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Performance of tomato grown under different water replacement depths and silicon application forms

Desempenho do tomateiro cultivado com diferentes reposições hídricas e formas de aplicação de silício

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Highlights

Water restriction during crop growth leads to decreased yields.
Silicon application helps mitigate water stress.
Silicon application benefits the development and yield of tomato.

Abstract

Water management has a direct impact on plant development, and under deficit conditions, it often results in reduced yields. Silicon (Si), however, has the potential to alleviate stress and enhance plant performance under unfavorable conditions. This study aimed to analyze the performance of tomato plants cultivated under different water replacement depths and forms of silicon application. The experiment was laid out in a completely randomized design with a 2 × 4 factorial arrangement represented by two water replacement depths (60% and 100% of crop evapotranspiration - ETc) and four forms of silicon application (without application, soil application - full dose, soil application - split dose, and foliar applications). Four replications were used. The plants were cultivated in a protected environment using drip irrigation for water replacement, and silicon oxide served as the source of the element. The analyzed parameters included daily evapotranspiration, leaf spectral reflectance, mass accumulation (root, stem, and leaf), yield indices (fruit weight, plant yield, and defective fruits), water productivity, and post-harvest fruit weight loss. The imposition of water deficit (60% of ETc) in tomato leads to reduced crop development and yield, with the effects partially mitigated by the application of silicon. Conversely, under conditions of adequate

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water replacement (100% of ETc), silicon application contributes to increased development and yield of tomato. The application of silicon in the soil, whether in a full or split dose, demonstrates a more favorable response in vegetative indices and yield for tomato.

Key words: Beneficial element. Irrigation. *Solanum lycopersicum* L.

Resumo

O manejo da água influencia diretamente no desenvolvimento das plantas, e em condições de déficit a produtividade é reduzida. Em condições desfavoráveis, o silício (Si) pode atenuar o estresse e melhorar o desempenho da planta. Este estudo teve como objetivo analisar o desempenho do tomateiro cultivado com reposições hídricas e formas de aplicação de silício. O experimento foi conduzido em delineamento inteiramente casualizado em esquema fatorial 2 x 4: duas lâminas de reposição de água (60 e 100% da evapotranspiração da cultura - ETc) e quatro formas de aplicação de silício (sem aplicação, aplicação no solo (dose total), aplicação no solo (dose parcelada) e aplicação foliar), com quatro repetições. As plantas foram cultivadas em ambiente protegido, foi utilizado irrigação por gotejamento para reposição hídrica e óxido de silício como fonte de elemento. Os parâmetros analisados foram evapotranspiração diária, refletância espectral foliar, acúmulo de massa (raiz, caule e folha), índices de produtividade (massa do fruto, produtividade da planta e frutos defeituosos), produtividade da água e perda de massa do fruto após a colheita. A imposição de déficit hídrico (60% da ETc) no tomateiro reduz o desenvolvimento e a produtividade da cultura, sendo os efeitos parcialmente atenuados pela aplicação do silício. Em cultivo com reposição hídrica adequada (100% da ETc), a aplicação de silício eleva o desenvolvimento e a produtividade do tomateiro. A aplicação de silício no solo, em dose total ou parcelada, apresenta melhor resposta dos índices vegetativos e de produtividade do tomateiro.

Palavras-chave: Elemento benéfico. Irrigação. *Solanum lycopersicum* L.

Introduction

Water deficit is a possible condition in agricultural production that exerts direct effects on plant growth, yield, and resource use efficiency (Nemeskéri & Helyes, 2019; Parkash & Singh, 2020). Various techniques and management tools can be employed to alleviate the impacts of water stress on plants. These encompass controlled water restriction during less sensitive stages (Terassi et al., 2021), the interval between water replacements (Santos et al., 2021), nutritional management (Saath et al., 2022), and the application of beneficial elements (Lozano et al., 2018; Hachmann et al., 2019).

Among the beneficial elements, silicon (Si) stands out due to its abundance on the planet, extensive research, and positive effects on plants under adverse growing conditions, such as water deficit (Chen et al., 2018; Chakma et al., 2021). However, Si availability is often low in weathered soils (Wenneck et al., 2022), which has led to increased exogenous application in production systems (Yan et al., 2018; Chakma et al., 2021; Tombeur et al., 2021; Wenneck et al., 2021). Furthermore, the interaction of Si with the production system may vary according to its application form and the crop of interest (Costan et al., 2019; Nocchi et al., 2021; Santos et al., 2021).

In tomato crops, several studies have investigated the potential use of silicon (Zhu et al., 2019; Moraes et al., 2020; Chakma et al., 2021), emphasizing the need for analysis under adverse cultivation conditions to understand the interaction between Si and the production environment. Thus, this study aims to analyze the methods of Si application in tomato grown under different water conditions.

