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Production, quality, and longevity of zinnia cultivated under silicate fertilization and water restriction

Produção, qualidade e longevidade de zínias cultivadas sob adubação silicatada e restrição hídica

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ABSTRACT

The effects of water deficit and fertilization are fundamentals for productivity and quality of ornamental plants. This study evaluated the production, quality, and longevity of zinnia flower stems under irrigation levels and silicon doses. In a greenhouse, irrigation levels corresponding to crop water requirement (V4 - 100%) and three deficits (V3 - 85%; V2 - 73%; V1 - 61%), and Si doses of 0 (S1), 75 (S2), 150 (S3) and 300 (S4) mg per plant, in five weekly applications, were evaluated. The irrigation system was composed of emitters with different flow rates and it was automatically activated in response to the soil water tension. The total volume applied in treatment V4 was 5.2 L per plant. The results showed that higher water levels increased stem length and total fresh mass, and the supplementation with S3 provided greater dry mass in leaves and flowers. Plants in V1S3 exhibited higher fresh mass and leaf area. Water absorption and fresh mass of the stems followed a similar post-harvest pattern, with stability for five to six days, and a subsequent gradual loss of mass. The commercial longevity of stems was 6.4 days, but the total longevity ranged from 9.7 to 12.7 days, being greater in V4S2. Application of 150 mg of Si and full water replacement are recommended to increase the growth and longevity of zinnia stem flower.

Index terms: *Zinnia elegans* Jacq.; cut flower; irrigation management; water deficit; silicon.

RESUMO

Os efeitos do déficit hídrico e da fertilização são fundamentais na produtividade e qualidade de plantas ornamentais. Objetivou-se avaliar a produção, qualidade e longevidade de hastes florais de zinnia sob níveis de irrigação e doses de silício. Em casa de vegetação, foram avaliados níveis de irrigação correspondentes à necessidade hídrica da cultura (V4 – 100%) e três déficits (V3 - 85%; V2 - 73%; V1 - 61%), e doses de Si de 0 (S1), 75 (S2), 150 (S3) e 300 (S4) mg por planta, em cinco aplicações semanais. O sistema de irrigação foi composto por emissores de diferentes vazões e era automaticamente acionado em resposta à tensão de água no solo. O volume total aplicado no tratamento V4 foi de 5,2 L por planta. Os resultados obtidos indicam que maiores suprimentos de água aumentaram o comprimento da haste e a massa fresca total, e a suplementação com S3 proporcionou maior massa seca de folhas e flores. As plantas em V1S3 apresentaram maior massa fresca e área foliar. A absorção de água e a massa fresca das hastes seguiram um padrão semelhante, com estabilidade por cinco a seis dias, e uma subsequente perda gradual de massa. A longevidade comercial das hastes foi de 6,4 dias, mas a longevidade total variou de 9,7 a 12,7 dias, sendo maior em V4S2. A aplicação de 150 mg de Si e reposição hídrica plena são recomendadas para aumentar o crescimento e a longevidade de hastes florais de zinnia.

Termos para indexação: *Zinnia elegans* Jacq.; flor de corte; manejo da irrigação; déficit hídrico; silício.

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Introduction

Zinnias (*Zinnia elegans*) are ornamental herbaceous plants cultivated in various parts of the world (Zulfiqar et al., 2024). They are known for their inflorescences with petals in a variety of colors, which, in addition to their commercial value, also attract bees and butterflies, playing an important role in the pollination of agricultural production areas (Pêgo, Antunes & Silva, 2020). Although widely grown as alternative cut flowers in the United States and Canada (Loyola, Dole & Dunning, 2019), their cultivation in Brazil is still relatively modest but is expanding (Pêgo, Antunes & Silva, 2020).

Most species produced in floriculture require a considerable amount of water, as well as financial resources to meet the high-quality standards required by the market. On the other hand, the water resources for irrigation and production of agricultural crops is progressively diminishing in quantity and quality (Amiri et al., 2021; Hatamian et al., 2019). Therefore, seeking approaches to maximize efficient water use, such as controlled

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water deficit (Gava et al., 2016), has been recommended for sustainable production of flower production (Sukpitak et al., 2024). Furthermore, the combination with other supplementary minerals, such as silicon, can improve plant performance under stress conditions (Wang et al., 2021).

Silicon is recognized as a beneficial element for plant growth, enhancing photosynthetic efficiency, above-ground architecture, resistance to pests and pathogens, and increasing tolerance to water stress (Calero Hurtado et al., 2020; Chakma et al., 2021; Ma et al., 2016; Ma & Yamaji, 2006; Song et al., 2014; Zhao et al., 2013). The role of silicon in these plants is associated with its accumulation in the cell wall, which provides greater physical resistance and, consequently, helps maintain turgor in plant tissues. Leaves also tend to exhibit a more intense green color, indicative of higher chlorophyll content (Ferrón-Carrillo & Urrestarazu, 2021; Kamenidou, Cavins & Marek, 2010; Zhao et al., 2013). Therefore, silicon-based fertilization can be a promising alternative for improving the productivity and/or quality of ornamental plants with longer shelf life (Hatamian & Souri, 2019), as well as contributing to more sustainable flower production. In ornamental plants, flower stems produced under silicon fertilization present higher antioxidant enzyme activities and greater mechanical resistance of the stem, with significant effects on post-harvest longevity (Song et al., 2021). The greater resistance of the stem is attributed to the accumulation of lignin, particularly S-lignin and G-lignin (Zhao et al., 2021), an important characteristic for cut flowers because it makes the classification, packaging and transportation stages easier, in addition to promoting greater support of the floral stem during post-harvest.

Based on the aforementioned assumption, the hypothesis is raised that silicon-based fertilization in zinnias reduces the detrimental effects caused by water deficit, contributing to increased water use efficiency. This study was conducted to evaluate the effect of irrigation levels combined with doses of silicon-based fertilization on the production, quality, and longevity of zinnia flowers.

Material and Methods

The experiment was carried out in a greenhouse located in the Horticulture Sector of UFRRJ (Seropédica, RJ, Brazil) (latitude 22º 45’48” S; longitude 43º 41’ 19” W; altitude of 33.0 m) using zinnia plants (*Zinnia elegans*), cv “Red California Giant”, from October to December 2022. The greenhouse was 35.0 m long, 8.0 m wide, 2.5 m ceiling height, involved with a shade screen and covered with 100-micron thick transparent plastic.

Using commercial seeds (Isla®, Brazil), the seedlings were prepared in plastic trays with 128 cells filled with commercial substrate (Carolina Soil®). At 23 days after sowing, they were transplanted into 8.0 L plastic containers filled with 6.0 L sandy soil material (71% sand, 9% clay, 20% silt) and 2.0 L cattle manure. The pots were positioned on the ground, supported by brick tiles, and the chemical properties of the substrate (soil + cattle manure) were: pH 6.8, 28.9 mg kg^{-1} K, 1573 mg kg^{-1} P, 2.6 cmol c kg^{-1} Mg, 4.6 cmol c kg^{-1} Ca, and content of 11.7 g kg^{-1} Si. Meteorological monitoring inside the greenhouse was conducted using a thermo-hygrograph (Ip-747, Impac), programmed to record temperature and relative humidity data in intervals of five minutes.

