^{-1}, precipitation between 1400 and 1600 mm year^{-1}, and evapotranspiration between 1000 and 1100 mm year^{-1} (Nitsche et al., 2019).

The soil of the cultivation area is classified as "NITOSSOLO VERMELHO distroférrico" according to the Brazilian Soil Classification System, which corresponds to Utissol in the US Soil Taxonomy (Santos et al., 2018). The granulometric characterization of the soil revealed 72, 16, 7, and 5% clay, silt, fine sand, and coarse sand, respectively, and an average bulk density of 1.10 Mg m^{-3}. The chemical characterization of the soil is presented in Table 1.

Experimental design, application of the treatments, and growth conditions

The experiment was carried out in a completely randomized design with four replications, using a factorial scheme 2 x 4: two water conditions (60 and 100% of the evapotranspiration of the crop - ETc) and four forms of Si application [without application, full dose of 100 kg ha^{-1} applied in the soil, split dose - 100 kg ha^{-1} divided into three applications at 0, 30, and 50 days after transplanting (DAT) - applied in the soil, and foliar application of 100 mL plant^{-1} (1 g L^{-1}) at intervals of 15 days (from 15 to 90 DAT)].

In all applications, silicon oxide (98%) was used as the nutrient source (AgriSil® Agrobiológica, Leme, SP, Brazil). The Si doses were determined considering the effect of application in different forms, amounts, and plant species (Lozano et al., 2018; Nocchi et al., 2021; Wenneck et al., 2021) and the dynamics of the element in the soil (Wenneck; Saath; Rezende, 2022).

Forthy-five-day-old tomato seedlings variety Grazianni (Sakata® Seed Sudamerica Ltda., Bragança Paulista, SP, Brazil) acquired in a commercial nursery in the region of Maringá were transplanted into beds (spacing of 0.75 m between seedlings and 1 m between

Table 1: Soil chemical characterization of the 0 - 0.2 m soil layer.

pH	MO	Cu	Fe	Mn	Zn	Si	P	S	Ca	Mg	K
$CaCl_2$	%	-----------------------------------mg dm^{-3}-----------------------------------							----------cmolc dm^{-3}----------		
6.30	1.99	15.24	55.86	127.98	9.06	10.97	84.01	21.63	7.62	1.80	0.46

MO: Organic matter; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc; Si: Silicon; P: Phosphorus; S: Sulfur; Ca: Calcium; Mg: Magnesium; K: Potassium.

beds), which received the application of 150 kg ha^{-1} N (urea, Mosaic® Fertilizantes do Brasil, Paranaguá, PR, Brazil), 131 kg ha^{-1} P (single superphosphate, Mosaic® Fertilizantes do Brasil, Paranaguá, PR, Brazil), 150 kg ha^{-1} K (potassium chloride, Mosaic® Fertilizantes do Brasil, Paranaguá, PR, Brazil), and 4 kg ha^{-1} B (boric acid, Fertilizantes Heringer®, Paulínia, SP, Brazil). NPK fertilization was defined considering the chemical characterization of the soil (Table 1) and the fertilization recommendations for tomatoes (Pauletti; Motta, 2019).

Water table lysimeters with constant levels (Andrean et al., 2022) and tensiometers were used to determine the daily evapotranspiration of the crop and the moment of water replacement, respectively. The critical moment for water replacement was based on the recommendations of Marouelli (2008). Water replacement was performed using a drip irrigation system, with self-compensating drippers spaced at 0.25 m, a flow rate of 4 L h^{-1}, and a pressure of 1.96 bar.

The plants were grown in a greenhouse in a double stem training until they reached 2 m from the soil surface. Crop management was carried out according to the recommendations proposed by Brandão-Filho et al. (2018). Topdressing fertilization with 50 kg ha^{-1} N (calcium nitrate) and 60 kg ha^{-1} K_2O (potassium chloride) was applied every 15 days.