Material and Methods

Study location

The experiment took place at the Technical Irrigation Center (CTI), affiliated with the State University of Maringá (UEM), in the municipality of Maringá-PR, Brazil (23°25′S, 51°57′W, and 542 m altitude). Conducted in the field between September 2021 and January 2022, the cultivation occurred in an arch-shaped greenhouse (a protected environment) with dimensions of 25 m in length, 7 m in width, and 3.5 m in height. The structure was covered with a transparent polyethylene film (150 μm), and the sides were shielded with a white nylon screen. Temperature and relative humidity within the protected environment were monitored using an automatic weather station (Campbell™) (Figure 1).

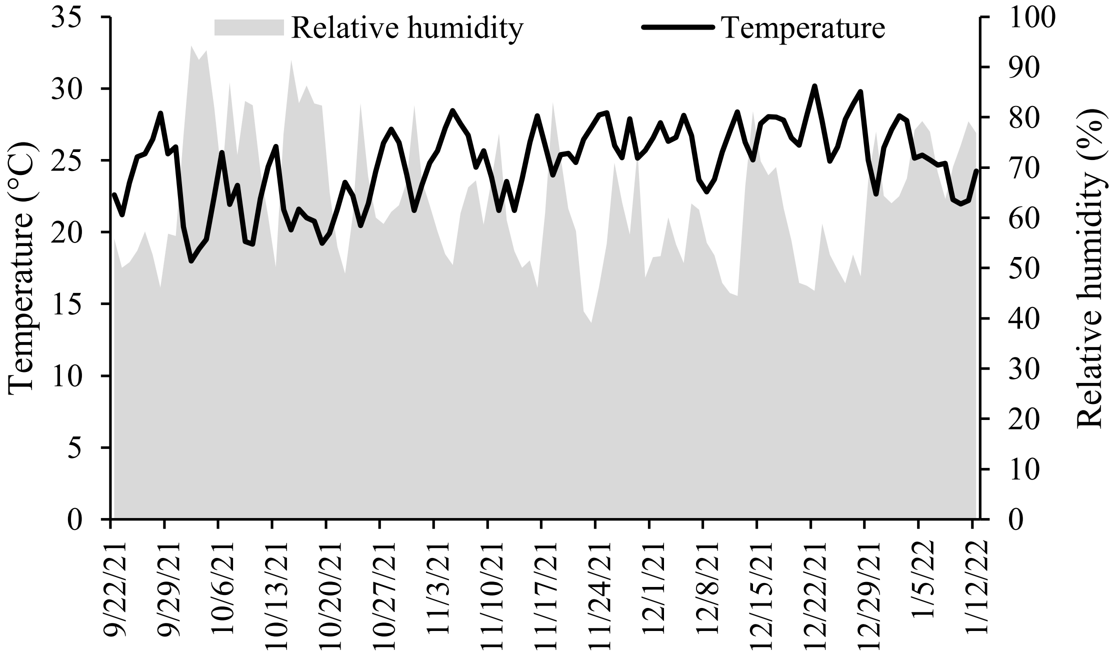

Figure 1. Mean temperature and relative humidity within the protected environment during tomato cultivation.

The soil inside the protected environment is classified as dystric red Nitisol according to the Brazilian Soil Classification (SiBCS) and as Utissol by the US Soil Taxonomy System (Santos et al., 2018). It exhibits a clayey texture (72% clay, 16% silt, 7% fine sand, and 5% coarse sand) and a bulk density of 1.10 Mg m^{-3}. Soil chemical indicators include pH CaCl2: 6.30; organic matter: 1.99%; calcium (Ca): 7.62 cmolc dm^{-3}; magnesium (Mg): 1.80 cmolc dm^{-3}; potassium (K): 0.46 cmolc dm^{-3}; phosphorus (P): 84.01 mg dm^{-3}; sulfur (S): 21.63 mg dm^{-3}; boron (B): 0.70 mg dm^{-3}; copper (Cu): 15.24 mg dm^{-3}; iron (Fe): 55.86 mg dm^{-3}; manganese (Mn): 127.98 mg dm^{-3}; zinc (Zn): 9.06 mg dm^{-3}; and silicon (Si): 10.97 mg dm^{-3}. Despite the natural presence of silicon in soils, it is considered low (Souri et al., 2021), justifying the study with the exogenous application of the element.

Experimental design

A completely randomized design was employed in a 2 × 4 factorial arrangement involving two water replacement depths (60 and 100% of crop evapotranspiration - ETc) and four forms of silicon application (without application, soil application - full dose, soil application - split dose, and foliar application). Four replications were used per condition.