The experiment was conducted using a randomized block design (RBD), with a factorial scheme comprising 4 levels of silicon-based fertilization and 4 levels of irrigation, with 5 replications (Figure 1A). The doses of potassium silicate (K_2SiO_3), using the commercial product Flex Silício (12% Si, 12% K_2O), were 0 (S1), 75 (S2), 150 (S3), and 300 (S4) mg Si per plant, prepared after dilution in 50 mL of water per plant and applied manually to the soil weekly, for five weeks. The irrigation levels applied corresponded to 61% (V1), 73% (V2), 85% (V3), and 100% (V4) of the species’ water requirement and were applied through emitters with different flow rates. Each experimental unit consisted of 3 plants per pot, spaced 0.15 m apart. The pots were spaced 0.15 m within rows and 0.60 m between rows, totaling 80 pots and 240 plants.

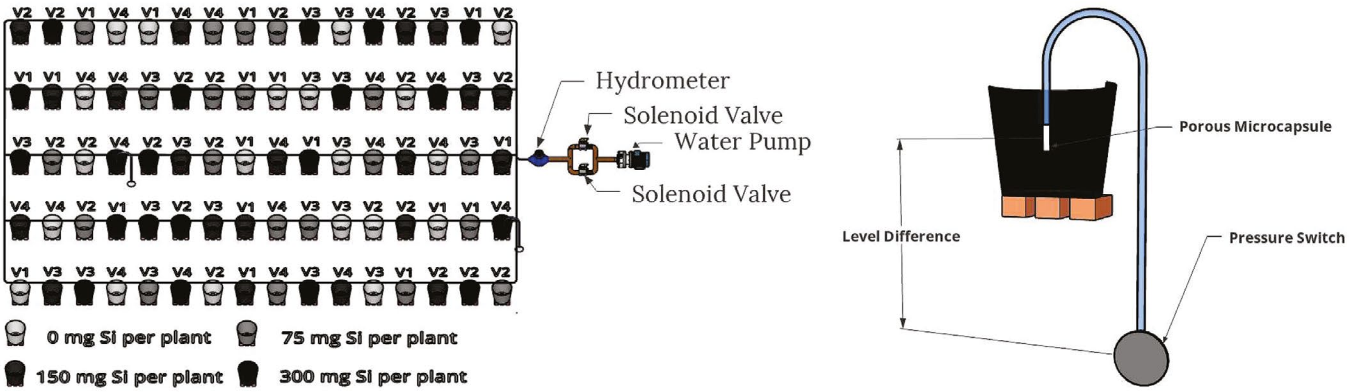
The drip irrigation system consisted of 16 mm polyethylene tubes and self-compensating emitters (PCJ-LCNL/Netafim), which combined provided flow rates of 4.0, 3.5, 3.0 and 2.5 L h^{-1}, characterizing the treatments V4, V3, V2 and V1, respectively. The emitters with different flow rates were installed in the same line, and therefore applied water simultaneously, characterizing the different water supplies. The system showed a distribution uniformity coefficient (DUC) of over 93% in all treatments, for a service pressure of 30.0 kPa at the beginning of the experimental area. In addition to satisfactory DUC, proper irrigation management is also crucial, especially for plants grown in pots (Sukpitak et al., 2024).

In this study, automated management was employed using automatic irrigation activators (AIA) proposed by Medici et al. (2010), installed in 2 pots from the treatment with the highest flow rate (V4) and highest dose of silicon-based fertilizer (S4). The porous microcapsules were produced manually from commercial homemade filter candles (mod. Traditional, Stéfani®, Jaboticabal, SP, Brazil), and tested for bubble tension (Moraes et al., 2006). The microcapsules were approximately 0.05 m in length and 0.01 m in diameter and were positioned vertically in the substrate at a depth of 0.10 m (Figure 1B). The pressure switches were installed 0.40 m above the microcapsules, corresponding to a triggering pressure of 4.0 kPa.

Apical pruning was performed thirteen days after transplanting (DAT) the seedlings to induce lateral branching. At this time, automated irrigation management was also initiated with the application of the first doses of K_2SiO_3. The amount of water applied was measured daily using a flow meter installed at the beginning of the irrigation line, with readings taken in the morning at 8:00 a.m. Based on the flow rate of the drippers, the daily amount of water applied per pot was calculated, and at the end of the cycle, the total volume of water applied per plant was determined.

Flowering began at 28 DAT, regardless of the treatments studied, and the harvest of the first stems was carried out at 33 DAT, reaching peak production at 41 DAT (Figure 2A). After that, flower production gradually declined. As the flowers were harvested, the stem length, flower and stem diameter, fresh mass of the stems, and leaf area were evaluated. Fresh mass was obtained by weighing the individual stems on an analytical balance with a precision of 0.2 g. The diameter of the flower stems was measured in the middle portion of the stem using a digital caliper (JOMARCA®). The stem length was measured with a graduated ruler, and the diameter of both flowers and stems was measured with the digital caliper.

The stems were always harvested early at 8:00 am and kept with the base immersed in water until they were classified according to the standard proposed by Martins et al. (2021a), which considers the combination of stem length and diameter, as well as flower diameter. The first four stems harvested per pot that met the commercial standard were standardized to 30 cm in length and two pairs of leaves, and then set aside for longevity analysis in the Post-harvest Laboratory, located next to the experimental site. After weighing, they were individually placed in pots containing approximately 200 mL of water and kept on a well-ventilated laboratory bench at temperature of 25 °C (Figure 2B).



(A) (B)

Figure 1: Arrangement of pots in a greenhouse (A) and detail of the automatic irrigation activator (B).

(A) (B)

Figure 2: Zinnia plants in the flowering phase (A) and evaluation of flower longevity (B).

The fresh weight variations (FWV) and the water absorption rate (WAT) were calculated daily until the senescence of the floral stems, using an analytical balance with a precision of 0.2 g, following the methodology presented by Santos et al. (2021). The longevity of the stems was assessed using the senescence scale proposed by Martins et al. (2021b).

For the remaining stems, the leaf area was measured using a leaf area integrator (model Li-Cor® 3100), and the number of leaves on these stems was quantified. Afterward, the stems were placed in an oven at 65 ºC for 48 hours to obtain the dry mass of flowers, stems, and leaves, using an analytical balance with a precision of 0.01 g.

The silicon levels in leaves and flowers were determined according to the methodology adapted by Korndörfer et al. (1999). The flowers and leaves, dried in the oven, were ground, and 1.0 g of material was separated for analysis, with 3 repetitions per treatment. The chemical characteristics of the substrate were analyzed after the experiment was completed in each pot, following the protocol of Teixeira et al. (2017).

Normality of data was assessed using the Shapiro-Wilk test, while homogeneity was verified using the Bartlett test, both considering a significance level of 5%. When necessary, data transformations were applied to meet the assumptions of the statistical tests. Subsequently, an analysis of variance (Two-way ANOVA) was performed to investigate differences between the evaluated treatments. When significant, regression analyses were conducted between the independent variables (irrigation levels and doses of silicon-based fertilization) and the assessed variables. The regression was segmented by each silicon dose for the stem longevity data.

The regression models were analyzed using the least squares method through matrix algebra (Ferreira, 2019). The significance of the model coefficients was tested using the t-test. The best models were selected based on the coefficient of determination (R^2), the significance levels of the model coefficients (t-test), and the residual non-significance (F-test). For silicon doses, Tukey's mean comparison test was performed with a significance level of 0.10. All statistical analyses were conducted using R software, version 4.2.1.