Si content in soil and plant organs

Soil samples were collected in the layer from 0 to 0.1 m deep, at the beginning and end of the experiment (105 DAT). The samples were dried in an oven with forced air circulation (65 °C) until they reached constant mass. The dry soil was stored in plastic packages for further analysis. Si content in the soil was quantified by spectrometry, using calcium chloride ($CaCl_2$) as an extractor (Korndörfer; Pereira; Nolla, 2004).

Samples from different plant organs were collected in different developmental phases. Leaves were collected from the upper third of the plants every 15 days between 15 and 90 DAT. Fruits were collected at 75 DAT. Roots and stems were collected at the end of the crop cycle (105 DAT). The samples were dried in an oven with forced air circulation (65 °C) until reaching constant mass. The dry material was ground in a stainless steel mill, 0.5 g of which was incinerated in a muffle furnace (550 °C) to obtain ash. From the ashes, the Si content was determined by spectrometry according to the methodology described by Silva (2009).

Statistical analysis

The data were submitted to analysis of variance by the F test and the averages were compared with the Tukey test at 5% significance level.

RESULTS AND DISCUSSION

The water replacement did not significantly influence the Si content in the soil (Table 2), which varied as a function of the evaluation period. The full dose applied in the soil caused an increase of 19.16 mg dm^{-3} (from 11.27 to 30.43) and 21.51 mg dm^{-3} (from 11.27 to 32.78) for water replacement of 60 and 100% of ETc, respectively, during the tomato cultivation period (105 days). In the split dose application in the soil, the increase was 15.69 mg dm^{-3} (from 12 to 27.69) and 16.32 mg dm^{-3} (from 10.98 to 27.30). In the condition without Si application or with the foliar application, no significant changes were observed between the evaluated periods (Table 2).

In tropical soils, especially those with a high degree of weathering, the Si content is low (Leroy et al., 2019; Souri et al., 2021). The initial Si levels, between 10.98 and 12 mg dm^{-3} (Table 2), were similar to those obtained by Wenneck, Saath and Rezende, (2022) in the same study site and the levels reported by Camargo and Keeping (2021) in other regions of Brazil.

Si content in the soil shows variation associated with characteristics of origin, degree of weathering, and mineral constitution, in addition to cycling and exogenous application (Leroy et al., 2019; Mandlik et al., 2020; Schaller et al., 2021). Although Si application benefits crop plants (Lozano et al., 2018; Camargo; Keeping, 2021; El-Saadony et al., 2021; Wenneck et al., 2021), the availability of the element is related to the chemical characteristics of the soil, amount applied, predominance of the Si species and reaction with mineral fractions and clays, being a normally slow process (Schaller et al., 2021).

An increase in Si content in the soil was observed after exogenous application (Table 2), but information on temporal persistence in the form readily available to plants is scarce. Even so, studies have encouraged Si application during the growing season (Yan et al., 2018) and the inclusion of the element in the nutritional management of tomatoes (Chakma et al., 2021). The associated effects of the element include the reduction of heavy metal content in the soil (El-Saadony et al., 2021) and improved nutrient absorption by plants (Nascimento et al., 2020).

Table 2: Soil silicon content before and after tomato cultivation under different forms of silicon application and soil water conditions.

Water replacement (% ETc)	Forms of application (FA)	Si content (mg kg^{-1})	
		Initial (15 DAT)	Final (105 DAT)
60	Without application	11.85 aA	10.55 cA
	Soil (full dose)	11.27 aB	30.43 aA
	Soil (split dose)	10.98 aB	27.30 bA
	Foliar	12.00 aA	12.14 cA
100	Without application	11.85 aA	10.12 cA
	Soil (full dose)	11.27 aB	32.78 aA
	Soil (split dose)	12.00 aB	27.69 bA
	Foliar	10.98 aA	10.41 cA
ETc		ns	ns
FA		**	*
ETc x FA		ns	ns
Evaluation period		**	
CV (%)		3.84	50.44

CV: Coefficient of variation; Significant differences (Tukey test for comparison of the means, $p < 0.05\%$) are indicated by letters. Lowercase (within columns) and uppercase (within lines) letters compare forms of application and evaluation period, respectively; *: $p<0.01$; **: $p<0.05$; ns: non-significant.