The amount of silicon applied was determined based on its levels in the soil (Wenneck et al., 2022) and previous studies involving different species and forms of application (Lozano et al., 2018; Nocchi et al., 2021; Wenneck et al., 2021). For soil applications, a total of 100 kg Si ha^{-1} was usd, with the full dose applied at transplanting. The application was split into three periods (0, 30, and 60 days after transplant - DAT), with both conditions involving surface application. Foliar application was carried out at a dose of 1 g of Si L^{-1} of water, applying 100 mL $plant^{-1}$ at 15-day intervals after transplanting. Silicon oxide (98%) served as the nutrient source (AgriSil® Agrobiológica) for all applications. Notably, the silicon content in the water used for irrigation and foliar application was disregarded, as indicated in the study by Wenneck et al. (2022) on the influence of irrigation depths and silicon application on the dynamics of the element in the production system.

Crop management

On September 22, 2021, commercial seedlings (Grazianni - AF 22834, Sakata®, Seed Sudamerica Ltda.) were transplanted into beds (3.0 × 0.5 m) with a spacing of 0.75 m between plants. Each replication consisted of a bed containing four plants, with the two central plants of each bed considered for evaluations in the experimental useful area. The beds were spaced 1.5 m apart. The crop was grown with two stems until reaching 2 m in height relative to the soil surface and was staked. Adventitious shoots were removed weekly from producing stems.

Fertilization was applied with 150 kg N ha^{-1} (urea - 45%), 300 kg P_2O_5 ha^{-1} (super single phosphate - 18%), 180 kg K_2O ha^{-1} (potassium chloride - 60%), and 4 kg B ha^{-1} (boric acid - 17%), based on soil chemical characterization and recommendations for the tomato crop (Pauletti & Motta, 2019).

Crop evapotranspiration was determined on a daily basis using three constant water table lysimeters (Andrean et al., 2022), as illustrated in Figure 2. These lysimeters were installed within the protected environment, with plant spacing mirroring that of the cultivation. According to Vellame et al. (2012), constant water table lysimeters yield values comparable to weighing lysimeters and are suitable for determining ETc.

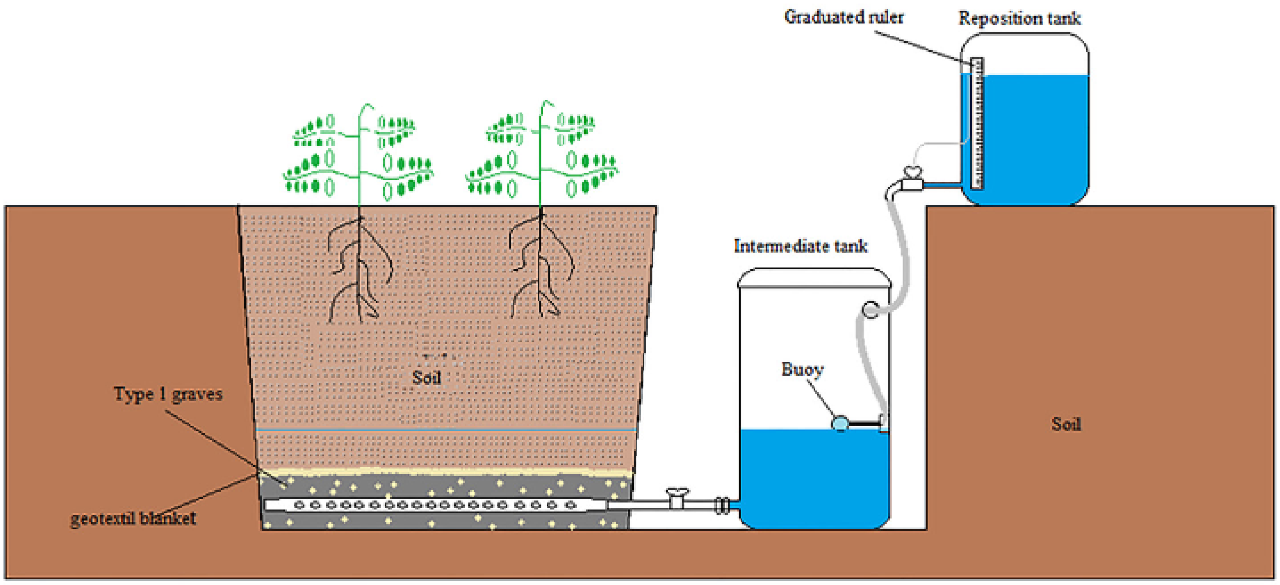

Figure 2. Illustration of constant water-table lysimeter.
Source: Andrean et al. (2022).

Water replenishment was achieved through drip irrigation employing self-compensating emitters (PCDS, IRRITEC™) spaced at 0.25-m intervals, delivering a flow rate of 4 L h^{-1}, a pressure of 1.96 bar, and a uniformity coefficient of 94%. The timing of water replacement was determined by monitoring soil moisture using tensiometers positioned at depths of 0.05 and 0.15 m in beds without water deficit (100% of ETc). The critical limit for water replacement was set at -30 kPa, following recommendations by Mourelli (2008) for the specific species and irrigation method. Under these conditions, soil moisture measured 0.422 m^{-3} based on the soil-water retention proposed by Trintinalha (2005). For management with (60% of ETc) and without water deficit (100% of ETc), water replacement was guided by soil water tension, but the volume was based on accumulated evapotranspiration, with the amounts applied simultaneously according to the treatment (60 or 100% of ETc).