Results and Discussions

Meteorological conditions and volume of water applied

After transplanting the seedlings, the duration of the experimental period was 58 days, from October 19 to December 16. During this time, the air temperature ranged from 16.3 to 49.7 ºC (Figure 3), with average values of 19.5 ºC (minimum) and 31.8 ºC (maximum). Phase I corresponds to the period between transplanting and the apical sprouting of the seedlings; Phase II occurs between sprouting and the appearance of the first floral buds; Phase III spans from the end of Phase II to the start of harvest; and Phase IV covers the period from the beginning of harvest to the end of the experiment. This last phase was the longest and thus required the most irrigation. The air relative humidity ranged from 26.5% to 98.9%, with average values of 40.3% (minimum) and 94.9% (maximum).

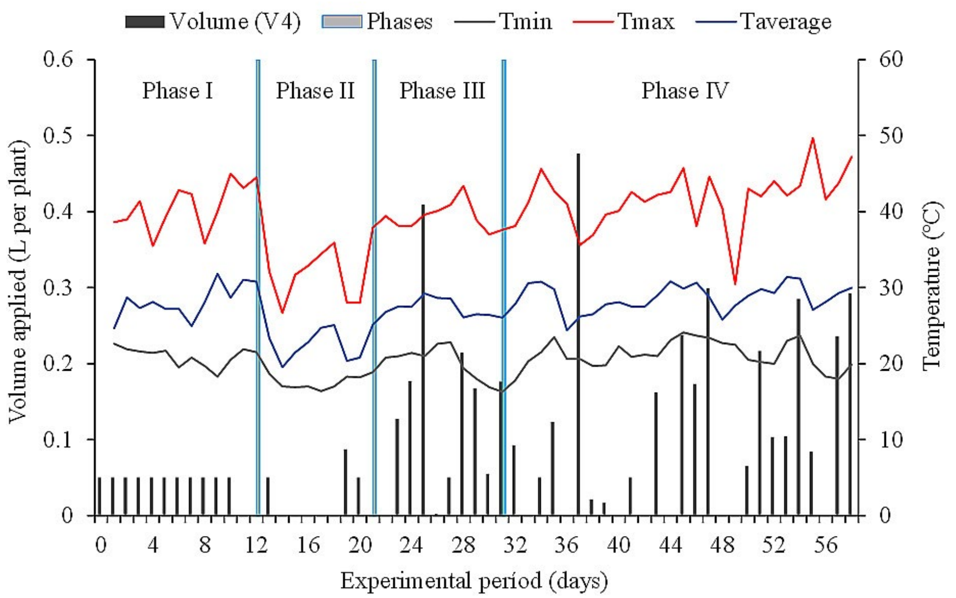


Figure 3: Average, maximum, and minimum temperature; and volume applied per irrigation in pots with 100% replacement of the water demand for zinnias "Red California Giant" during the experimental period.

The volume of water applied varied according to the water replacement levels in the different treatments. However, for the first 11 days of the experimental period (Phase I), all seedlings received 50 mL of water daily. In total, the treatment with 100% water replacement (V4) received 5.2 L per plant during the experimental period (Table 1). For plants irrigated with 85% (V3), 73% (V2), and 61% (V1) water replacement, the volumes applied were 4.4, 3.9, and 3.3 L per plant, respectively. There was a variation in the volume of water applied throughout the experiment, with the highest demand occurring during the weeks in Phase IV (Figure 3). It is important to note that irrigation management was automated after Phase I, meeting the plant's needs throughout the remainder of the cycle, according to the treatment with the highest water replacement (V4).

Greater water availability allows for better plant hydration, reducing symptoms, such as wilting in the plant organs. This is particularly important during the vegetative phase, when there is intense leaf production to support growth, and during flowering, to produce high-quality stems. According to Martins et al. (2021a), zinnias have higher water demand during the vegetative phase, peaking during floral differentiation until harvest. However, in the current experiment, the highest demand was observed in Phase IV, likely due to the high air temperature and the longer duration of this phase. In a study using dianthus (*Dianthus chinensis*), Schwab et al. (2013) reported that water consumption increased throughout the cultivation cycle due to plant development, particularly the increase in leaf area and, consequently, in transpiration intensity. In alstroemeria (*Alstroemeria x hybrid*), Girardi et al. (2016) found that the highest water consumption occurred close to harvest, due to increased translocation of photoassimilates for flower formation and because the existing leaf area was the highest throughout the production cycle.

Production variables

The irrigation levels applied affected the stem length ($p<0.001$) and the dry weights of the flowers ($p<0.001$) and the aerial parts ($p<0.0792$), while the silicon doses influenced the dry weights of the leaves ($p<0.0029$) and the flowers ($p<0.0031$). There was an interaction between treatments for the flower diameter ($p<0.0177$), fresh weight of the aerial parts ($p<0.0801$), and leaf area ($p<0.001$). The average stem diameter was 3.3±0.1 mm and was not affected by the applied treatments.

Studies indicate that moderate water restriction can be used for the cultivation of ornamental plants, aiming at optimizing water use (Sánchez-Blanco et al., 2019). However, ornamental plants grown under severe water deficit conditions tend to have lower stomatal conductance to regulate the transpiration rate and reduced photosynthetic rate, resulting in lower growth rates in height, biomass or productivity (Caser, Lovisolo & Scariot, 2017).

The length of the floral stems ranged from 36±1.52 cm to 43.6±1.83 cm depending on the irrigation levels (Figure 4A). The highest values obtained were when 5.2 and 4.4 L per plant^{-1} were applied, corresponding to 21.0% and 18.8% higher, respectively, compared to the length measured in plants irrigated with 3.3 L per plant.

The dry mass of the aerial part ranged from 1.85±0.23 g to 2.25±0.18 g, in response to the increase in the amount of water applied (Figure 4B). A similar behavior was observed in the dry mass of the flowers, which ranged from 0.56±0.14 g to 0.70±0.08 g. The increase in biomass production is associated with the increase in water supply, as plants show greater development, resulting in greater height and leaf area.

Plants experience stress when water availability at the roots is limited, leading to water deficit with some morphological, physiological and biochemical changes (Lisar et al., 2012). Under such conditions, plant growth and biomass production are affected, resulting in shorter plants and, consequently, lower fresh mass production (Ebrahimi et al., 2021; Souri & Hatamian, 2019). Water deficit profoundly affects plant physiology, both through stomatal and non-stomatal limitations. Diffusive limitation, resulting from reduced stomatal conductance, reduces access to CO_2. The worsening of the deficit also induces non-diffusive limitations, such as oxidative stress, compromising plant productivity and even survival (Baroni et al., 2024).

Table 1: Number of irrigation activations and volume of water applied by zinnia cv "Red California Giant" development phase in the highest water replacement treatment (V4).

Phases*	Number of activations	Volume of water applied (L per plant)		
		AIA	By fertilizing	Total
I	0	0.55	0.05	0.60
II	1	0.09	0.05	0.55
III	9	1.42	0.05	0.09
IV	18	2.90	0.10	3.00
Total	28	4.96	0.25	5.21

*I – from transplanting to the apical sprouting of the seedlings; II – from sprouting to the appearance of the first floral buds; III – from the end of Phase II to the start of harvest; IV – from the beginning of harvest to the end of the experiment. AIA – automatic irrigation activator.