On the day of transplanting the tomato seedlings, 2.35, 2.38, and 2.42 mg kg^{-1} Si was found on roots, stems, and leaves, respectively, with an average Si content of 2.38 mg kg^{-1}. The rate of Si absorption by the tomato plant, considering its content in leaves during cultivation (Table 3), tended to increase during the crop cycle (up to 90 DAT) in relation to the initial evaluation at 15 DAT. This might be associated with the morphological development of the plant, especially the root system. The forms of Si application and water replacement significantly influenced the accumulation of the element throughout the evaluated period (Table 3).

A significantly lower Si accumulation was found in leaves of unfertilized plants (Table 3), which have only the natural content of the element in the soil. Si contents were variable in foliar application in comparison with conditions without application and soil application (Table 3).

The average Si accumulation in the different plant organs was significantly influenced by water replacement and the form of Si application (Table 4). The accumulated Si content tended to be higher when its application was on soil and also on water replacement of 100% ETc (Table 4).

According to data in Table 4, higher values of Si accumulation were obtained in leaves (between 6.45 and 8.82 mg kg^{-1}) and fruits (between 6.85 and 8.95 mg kg^{-1}) in comparison to roots (between 2.45 and 3.48 mg kg^{-1}) and stems (between 3.70 and 5.20 mg kg^{-1}). The transport of Si absorbed by the roots occurs through the xylem, with deposition rates in tissues that vary with the analyzed species, being normally higher in leaves due to the flow generated by the transpiration process (Mandlik et al., 2020).

The Si levels obtained in this study are similar to those reported by Zhang et al. (2019) in roots, while in the stems and leaves we observed higher values. The absorption capacity of Si is also related to genetic, climatic, and management factors (Lozano et al., 2018; Leroy et al., 2019; Katz et al., 2021; Nocchi et al., 2021), explaining the changes in absorption and deposition rates in plant organs.

Leaves and fruits showed greater Si accumulation than roots and stems (Table 4), with the same trend observed in Si extraction (Table 5), which also considers the dry mass of each organ. The extraction of Si by the tomato plant was influenced by the water management adopted and by the form of Si application.

Plants with adequate water replacement (100% ETc) could significantly incorporate more Si (higher Si extracted from stems, leaves, roots, fruits, and total extraction) in relation to plants cultivated under controlled deficit (60% ETc) (Table 5). This result is associated with water flow for Si transport, evapotranspiration rates, and plant development (Hoffmann et al., 2020; Schaller et al., 2021; Souri et al., 2021). Although the application of Si is recommended to improve yield under adverse conditions, such as water stress, Si fertilization tends to be responsive mainly under conditions of adequate water management or moderate water deficit (Chakma et al., 2021; Wenneck et al., 2021).

Table 3: Silicon content (mg hg^{-1}) in tomato leaves of plants cultivated under different forms of element application (FA) and water replacement conditions (ETc).

Source of variation		Days after transplanting - DAT					
ETc (%)	FA	15	30	45	60	75	90
60	WA	4.19 bA	6.86 bA	6.87 bA	6.92 cA	6.86 cA	6.91 cA
	FD	6.10 aB	7.29 aB	7.30 aB	7.91 bB	7.82 bB	7.97 bB
	SD	5.01 aA	7.29 aA	8.59 aB	8.47 aB	8.28 aB	8.71 aA
	Foliar	4.09 bB	7.11 aA	6.98 aB	7.60 bB	7.29 aB	7.85 bB
100	WA	4.22 cA	6.85 cA	6.86 cA	6.87 bA	6.98 cA	6.89 cA
	FD	7.21 aA	8.10 aA	9.82 aA	8.96 aA	9.27 aA	9.57 aA
	SD	5.31 bA	7.54 bA	9.33 aA	8.71 aA	8.73 bA	8.90 bA
	Foliar	5.09 bA	7.67 bA	8.47 aA	8.90 aA	8.96 bA	9.33 aA
ETc		*	**	*	*	**	**
FA		**	*	*	**	*	*
ETc x FA		**	**	**	**	**	**
CV (%)		18.97	5.75	14.72	10.56	11.55	12.45