Fertilization included applications of 50 kg N ha^{-1} (calcium nitrate - 15%) and 60 kg K_2O ha^{-1} (potassium chloride - 60%) at 15-day intervals using a fertigation system.

Assessments

Radiometric readings were taken on the upper-third leaves of tomato plants between 50 and 70 DAT. The evaluation covered plants in the useful area of the plot (two central plants), with two readings per plant and one reading per stem. The spectrometer used was the ASD Fieldspec 3 (ASD Inc.™) connected to the Plant Probe reader. Readings were performed under two conditions: 1) soil-water tension near the critical threshold for water replacement (-30 kPa); and 2) after water replacement. Readings were taken in a wavelength range between 350 and 2500 nm.

Fruit harvest occurred from 60 to 105 DAT, collecting fruits with red color and meeting commercial standards. Fruit fresh weight was determined using an analytical scale to calculate fruit yield per plant. During harvest, commercially sized fruits with physiological damage due to malformation were quantified.

At the end of the cycle (105 DAT), mass accumulation of the morphological components of plants (root, stem, and leaves) was determined using an analytical scale after drying in an air circulation oven at 65 °C until reaching constant mass (dry weight). Leaf area was measured using LI 3100 equipment (LI-COR™).

Water productivity was calculated using data on fruit yield per plant and the replaced water volume, as shown in Equation 1.

$$WP = \frac{FY}{RWV} \quad (1),$$

where WP = water productivity (kg L^{-1}); FY= fruit yield (kg $plant^{-1}$); and RWV= replaced water volume (L $plant^{-1}$).

Fruits harvested at 90 DAT underwent an evaluation for weight loss post-harvest. Samples consisted of three tomato fruits, with four replications per treatment. The harvested fruits were washed with running water and immersed in a sodium hypochlorite solution (1%) for 10 min. Subsequently, the sanitized fruits were packed in plastic films (190 × 120 × 58 mm). These packages were stored in biochemical oxygen demand (BOD) chambers set at 15 °C with a relative humidity above 80%. Over 13 days, the fruits were weighed, and daily variations were determined for each condition.

Data analysis

Data for daily crop evapotranspiration (ETc) over time are graphically presented, relying on the daily evapotranspiration rate estimated with constant groundwater lysimeters (Figure 2). Radiometric readings of the leaves were used to determine the average wavelength, and these values were graphically compared as a function of the cultivation condition (water replacement and silicon application).

Morphological indices and yield data were subjected to analysis of variance using the F test, with means compared by Tukey’s test at a 5% probability of error for both water replacement depths and silicon application forms. Linear correlation analyses were also conducted. Additionally, data on fruit mass changes were subjected to analysis of variance and linear regression. For statistical analysis, MS Excel™, SISVAR 5.6 (Ferreira, 2019), and Past4.06b (Hammer et al., 2001) software were employed.

Results and Discussion

Daily evapotranspiration exhibits variability based on environmental conditions and plant development. Daily evapotranspiration were rates determined in the study using a constant water table lysimeter (Figure 2), as depicted in Figure 3.

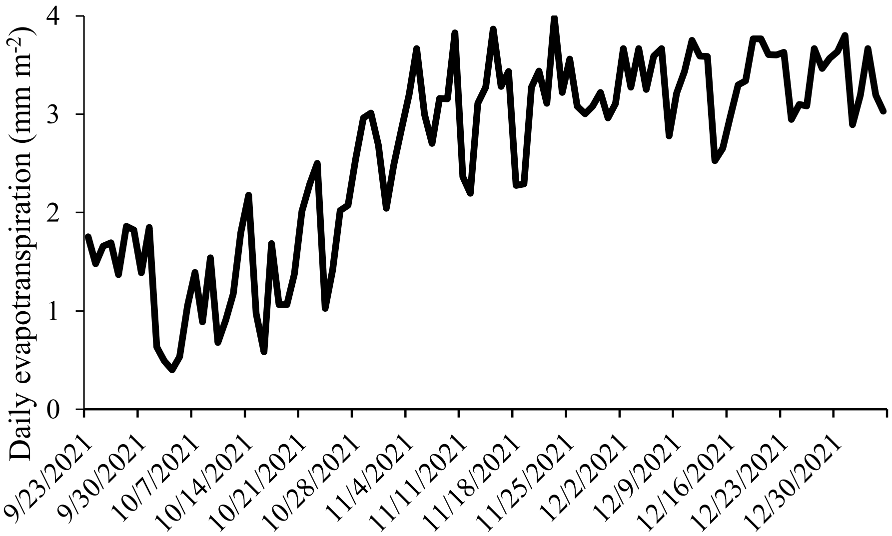

Figure 3. Daily evapotranspiration of the tomato crop. Maringá, PR, Brazil.