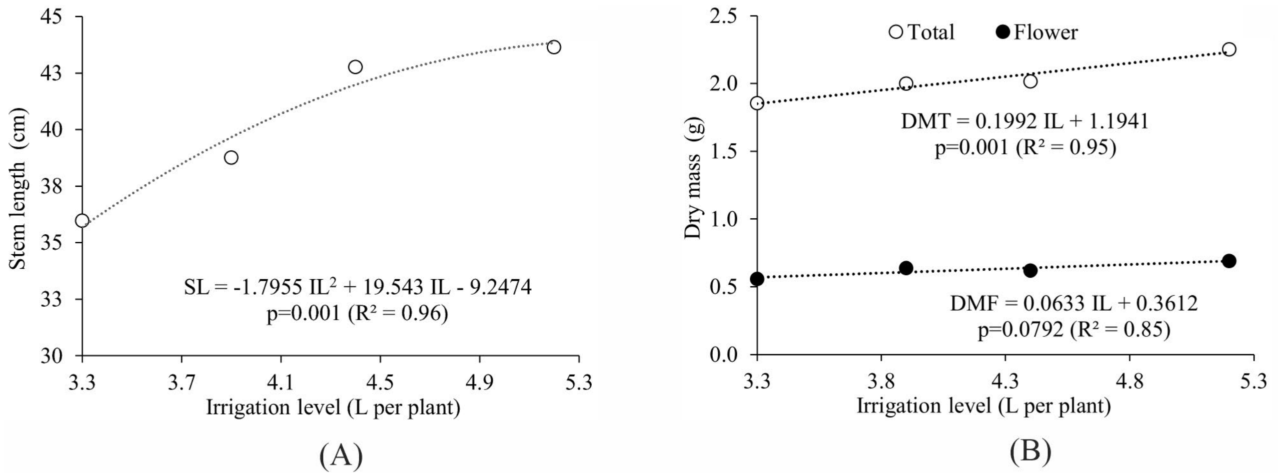


Figure 4: Stem length (cm) (A), and dry mass of aerial part (g) and dry mass of flowers (g) (B) of zinnias cv "Red California Giant" cultivated under different irrigation levels.

The S3 treatments exhibited a dry mass of leaves of 0.89±0.12 g, which is 21.3% higher than S1 treatment (Figure 5). A similar effect was observed in the dry mass of flowers, which showed a value 28.6% higher compared to the S1 treatments, in response to fertilization with 150 mg Si per plant.

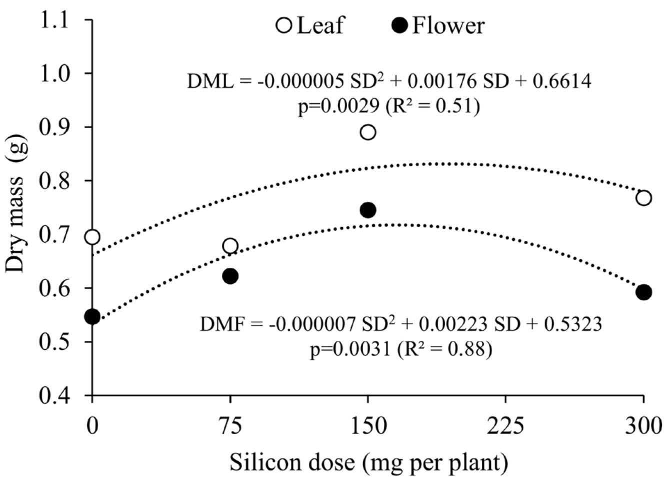


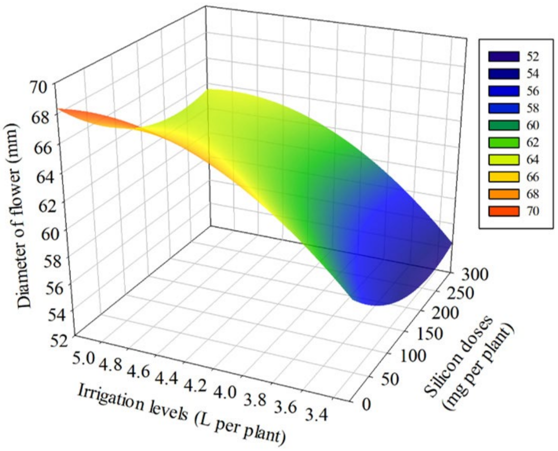
Figure 5: Dry mass of the aerial part of Zinnias cv "Red California Giant" cultivated under different Si doses.

The presence of silicon has been shown to positively affect growth and biomass production in various plant species, especially under stress conditions (Epstein, 1994). Studies have also demonstrated that silicon leads to cell elongation, possibly due to increased cell wall extensibility in rice and sorghum (Ma & Yamaji, 2006). Additionally, silicon is associated with increased photosynthesis and higher water retention capacity in strawberries (Dehghanipoodeh et al., 2018), radishes (Lacerda et al., 2022), and cherry tomatoes (Chakma et al., 2021).

The treatment that received 5.2 L of water and 300 mg Si per plant provides an average flower diameter of 60.4±2.8 mm, 12.8% smaller than that of plants not receiving silicon (Figure 6). These results contradict findings by Kamenidou, Cavins and Marek (2009), who reported a significant increase ($p<0.01$) in the flower diameter of zinnias treated with 75 and 150 mg of $KSiO_3$ using a substrate consisting of peat, perlite, and vermiculite. However, the reduction in flower diameter did not significantly affect the ornamental quality, allowing for commercially acceptable stems (Martins et al., 2021a). These contradictory results may, at least partially, be related to the substrates used in the studies. In the cited work showing positive results, there was no soil, which could be a source of Si. Thus, it is hypothesized that in the present study, the soil may have provided all the necessary Si making any application beyond 75 mg Si excessive for the flower diameter variable. The literature shows that silicon applications can both promote growth and cause toxicity, depending on the dose and form in which the element is supplied, and also on the species cultivated (Mantovani et al., 2020). These results highlight the importance of optimizing parameters for each species.

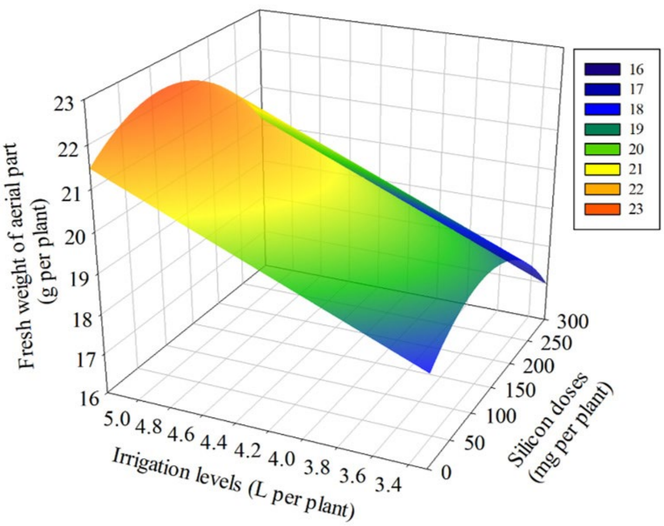
The average fresh weight of the aerial part of plants that received 3.9 L of water and 150 mg Si was 23±2.4 g, representing a 15.2% increase compared to plants that did not receive silicon application (S1) (Figure 7).