CV: Coefficient of variation; WA: Without application; FD: Full dose in soil; SD: Split dose in soil; Significant differences (Tukey test for comparison of the means, $p < 0.05\%$) are indicated by letters. Lowercase and uppercase letters compare forms of application and water conditions, respectively, in the same harvest date; *: $p<0.01$; **: $p<0.05$.

Table 4: Silicon content (mg kg^{-1} dry mass) in tomato organs of plants cultivated under different application forms of the element and water conditions.

Source of variation		Roots	Stems	Leaves[a]	Fruits
Water replacement (% ETc)	Forms of application (FA)				
60	Without application	2.45 cA	3.70 bA	6.43 dA	6.98 cB
	Soil (full dose)	3.37 aB	4.35 aB	7.40 bB	8.83 aB
	Soil (split dose)	2.77 bB	4.35 aA	7.73 aB	8.71 aA
	Foliar	2.52 cA	3.73 bB	6.96 cB	7.35 bA
100	Without application	2.45 cA	3.74 cA	6.45 cA	6.85 bA
	Soil (full dose)	3.48 aA	5.20 aA	8.82 aA	8.95 aA
	Soil (split dose)	3.09 bA	4.38 bA	8.09 bA	8.71 aA
	Foliar	2.59 cA	3.84 cA	8.07 bA	6.98 bB
ETc		**	**	*	**
FA		**	*	*	**
ETc x FA		**	**	**	**
CV (%)		14.74	12.45	11.30	11.60

[a]Average during the crop cycle (15 to 90 days after transplanting); Significant differences (Tukey test for comparison of the means, $p < 0.05\%$) are indicated by letters. Lowercase and uppercase letters compare forms of application and water conditions, respectively; *: $p<0.01$; **: $p<0.05$.

Table 5: Silicon extraction from tomato organs and percentage of silicon in dry mass in plants cultivated under different application forms of the element and water conditions.

Source of variation		Roots	Stems	Leaves	Fruits	Total extraction	Percentage of Si in dry mass
Water replacement (% ETc)	Forms of application (FA)	------------------- mg plant^{-1} -------------------			------ g plant^{-1} ------		%
60	Without application	17.27 cB	252.45 bB	745.88 dB	3.92 dB	4.94 cB	0.66 bA
	Soil (full dose)	29.93 aB	369.20 aB	1517.00 bB	7.12 aB	9.03 bB	0.83 aA
	Soil (split dose)	25.62 bA	364.42 aB	1762.44 aB	6.19 bB	8.35 aB	0.81 aA
	Foliar	16.60 cA	242.30 bB	863.04 cB	4.63 cB	5.76 cB	0.70 bA
100	Without application	19.80 cA	305.25 bA	1373.85 cA	5.11 cA	6.81 cA	0.65 cA
	Soil (full dose)	37.17 aA	454.58 aA	2557.80 aA	8.16 aA	11.21 aA	0.85 aA
	Soil (split dose)	25.23 bA	467.63 aA	1925.42 bA	7.17 bA	9.59 bA	0.81 bA
	Foliar	15.83 cA	279.75 bA	1404.18 cA	5.53 cA	7.23 cA	0.71 bA
ETc		**	*	**	*	*	ns
FA		*	**	*	**	**	**
ETc x FA		**	**	**	**	**	ns
CV (%)		32.05	25.42	38.28	24.08	25.39	11.62

Significant differences (Tukey test for comparison of the means, $p < 0.05\%$) are indicated by letters. Lowercase and uppercase letters compare forms of application and water conditions; *: p<0.01; **: p<0.05.