The accumulated evapotranspiration of tomato plants in the present study was 272.86 mm m^{-2}. Considering the adopted population density, this rate corresponds to the application of 102.32 L $plant^{-1}$ in the condition without water deficit (100% of ETc) and 61.30 L $plant^{-1}$ in the water deficit condition (60% of ETc).

The mass accumulation of morphological components (root, stem, and leaves) reflects aspects of tomato growth significantly influenced by water replacement depth and the application forms of silicon (Table 1). Under water stress (60% of ETc), mass accumulation (root, stem, and leaf) was notably reduced. Silicon application, especially in the soil, partially mitigated the effects of water stress on plant morphological development, resulting in mass accumulations superior to those without silicon application, as indicated in Table 1.

As a result of changes in morphological development (Table 1), significant differences were observed for the production components of tomato. While tomato is not a typical silicon accumulator plant, Wenneck et al. (2023) found an increase in the accumulation and percentage of dry matter with exogenous application of the element. Tomato fruits from plants under water deficit (60% of ETc) exhibited significantly lower fresh weights and yields compared to fruits from plants under no stress (100% of ETc), as detailed in Table 2.

Under water deficit conditions (60% of ETc), the number of tomato fruits with physiological changes (damaged) was significantly higher, influencing plant yields (Table 2). According to Wenneck et al. (2022), different irrigation depths had no significant effect on the contents of elements in the soil, but plant uptake was affected. Plant uptake of elements is also dependent on water availability in the soil (Zhu et al., 2019). In our study, the application of silicon in the soil, either in a total or split-dose regimen, yielded the best indices for morphological (Table 1) and productive (Table 2) components.

Table 1
Morphological development of tomato grown under different water replacement depths and silicon application forms

Water replacement depth (% ETc)	Application form	Root	----- Stem ------		------------ Leaf -------------		
		Dry weight (g)	Fresh weight (g)	Dry weight (g)	Fresh weight (g)	Dry weight (g)	Area (mm^2)
100	Without application	8.08 bA	432.5 bA	82.5 bA	1084 bA	213 bA	12577.0 bA
	Foliar application	6.28 cA	385.5 cA	75.0 bA	940 bA	174 cA	12068.2 bA
	Soil (full dose)	11.03 aA	556.0 aA	104.5 aA	1493 aA	290 aA	13290.2 aA
	Soil (split dose)	9.11 aA	554.5 aA	107.5 aA	1155 abA	238 abA	14053.5 aA
60	Without application	7.05 bB	320.0 bB	67.5 bB	522 cB	116 bB	7188.9 bB
	Foliar application	6.41 bA	280.5 cB	63.1 bB	509 cB	124 bA	6069.8 bB
	Soil (full dose)	8.60 aB	366.0 bB	71.0 aB	981 aB	205 aB	12631.6 aA
	Soil (split dose)	8.29 aB	420.5 aB	83.2 aB	693 bB	228 aB	11108.6 aB
Mean		8.16	414.5	81.75	922.12	198.5	11123.52
CV (%)		35.81	30.37	28.00	43.24	32.97	41.53
Water replacement depth (WR)		**	***	***	***	**	**
Application form (AF)		**	**	*	*	*	**
WR × AF		*	*	*	*	**	*

Different letters indicate a significant difference by the Tukey test at a 5% error probability, with uppercase letters indicating irrigation replacement and lowercase letters denoting silicon application forms; *** p<0.01; ** p<0.05; *p<0.1.

Table 2
Production components of tomato grown under different water replacement depths and silicon application forms

Water replacement depth (% ETc)	Application form	Fruit fresh weight (g)	Fruit yield (kg plant^{-1})	Damaged fruits (fruits plant^{-1})	Water productivity (kg L^{-1})
100	Without application	91.45 cA	12.44 cA	9 bA	0.122 cB
	Foliar application	93.71 cA	12.75 cA	7 bA	0.125 cB
	Soil (full dose)	111.79 aA	15.20 aA	4 aA	0.149 aB
	Soil (split dose)	100.87 bA	13.72 bA	3 aA	0.134 bB
60	Without application	70.89 cB	9.36 dB	21 cB	0.152 dA
	Foliar application	74.02 cB	10.51 cB	16 bB	0.171 cA
	Soil (full dose)	97.30 aB	13.43 aB	11 aB	0.219 aA
	Soil (split dose)	88.46 bB	11.85 bB	13 aB	0.193 bA
Mean		91.06	12.40	10.80	0.158
CV (%)		14.82	13.89	18.89	21.69
Water replacement depth (WR)		***	***	***	**
Application form (AF)		**	**	***	**
WR × AF		***	**	***	*

Different letters indicate a significant difference by the Tukey test at 5% error probability, with uppercase letters indicating irrigation replacement and lowercase letters denoting silicon application forms; *** p<0.01; ** p<0.05; *p<0.1.