The doses of 75 and 150 mg Si per plant showed average leaf areas of 186 and 192 cm², respectively, representing increases of 10.05% and 13.61% compared to S1. The interaction between treatments was most notable at plants that received 5.2 L of water and 150 mg Si, and in plants irrigated with 3.3 L and fertilized with 75, 150 and 300 mg (Figure 8). Thus, Si doses contributed to a linear increase in leaf area under water deficit conditions but showed a quadratic effect under full irrigation. These results are consistent with studies indicating drought tolerance with Si application (Chakma et al., 2021; Ma et al., 2004; Ma & Yamaji, 2006) and also suggest benefits up to a certain dose even under well-irrigated conditions.



FD = - 11.5877 + 32.0214 IL - 3.2020 IL^2 - 0.0448 SD + 0.000096 SD^2
R^2 = 0.503 p< 0.0001

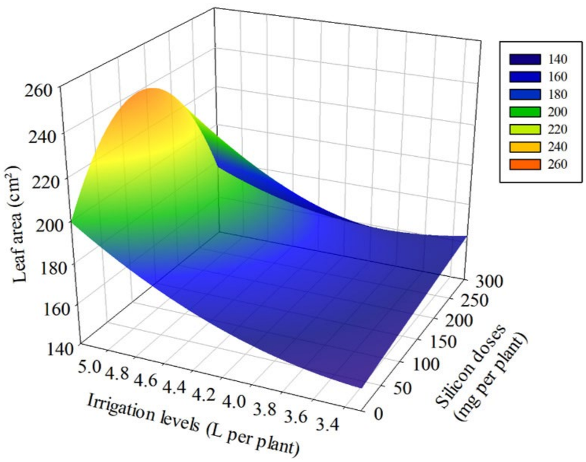
Figure 6: Flower Diameter of zinnias cv "Red California Giant" cultivated under different irrigation levels (IL) and silicon doses (SD).



FW = 12.7580 + 1.6753 IL + 0.0149 SD - 0.0000644 SD^2
R^2 = 0.374 p< 0.0001

Figure 7: Fresh weight (g) of the aerial part of zinnias, cv " Red California Giant" cultivated under different irrigation levels (IL) and silicon doses (SD).

Silicon applications have the potential to alter the architecture of the cell wall, leading to increased extensibility of this structure. Morphological changes resulting from Si accumulation on the leaf epidermis can confer greater thickness, verticality, and rigidity to the leaves, thus enhancing their exposure to light (Savvas & Ntatsi, 2015). Moreover, the accumulation of silica on the leaf epidermis can reduce transpiration and mitigate the effects of water deficit, such as reduced leaf area (Ferrón-Carrillo & Urrestarazu, 2021). Silicon also stimulates antioxidant enzyme activity in leaves and roots, reducing the impacts of oxidative stress and enhancing osmotic regulation (Avila et al., 2021). These mechanisms play a crucial role in the continued growth, development, and production of plants, thereby justifying the increased leaf area in zinnias treated with Si.



LA = 260.8939 – 70.9209 ID + 11.3694 ID^2 – 0.9202 SD + 0.0039 SD^2
+ 0.2928 ID.SD – 0.0012 ID SD^2
R^2 = 0.35 p< 0.0001

Figure 8: Leaf area (cm²) of zinnias cv "Red California Giant" cultivated under different irrigation levels (IL) and silicon doses (SD).

Analyzing the floral stem quality

A total of 562 floral stems were harvested, of which 457 (81.3%) were classified as A_1 (flower diameter > 4.0 cm) and only two (0.35%) were classified as A_2 (2.0 cm ≤ flower diameter ≤ 4.0 cm). About 103 stems (18%) did not meet the commercial standard (flower diameter < 2.0 cm), according to the quality evaluation methodology proposed by Martins et al. (2021a). The classification of stems per plant based on length (P_{30}, 30.0 ≤ L ≤ 40.0 cm; P_{40}, 40.0 < L ≤ 50.0 cm, and P_{50}, L > 50 cm), as well as those not meeting the standard, are presented in Figure 9. There was a significant effect of irrigation levels on the classification of P_{40} stems (p<0.0014), P_{50} (p<0.001), and those not meeting the standard (p<0.0054).

Plants irrigated with 4.4 and 5.2 L produced longer stems. On average, 1.1±0.17 and 1.2±0.36 stems per plant were classified as P_{40}, respectively, and 0.5±0.1 and 0.3±0.2 stems per plant were classified as P_{50}. Plants that received 3.3 liters produced a higher number of out-of-standard stems, with an average of 0.8±0.4 stems per plant (Figure 9).

Quality characteristics of zinnia flower stems are influenced by water availability. In dry conditions, there is reduced plant growth and the production of shorter, low-quality flower stems (Martins et al., 2021a). Studies show that under drought stress conditions zinnia plants significantly reduce photosynthetic rate, stomatal conductance and transpiration which can lead to lower plant growth; as well as the increase in the enzymatic activities of catalase (CAT), peroxidase (GPX) and superoxide dismutase (SOD), which are activated as defense mechanisms under stress conditions (Toscano & Romano, 2021).

Silicon analysis in plant material

The irrigation level affected the silicon (Si) content in the zinnia leaves ($p<0.001$). Higher irrigation levels resulted in increased Si concentrations in the leaves, ranging from 1.35 to 2.39 % (Figure 10).

The average Si concentration was 0.5% in the flowers, regardless of the treatment. These results support the hypothesis that Si is primarily absorbed through mass flow, as proposed by Jones and Handreck (1967). According to Imtiaz et al. (2016), plants absorb silicon (Si) through their roots as monosilicic acid (H_4SiO_4), both by diffusion and by the influence of root absorption caused by transpiration, known as mass flow. The H_4SiO_4 is translocate from the roots through the xylem until it deposits under the cuticle and in intercellular spaces, contributing to reinforcement of cell walls by deposition of solid silica (Yuvaraj & Gangothri, 2017). Similar results were observed by Dehghanipoodeh et al. (2018), who found that Si content in strawberry (Fragaria × ananassa 'Camarosa') leaves increased under moderate water deficit and decreased under severe water deficit. Even in Poaceae, which is one of the families that accumulates the most Si, the water deficit reduces its accumulation (Motomura, Mita & Suzuka, 2002). Melo et al. (2003) found that Si accumulation in brachiaria grass (*Brachiaria decumbens* Stapf and *Brachiaria brizantha* Hochst) leaves was higher in plants treated with 80% field capacity (FC) compared to those treated with 60% FC, but there was no difference in Si content among the different applied concentrations.