The total extraction of Si in unfertilized plants was 4.94 and 6.81 g plant^{-1}, representing 0.66 and 0.65% of the dry mass at the water replacement of 60 and 100% ETc, respectively (Table 5). This percentage is close to the rate that characterizes Si excluder plants and non-accumulators mentioned in the literature (Hoffmann et al., 2020; Schaller et al., 2021). However, when considering cultivation conditions with Si application, in soil or foliar, the percentage of Si in the dry mass varied from 0.7 to 0.85% suggesting that tomato is an intermediate accumulator. Interestingly, the percentage of Si in the dry mass of unfertilized plants was similar to the ones that received foliar application at 60% ETc, indicating that soil application can be more advantageous depending on the water status.

Si accumulation was predominantly higher in the aerial part, mainly in fruits, regardless of water management or form of Si application (Tables 3 and 4). This is related to the extraction rates (Table 5), showing that the element is deposited mainly in organs with high transpiration flow rates and strong drains (Mandlik et al., 2020).

The foliar application of Si, although in a lower amount compared to soil application, allowed an increase in the accumulation of the element, mainly in leaves and fruits (Tables 4 and 5). This is advantageous when considering the bioavailability of the element in the soil (Zhu; Gong; Yon, 2019; Nocchi et al., 2021). However, the increment in extraction (Table 5) and accumulation in different plant organs (Table 4) are significantly lower compared to soil applications (full or split). Together, these results indicate that supplementary information associated with production increment and cost is required to define the agronomic efficiency ratio of the application methods.

When considering the amount of Si supplied, the increment in Si was low, being 4.09 and 4.40 mg plant^{-1} for water replacement of 60 and 100% ETc, respectively, when comparing plants without application and the ones receiving the full dose (Table 5). In the same comparison, the increase in the percentage of Si in dry mass was up to 0.2% (Table 5). This result is mainly related to the passive absorption form of Si, without specific channels for the element (efflux), in non-accumulating species (Yan et al., 2018; Bhat et al., 2021; Katz et al., 2021). However, non-accumulating plants tend to present morphological and biochemical responses according to element availability (Leroy et al., 2019; Souri et al., 2021)

The increase in Si content was significantly higher with soil applications and varied with water management. Under adequate water replacement (100% ETc), the application of the element in full dose resulted in superior results, while in conditions of water deficit (60% ETc) the application in split doses led to the highest levels of Si in the plants (Table 4 and Table 5). This differs from the characteristic of Si accumulation in the soil, verified in the present study (Table 2) and by Wenneck, Saath and Rezende (2022). Possibly, under water stress (60% of ETc), the plant has greater efficiency of Si absorption with split dose fertilization, which was also reported by Zhang et al. (2019) when evaluating nitrogen fertilization under different water management conditions.

More than 72% of Si extracted from the plants accumulated in fruits (72.80 to 80.51 %), followed by leaves (14.99 to 22.81 %), stems (3.87 to 5.11 %), and roots (0.22 to 0.35 %) (Table 5). The profile of Si distribution in the different plant organs showed variation depending on the Si form of application and water management during cultivation (Table 6).

Si distribution in the different tomato organs has a direct impact on the dynamics of the element in the production environment. According to Mandlik et al. (2020) and Schaller et al. (2021), Si losses occur mainly through leaching and exportation through harvesting. When considering that tomato fruits have more than 72% of the total Si extracted by the plant (Table 6), most of the Si content absorbed and incorporated into the plant biomass does not return to the soil. Si cycling occurs through the decomposition of the crop biomass (roots, stems, and leaves) but is not immediate as it involves aspects related to decomposition time, biomass composition, and microorganism action (Marxen et al., 2016; Katz et al., 2021; Schaller et al., 2021; Souri et al., 2021).