Regarding silicon application, applying the element in the soil at a full dose resulted in superior productive indexes under 100% ETc water replacement, while under 60% ETc water replacement, the best indexes were achieved with silicon application in the soil in a split dose (Table 2). Water productivity displayed higher means only under water stress, particularly when silicon was applied to the soil at a total dose at the beginning of cultivation (Table 2).

In drought conditions, silicon acts to reduce oxidative damage in root membranes and the action of aquaporins, leading to improved hydraulic conductivity and, consequently, facilitating water absorption (Chen et al., 2018). Silicon absorbed by the roots and transported by the xylem plays a role in the shoots in mediating gas exchange, photosynthetic efficiency, biochemical protection, phytochemical synthesis, and changes in tomato morphology (Chaudhary et al., 2018; Hoffmann et al., 2020).

Aires et al. (2022) also observed a reduction in tomato fruit production (Table 2) under a water deficit with 60% ETc replacement. As indicated in Table 3, water replacement showed a high correlation with morphological and production components, resulting in decreased fruit weight and yield per plant but an increase in the number of fruits damaged due to physiological disorders (Table 2).

Table 3
Pearson's linear correlations between variables

	WR	RDW	SFW	SDW	LFW	LDW	LA	FW	Y	DF	WP
WR	1.00	-	-	-	-	-	-	-	-	-	-
RDW	0.35	1.00	-	-	-	-	-	-	-	-	-
SFW	0.72	0.83	1.00	-	-	-	-	-	-	-	-
SDW	0.69	0.81	0.99	1.00	-	-	-	-	-	-	-
LFW	0.78	0.81	0.87	0.81	1.00	-	-	-	-	-	-
LDW	0.55	0.89	0.90	0.86	0.87	1.00	-	-	-	-	-
LA	0.69	0.66	0.83	0.75	0.86	0.85	1.00	-	-	-	-
FW	0.66	0.80	0.86	0.80	0.95	0.93	0.91	1.00	-	-	-
Y	0.65	0.78	0.82	0.76	0.94	0.90	0.89	0.99	1.00	-	-
DF	-0.83	-0.60	-0.85	-0.82	-0.89	-0.81	-0.88	-0.92	-0.92	1.00	-
WP	-0.80	0.08	-0.34	-0.35	-0.30	-0.04	-0.18	-0.10	-0.07	0.37	1.00

WR: water replacement depth; RDW: root dry weight; SFW: stem fresh weight; SDW: stem dry weight; LFW: leaf fresh weight; LDW: leaf dry weight; LA: leaf area; FW: fruit weight; Y: fruit yield per plant; DF: damaged fruits. WP: water productivity.
* Significance level (0.05).

Given the responses of tomato plants to water replacement, the use of silicon proves relevant in mitigating the effects of water stress (Chen et al., 2018; Chakma et al., 2021; Nocchi et al., 2021; Santos et al., 2021). This potential, coupled with the low silicon accumulation in tomato (Zhu et al., 2019) and its low levels in the region's soil, ranging from 10 to 20 mg dm^{-3} (Wenneck et al., 2022), highlights the significance of the results presented here.

According to Chakma et al. (2021), the application of 300 kg ha^{-1} of silicon improves fruit yield in tomato under moderate water stress. Under conditions similar to the present study, Santos et al. (2021) achieved better assimilate partitioning and higher yields in melon under severe water deficit (40% of ETc) when applying silicon via fertigation. Lozano et al. (2018) also evaluated silicon application on melon and noted improvements in postharvest traits such as soluble solids content and the maturity index. Additionally, Wenneck et al. (2023) observed improvements in yield, economic return, and water use efficiency in cauliflower with silicon application.

In comparison to foliar application, the application of silicon in the soil demonstrated superiority in increasing its content in the production system, influencing its bioavailability, and interacting with other environmental factors (Khan et al., 2019). Soil applications necessitate consideration of the chemical, physical, and biological processes involved in soil-plant interactions (Tombeur et al., 2021). Apart from influencing morphological and production components, the form of silicon application also impacted the spectral signature of plants under optimal (after water replacement) and critical (before water replacement) water conditions. The most significant variations were observed in the absence of application and under foliar application, as depicted in Figure 4.