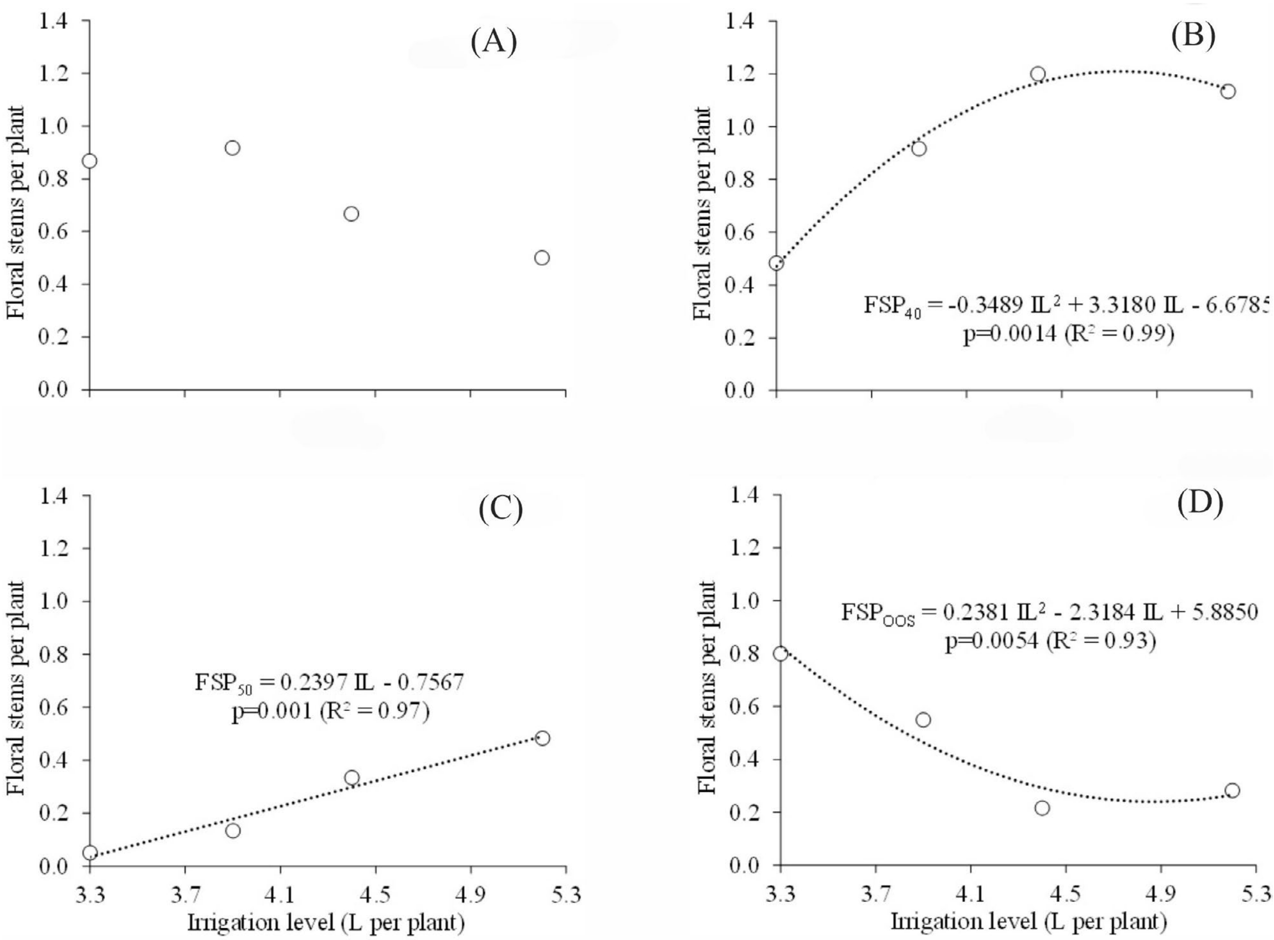


Figure 9: Number of floral stems per plant of zinnia cv "Red California Giant" classified as standard P_{30} (A), P_{40} (B), P_{50} (C), and out of standard (OOS) (D) obtained from cultivation under irrigation levels.

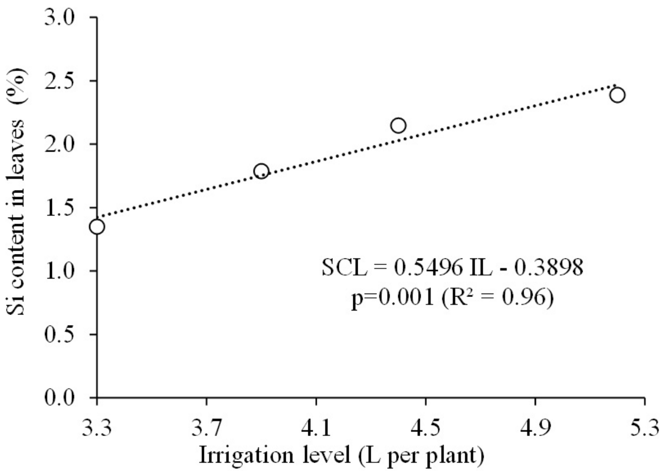


Figure 10. Si content in leaves of zinnias cv "Red California Giant" after cultivation with different irrigation levels.

All these results occur because the transport of Si is similar to that of Ca to the shoot, through the xylem and driven by transpiration. Thus, with more water available in the soil, more Si will be taken to the shoot (Souri & Hatamian, 2019; Amiripour et al., 2021). Transpiration is lower in the petals than in the leaves, due to the absence of photosynthesis, explaining, at least in part, the fact that the accumulation of Si in the flowers was not proportional to the irrigation levels in the present work.

The initial silicon levels in the substrate were 11.2 mg dm^{-3} of soil. These values are similar to those reported by Szulc et al. (2019), who found silicon levels in the soil of 7 mg dm^{-3} and 10.11 mg dm^{-3} after adding manure. Song et al. (2014) demonstrated that long-term application of organic fertilizers contributed to an increase in the available silicon content in the soil.

The doses of 75 and 150 mg Si per plant per application were sufficient for the plants to accumulate the maximum amount of the element under these cultivation conditions, and the zinnia plants responded positively with increased fresh and dry mass in the treatments with 150 mg Si per plant. However, in the treatments that did not receive potassium silicate, the silicon content in the leaves was above 1.7%. Kamenidou, Cavins and Marek (2009) found this same Si concentration in zinnia leaves treated with applications of 300 mg Si per plant. Frantz et al. (2008) observed a maximum accumulation of 1.2% Si in zinnia leaves treated with 2.0 mM K_2SiO_4. These results suggest that the initial silicon levels in the soil were already sufficient and that zinnias have a limit for accumulating the element.

Analyzing stem longevity

The variation in fresh weight of zinnia stems followed a similar pattern across all irrigation levels, showing an increase in fresh weight variation of the stems during the first 24 hours post-harvest. It is noteworthy that water uptake and the variation in the fresh weight of cut flowers are the primary indicators of longevity. The fresh weight generally remained stable until the fifth day after beginning the test, after which weight loss began. On average, zinnia stems took 5 to 6 days to reach a rating of 3 on the senescence scale. For the different silicon doses applied, there was no significant difference between the irrigation levels for fresh weight of zinnia stems (Figure 11).

Fresh weight tends to increase by an average of 5%, 5%, 5%, and 4% in stems obtained with irrigation levels of 4.4, 5.2, 3.9, and 3.3 L per plant, respectively, up to the 3rd day of storage. After the fifth day, the stems tend to lose fresh weight at all levels. On average, the stems lost 5.3% of fresh weight from the first day until the end of their longevity.

On the first day of evaluation, the absorption rates tended to be higher across all treatments, indicating that water absorption by the stems is very quick at the beginning of storage. Although there was no statistical difference, water absorption in treatments with irrigation levels of 5.2 and 4.4 L per plant was higher, at 1014 and 1062 mg g^{-1} of fresh stem weight, respectively. Treatments with 75 and 150 mg of Si per plant also showed higher water absorption rates, at 1041 and 1025 mg g of fresh stem weight, respectively.