Si application in a production environment similar to the present study resulted in partial compensation of melon and cauliflower yield under water stress conditions (Lozano et al., 2018; Wenneck et al., 2021). Chakma et al. (2021) obtained a similar effect for tomato. Here, we demonstrated that although tomato is not a typical Si-accumulating plant, the supply of the element in the productive environment leads to increased accumulation and extraction in different plant organs. When Si is applied in the soil, an increase in its soil content remains for the next crop cycle. Future studies are needed to define the interaction of the element in soils, bioavailability over time, decomposition and cycling of the element in the system to support strategies for managing Si in species with different accumulation profiles and responsiveness.

Table 6: Distribution of accumulated silicon in tomato organs in plants cultivated under different application forms of the element and water conditions.

Water replacement (%ETc)	Forms of application	Roots	Stems	Leaves	Fruits
		%			
60	Without application	0.35 aA	5.11 aA	15.11 bB	79.42 aA
	Soil (full dose)	0.33 aA	4.09 cA	16.80 bB	78.78 aA
	Soil (split dose)	0.31 aA	4.37 bA	21.12 aA	74.21 bA
	Foliar	0.29 bA	4.21 bA	14.99 bB	80.51 aA
100	Without application	0.29 bB	4.48 bB	20.17 aA	75.06 aA
	Soil (full dose)	0.33 aA	4.05 bA	22.81 aA	72.80 aB
	Soil (split dose)	0.26 bB	4.88 aA	20.08 aA	74.78 aA
	Foliar	0.22 bB	3.87 cB	19.42 aA	76.49 aB
ETc		*	**	**	**
FA		**	**	**	**
ETc x FA		**	**	**	**
CV (%)		14.27	9.75	15.23	3.62

Significant differences (Tukey test for comparison of the means, p < 0.05%) are indicated by letters. Lowercase and uppercase letters compare forms of application and water conditions, respectively; *: p<0.01; **: p<0.05.

CONCLUSIONS

Si content in the soil increased depending on the application mode (i.e., full or split doses) at the end of the crop cycle. The dynamics of Si accumulation and extraction by tomatoes are influenced by water management and its application form, being higher in fruits and leaves. Si application, mainly in the soil, increased the rate of Si accumulation and extraction by tomatoes cultivated in different water conditions.

AUTHOR CONTRIBUTION

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REFERENCES

ANDREAN, A. F. B. A. et al. Water requirements and fruit development rate of Cantaloupe melons cultivated in summer-autumn. Comunicata Scientiae, 13:e3879, 2022.

BHAT, J. A. et al. Silicon nanoparticles (SiNPs) in sustainable agriculture: Major emphasis on the practicality, efficacy and concerns. Nanoscale Advances, 3:4019-4028, 2021.

BRANDÃO-FILHO, J. U. et al. Hortaliças-fruto. Maringá, EDUEM, 2018. 535p.

CAMARGO, M. S.; KEEPING, M. G. Silicon in sugarcane: Availability in soil, fertilization, and uptake. Silicon, 13:3691-3701, 2021.

CHAKMA, R. et al. Growth, fruit yield, quality, and water productivity of grape tomato as affected by seed priming and soil application of silicon under drought stress. Agricultural Water Management, 256:107055, 2021.

EL-SAADONY, M. T. et al. Biological silicon nanoparticles improve *Phaseolus vulgaris* L. yield and minimize its contaminant contents on a heavy metals-contaminated saline soil. Journal of Environmental Sciences, 106:1-14, 2021.

HOFFMANN, J. et al. A review on the beneficial role of silicon against salinity in non-accumulator crops: Tomato as a model. Biomolecules, 10(9):1284, 2020.