Growing plants under stressful conditions such as drought and salinity affect the spectral reflectance of leaves, making it a sophisticated variable for measuring stress effects on plants (Boshkovski et al., 2020). Zhao et al. (2020) demonstrated a significant relationship between the water status of tomato plants and results obtained from hyperspectral images. Ihuoma and Madramootoo (2019) found a significant reduction in yield in tomato plants subjected to water replacement of less than 80% and highlighted the sensitivity of spectral indices for analyzing the plant's water status, offering potential tools for managing irrigation in the crop.

Considering the spectral reflectance obtained in the study during two assessment periods (before and after water replacement), it is identified that the application of silicon mitigates the effects of water deficit, whether controlled or temporal. This mitigation is also observed when analyzing the development of morphological components (Table 1) and yield (Table 2).

In the study, the application of silicon also influenced fruit weight losses during storage. Without the application of silicon, rates above 8% were obtained, while silicon application resulted in lower rates, as depicted in Figure 5.

Costan et al. (2019) asserted that the application of silicon improves the postharvest traits of tomato, with effects mostly related to the application method used. Although foliar application of silicon yielded lower responses than soil application (full or split dose), the effects were positive on development and productivity indices when compared with no application (Table 1, Table 2, and Figure 5). Adopting foliar application of silicon, Moraes et al. (2020) achieved improvements in gas exchange in industrial tomato. Technological advances involving foliar application of silicon may be associated with the adoption of nanoparticles and the action of molecules on plant metabolism (Rastogi et al., 2019).

In foliar applications, differences in the amount of the element and the relationship between its application and absorption are relevant, directly impacting production costs. Nonetheless, in soil applications, consideration should be given to the residual effect on production systems (Yan et al., 2018), which leads to an increase in available silicon content in the soil for the crop of interest (Wenneck et al., 2022).

Given that silicon enhances drought tolerance in tomato, Chakma et al. (2021) proposed including silicon in tomato nutritional management. According to the present study, silicon mitigates water deficit effects on tomato, improving its development and yield. However, several issues need to be analyzed in future studies to understand silicon absorption and accumulation dynamics in tomato, as well as the persistence of the element in the soil after application. Elucidating processes involving silicon in the production system aims to increase its efficiency and allows for defining management strategies.