There was a correlation between the variation in fresh weight, water absorption by the stems, and senescence scores. Initial water absorption was high (Figure 12), which led to an increase in the fresh weight of the stems in the first days of post-harvest evaluation (Figure 11).

Additionally, the increase in fresh weight was also due to the central flowers blooming, as at harvest time they were just beginning to open. This process was completed in the first days of stem storage. During these early days, the flowers received scores of 5 and 4 on the senescence scale, indicating they were still in full vigor. From the fifth and sixth days onward, the average score for all treatments was 3, showing a decline in fresh weight and water absorption rates.

Daily assessments, using a rate scale from 5 to 0 for zinnia flowers, enabled the monitoring of quality variation over storage days. The commercial longevity of the stems (rating 3) averaged 6.4 days, regardless of the treatment. The total longevity of the stems (rating 0) was influenced by irrigation levels ($p<0.001$), and there was an interaction between treatments ($p<0.0013$). The average longevity of the stems was 11.1 days, regardless of silicon doses. In contrast, the different irrigation levels influenced the longevity of the stems, which varied from 9.7 to 12.7 days.

At the irrigation levels of 3.9 and 4.4 L per plant, the treatments receiving 75 mg of Si per plant had a longevity of 12.9 and 12.7 days, respectively. This is 15.17% and 25.7% longer than the treatments that did not receive silicon fertilization (Figure 13).

Similar results were observed in peonies, where silicon applications increased longevity and improved flower quality during post-harvest storage (Song et al., 2021). According to the authors, adding silicon reduced the loss of fresh weight during storage, increased the amount of antioxidant enzymes, and improved the mechanical strength of the stems. In addition, silicon reduces the harmful effects of reactive oxygen species and provides better stability to the permeability of plasma membranes and their functioning (Shahzad et al., 2022). Thus, floral stems treated with silicon are more resistant and rigid, facilitating the harvesting, classification, and packaging of flowers, making them less susceptible to wilting during post-harvest. Maintaining the turgor of floral stems during post-harvest is one of the determining factors in prolonging the longevity of cut flowers, as these characteristics are highly affected by the balance between water absorption and loss (Tofighi Alikhani, 2021). The longevity of tuberose stems (*Polianthes tuberosa* L.) was also positively affected after being cultivated with Si nanoparticles at concentrations of 400 mg L^{-1} (Karimian, Nazari & Samadi, 2021) and in roses treated with 800 g L^{-1} Si via soil (Geerdink et al., 2020).

The longevity of cut flowers is limited by various factors, such as the depletion of carbohydrate reserves due to respiration, transpiration, and ethylene production, fungal and bacterial infections, wilting, mechanical damage, storage temperature, and water quality (Costa et al., 2021). The experiment was conducted during the spring (October to December), a period of high temperatures which may have negatively affected the longevity of the stems. Previous studies reported greater longevity of zinnias when grown during the fall-winter period in the region, when temperatures are lower (Martins et al., 2021a). Environmental factors, such as temperature and relative humidity, have been documented to have a strong correlation with flower longevity due to their influence on stomatal function, transpiration rate, and water relationship, all of which are important for flower longevity (Kalinowski, Moody & Dole, 2022).

The variation in fresh weight and water absorption rate are directly associated with the longevity of the stems. As water absorption decreases, the fresh mass of the stems tends to decrease, leading to flower senescence (Martins et al., 2021a). Some studies have investigated the positive effects of Si on the longevity and quality of different cut flower species (Geerdink et al., 2020; Karimian, Nazari & Samadi, 2021; Song et al., 2021). However, there is still limited information available on the effects of Si on cut flowers grown under water stress conditions.

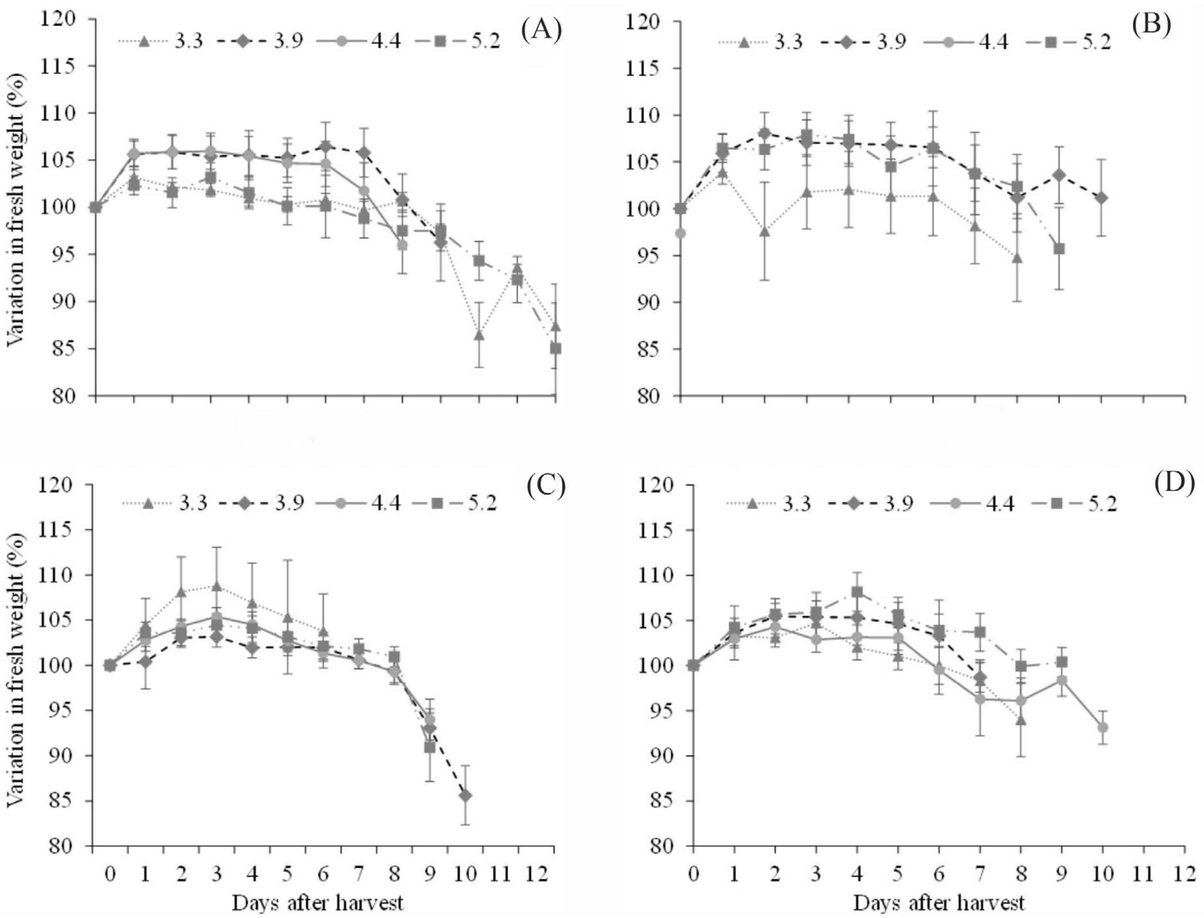


Figure 11: Variation in fresh weight (%) during the post-harvest period of zinnia stems cv "Red California Giant," under potassium silicate concentrations of (A) 0, (B) 75, (C) 150, and (D) 300 mg Si per plant and different irrigation levels (L per plant).