KATZ, O. et al. Silicon in the soil: Plant continuum: Intricate feedback mechanisms within ecosystems. Plants, 10(4):652, 2021.

KORNDÖRFER, G. H.; PEREIRA, H. S.; NOLLA, A. Análise de silício: Solo, planta e fertilizante. Uberlândia: GPSi-ICIAG-UFU, 2004. 34p.

LEROY, N. et al. Silicon and plant natural defenses against insect pests: Impact on plant volatile organic compounds and cascade effects on multitrophic interactions. Plants, 8(11):444, 2019.

LOZANO, C. S. et al. Produtividade e qualidade de melão sob doses de silício e lâminas de irrigação em ambiente protegido. Pesquisa Agropecuária Tropical, 48(2):140-146, 2018.

MANDLIK, R. et al. Significance of silicon uptake, transport, and deposition in plants. Journal of Experimental Botany, 71(21):6703-6718, 2020.

MARXEN, A. et al. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system. Plant and Soil, 398:153-163, 2016.

MITANI-UENO, N.; MA, J. F. Linking transport system of silicon with its accumulation in different plant species. Soil Science and Plant Nutrition, 67(1):10-17, 2021.

MORAES, D. H. M. et al. Combined effects of induced water deficit and foliar application of silicon on the gas exchange of tomatoes for processing. Agronomy, 10(11):1715, 2020.

MAROUELLI, W. A. Tensiômetros para o controle de irrigação em hortaliças. Circular Técnica 57. Brasília: Embrapa Hortaliças, 2008, 15p.

NASCIMENTO, C. W. A. et al. Influence of silicon fertilization on nutrient accumulation, yield and fruit quality of melon grown in northeastern Brazil. Silicon, 12:937-943, 2020.

NITSCHE, P. R. et al. Atlas climático do estado do Paraná. Londrina, PR: IAPAR, 2019. 210p.

NOCCHI, R. C. F. et al. Cotton fiber quality affected by water availability and silicon application. Colloquium Agrariae, 17(6):80-86, 2021.

PAULETTI, V.; MOTTA, A. C. V. Manual de adubação e calagem para o estado do Paraná. 2.ed. Curitiba: SBCS-NEPAR, 2019. 289p.

SANTOS, H. G. et al. Brazilian soil classification system. 5ed. rev. and exp. Brasília, DF: Embrapa, 2018. 303p.

SCHALLER, J. et al. Silicon cycling in soils revisited. Plants, 10(2):295, 2021.

SILVA, F. C. Manual de análises químicas de solos, plantas e fertilizantes. 2ed. rev. Brasília: Embrapa Informação Tecnológica, 2009. 627p.

SOURI, Z. et al. Silicon and plants: Current knowledge and future prospects. Journal of Plant Growth Regulation, 40:906-925, 2021.

WENNECK, G. S.; SAATH, R.; REZENDE, R. Silicon accumulation in cauliflower grown in a protected environment with different water availability conditions. Pesquisa Agropecuária Brasileira, 57:e02392, 2022.

WENNECK, G. S. et al. Agronomic response of cauliflower to the addition of silicon to the soil under water deficit. Pesquisa Agropecuária Tropical, 51:e66908, 2021.

YAN, G. C. et al. Silicon acquisition and accumulation in plant and its significance for agriculture. Journal of Integrative Agriculture, 17(10):2138-2150, 2018.

ZHANG, Y. et al. Silicon compensates phosphorus deficit-induced growth inhibition by improving photosynthetic capacity, antioxidant potential, and nutrient homeostasis in tomato. Agronomy, 9(11):733, 2019.

ZHOU, R. et al. Physiological response of tomatoes at drought, heat and their combination followed by recovery. Physiologia Plantarum, 165(2):144-154, 2019.

ZHU, Y. X.; GONG, H. J.; YON, J. L. Role of silicon in mediating salt tolerance in plants: A review. Plants, 8(6):147, 2019.