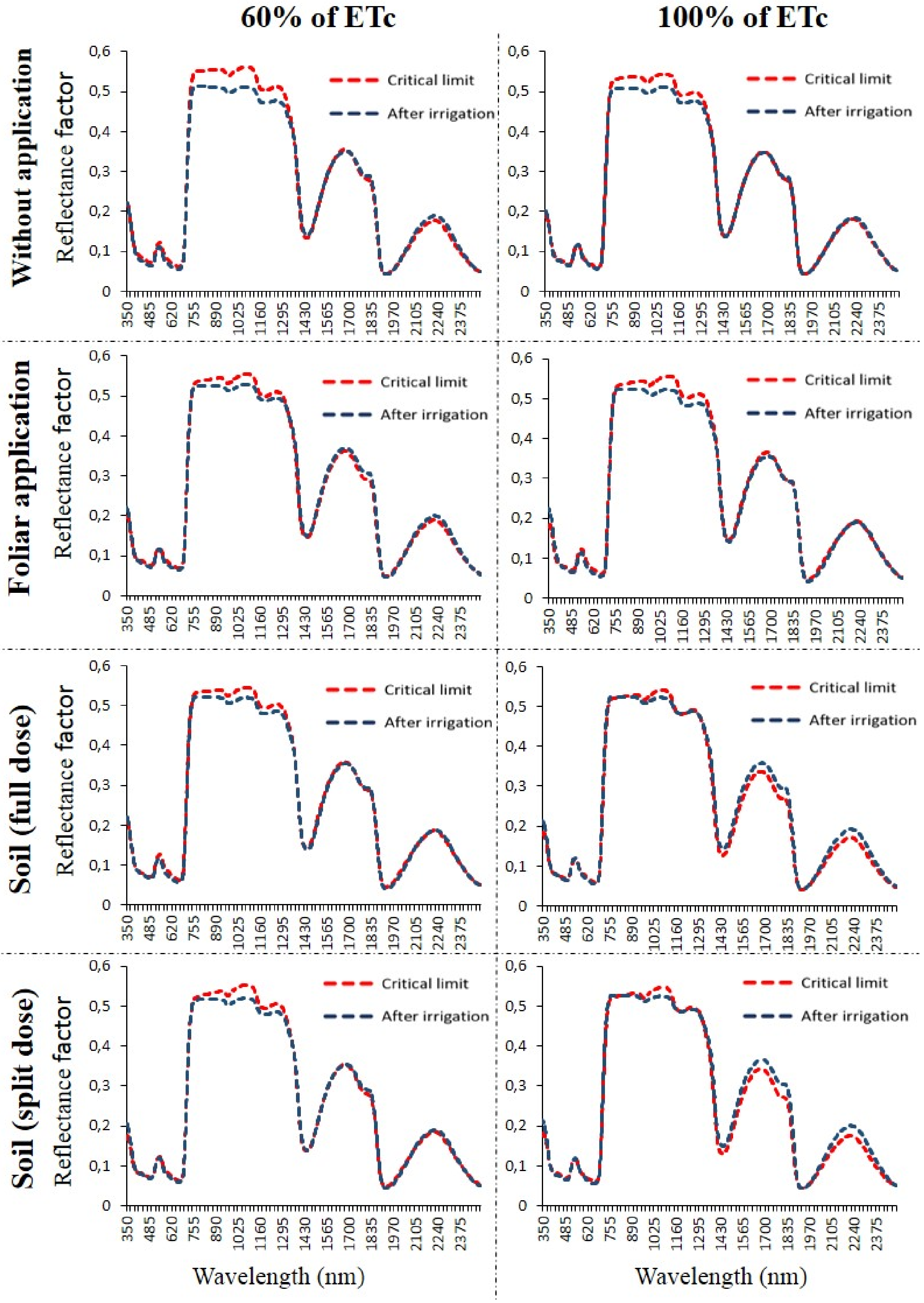

Figure 4. Spectral behavior of tomato plants under different grown conditions.

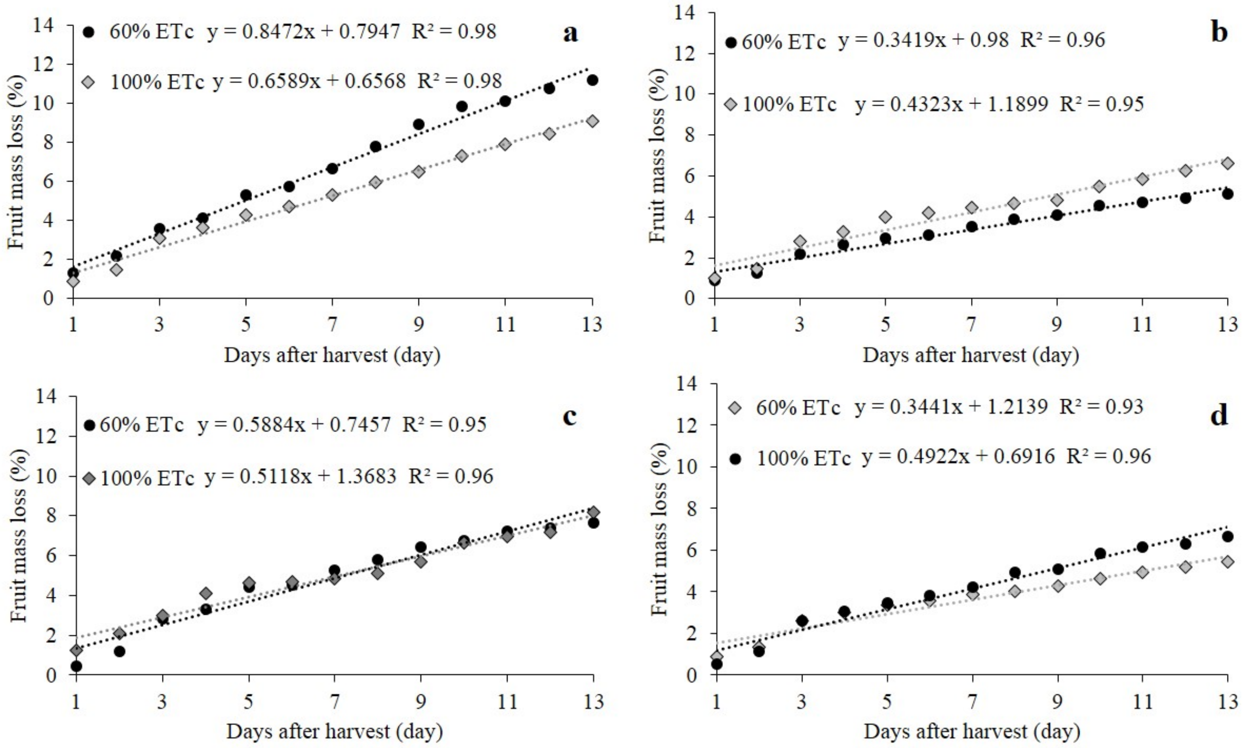

Figure 5. Weight loss in tomato fruits after harvest from cultivations under different water conditions and silicon (Si) application forms. a) Without application, b) Foliar application, c) Silicon application in soil (full dose), d) silicon application in soil (split dose). *Regression significant at 5%.

Conclusion

Imposing a water deficit (60% of ETc) in tomato reduces the development and yield of the crop, with these effects partially mitigated by the application of silicon.

In cultivation with sufficient water replacement (100% of ETc), the application of silicon enhances the development and yield of tomato.

The application of silicon in the soil, whether in a full or split dose, elicits a more favorable response in vegetative indices and yield in tomato.

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