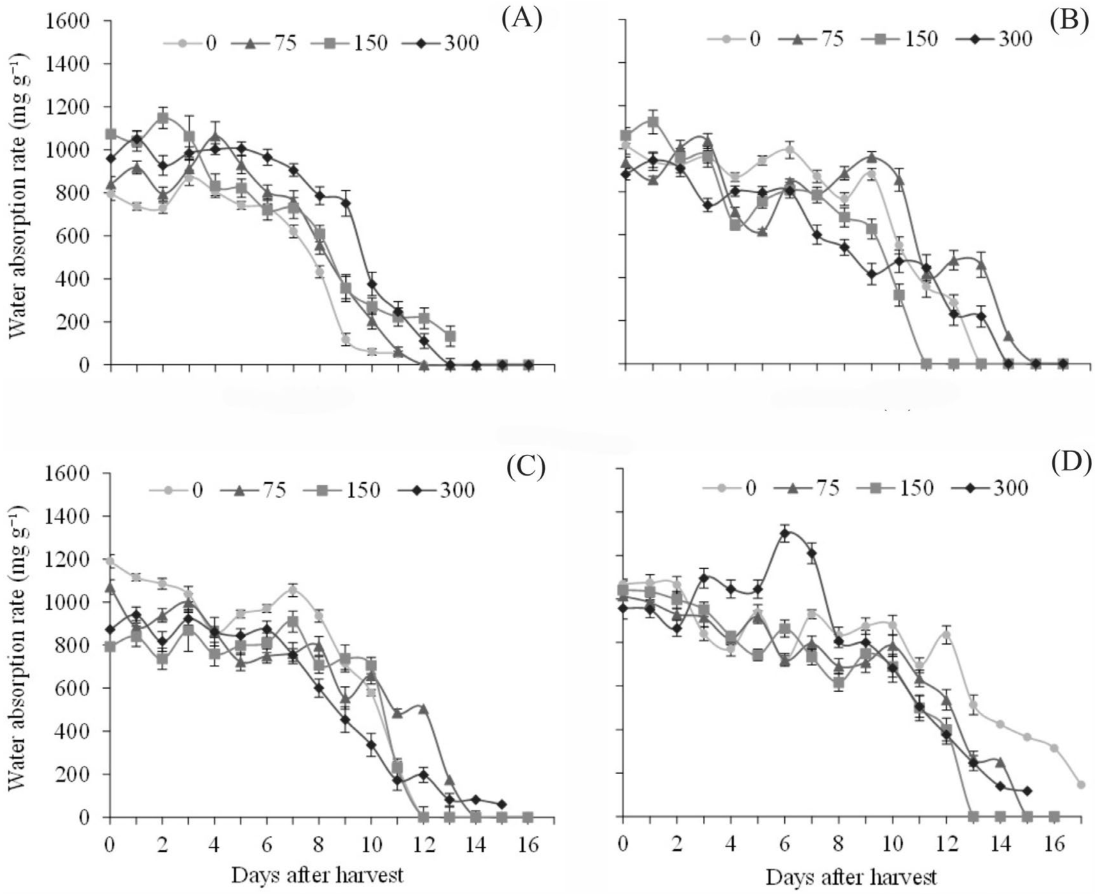
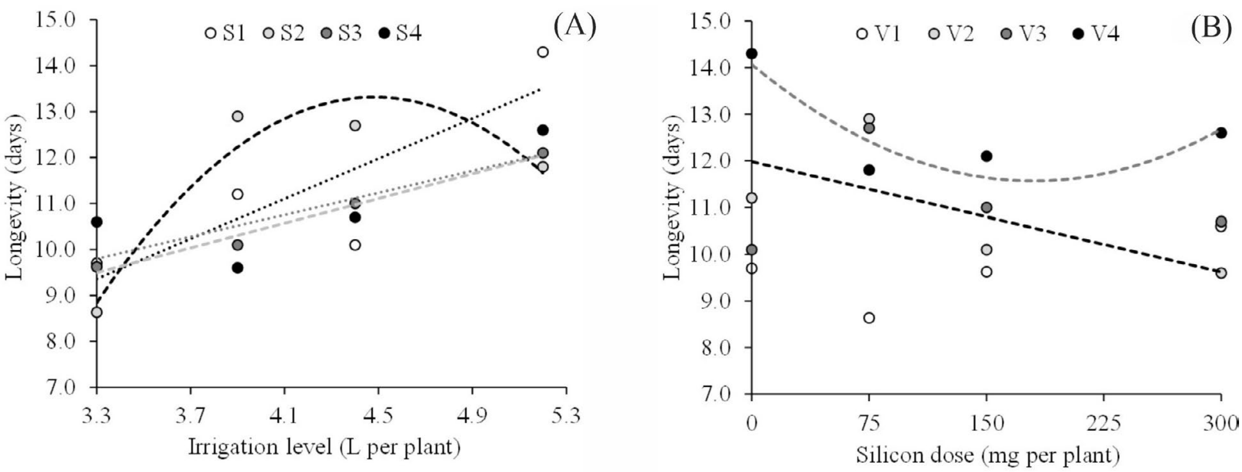


Figure 12: Variation in water absorption rate (mg g^{-1} of fresh stem weight) during post-harvest of zinnia cv "Red California Giant" floral stems obtained from plants grown under irrigation levels of (A) 3.3; (B) 3.9; (C) 4.4; and (D) 5.2 L per plant and different doses of silicon-based fertilization (mg Si per plant).



$L_{S1} = 2.1804\ IL + 2.1673\ \ (R^2 = 0.71)$

$L_{S2} = -3.1980\ IL^2 + 28.6690\ IL - 50.9368\ \ (R^2 = 0.93)$

$L_{S3} = 1.3441\ IL + 5.0611\ \ (R^2 = 0.98)$

$L_{S4} = 1.1959\ IL + 5.8523\ \ (R^2 = 0.59)$

$L_{V2} = -0.0078\ SD + 11.9800\ \ (R^2 = 0.76)$

$L_{V4} = 0.0001\ SD^2 - 0.0278\ SD + 14.0682\ \ (R^2 = 0.82)$

Figure 13: Total longevity (days) of zinnias cv "Red California Giant" cultivated under different irrigation levels (A) and Si doses (B).

Conclusions

Zinnia plants responded positively to irrigation levels, exhibiting higher values of stem length, total fresh mass of leaves and flowers. At the lowest and highest irrigation levels, the dose of 150 mg per plant caused an increase in fresh mass compared to treatments without Si supplementation, but the dose of 300 mg caused a negative effect. Applications of 150 mg of Si and full water replacement are recommended to increase the zinnia stem flower growth and longevity.

Author Contribution

Conceptual idea: Moreira, K. F. A.; Pêgo, R.G.; Shultz, N; Carvalho, D. F.; Methodology design: Moreira, K. F. A.; Pêgo, R.G.; Shultz, N; Carvalho, D. F.; Data collection: Moreira, K. F. A.; Pêgo, R.G.; Carvalho, D. F.; Data analysis and interpretation: Moreira, K. F. A.; Pêgo, R.G.; Shultz, N; Carvalho, D. F., and Writing and editing: Moreira, K. F. A.; Pêgo, R.G.; Shultz, N; Medici, L.; Carvalho, D. F.

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