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Horticultural Science/ Original Article

Silicon accumulation in cauliflower grown in a protected environment with different water availability conditions

Abstract – The objective of this work was to determine the accumulation of silicon in the plant components of cauliflower (*Brassica oleracea* var. *botrytis*) grown with different levels of water replacement and rates of Si. The experimental design was a randomized complete block with three water replacement conditions (40, 70, and 100% evapotranspiration), four Si rates (0, 50, 100, and 150 kg ha^{-1}), and four replicates. Daily evapotranspiration was determined with constant water table lysimeters, with water replacement by a drip system. As a source of Si, silicon oxide was applied three times in the crop cycle – at the initial, intermediate, and final development stages of the plant. At the end of the cycle, samples of plant tissue (root, stem, leaves, and inflorescence) and soil were collected to determine Si by spectrometry. The Si content in the soil was not influenced by water replacement, only by silicate fertilization. The silicon applied to the soil increased the content of the element in the plant components, especially in the roots. Water replacement influences the accumulation of Si in cauliflower plant tissues, with lower amounts of the element under water deficit conditions.

Index terms: *Brassica oleracea* var. *botrytis*, beneficial element, irrigation.

Acúmulo de silício em couve-flor cultivada em ambiente protegido com diferentes condições de disponibilidade hídrica

Resumo – O objetivo deste trabalho foi determinar o acúmulo de silício nos componentes vegetais de couve-flor (*Brassica oleracea* var. *botrytis*) cultivada com diferentes níveis de reposição hídrica e doses de Si. O delineamento experimental foi em blocos ao acaso, com três condições de reposição hídrica (40, 70 e 100% da evapotranspiração), quatro doses de Si (0, 50, 100 e 150 kg ha^{-1}) e quatro repetições. Determinou-se a evapotranspiração diária com lisímetros de lençol freático de nível constante, com reposição da água por sistema de gotejamento. Como fonte de Si, o óxido de silício foi aplicado três vezes no ciclo da cultura – nos estágios inicial, intermediário e final de desenvolvimento da planta. Ao final do ciclo, foram coletadas amostras de tecido vegetal (raiz, caule, folhas e inflorescência) e solo para determinação de Si por espectrometria. O teor de Si do solo não foi influenciado pela reposição hídrica, apenas pela adubação silicatada. O silício aplicado no solo aumentou o teor do elemento nos componentes da planta, principalmente nas raízes. A reposição hídrica influencia o acúmulo de Si nos tecidos da planta de couve-flor, com menor teor do elemento em condições de deficit hídrico.

Termos para indexação: *Brassica oleracea* var. *botrytis*, elemento benéfico, irrigação.

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Introduction

Silicon, although not considered an essential element for plants, is beneficial for their growth and development under unfavorable physicochemical conditions, as well as under biotic and abiotic stresses (Menegale et al., 2015; Kaushik & Saini, 2019). In plants, the transport of elements occurs through the xylem, but the required regulation is not well known and carriers have been identified only in a few species (Savvas & Ntatsi, 2015; Yan et al., 2018).

Under conditions of tropical and subtropical climate, the availability of Si is low due to soil characteristics, which makes it necessary to use mineral sources to increase the levels of the element for the long term (López-Pérez et al., 2018; Yan et al., 2018). In vegetable cultivation, the use of silicate fertilizers has resulted in yield, commercial, and post-harvest quality (Barreto et al., 2017; Lozano et al., 2018; Nunes et al., 2019). However, these benefits are associated with the extraction capacity of the plant, which is influenced by Si availability in the soil and form of application, as well as by the used plant species (Menegale et al., 2015).

In species that do not accumulate the element – such as cauliflower (*Brassica oleracea* var. *botrytis* L.), with an accumulation from 0.2 to 0.4% in relation to dry mass –, silicate fertilization also contributes to increments in yield indexes (Matichenkov et al., 2008; Yan et al., 2018). However, information related to the accumulation of Si in different plant tissues in cauliflower and to the influence of water conditions in the extraction of this element by the plant are still little known.

The objective of this work was to determine the accumulation of silicon in the plant components of cauliflower grown with different levels of water replacement and rates of Si.

Materials and Methods

The study was carried out at the Technical Irrigation Center of Universidade Estadual de Maringá, located in the municipality of Maringá, in the state of Paraná, Brazil. The region presents annual rainfall between 1,400 and 1,600 mm, temperature between 21.1 and 22.0°C, evapotranspiration from 1,000 to 1,100 mm, and solar radiation from 14.5 to 15.0 MJ m^{-2} per day (Nitsche et al., 2019).

The experiment was performed in a greenhouse, using a randomized complete block design. The treatments were characterized in a 3x4 factorial arrangement, with three levels of water replacement – 40, 70, and 100% evapotranspiration (ETc) – and four Si rates – 0, 50, 100, and 150 kg ha^{-1} –, with four replicates per treatment. To define the applied rates, the study of Lozano et al. (2018) with the same soil was considered.

In the greenhouse, the Sharon cauliflower hybrid was seeded in polystyrene trays with 128 cells containing the Horta-1 commercial substrate (MecPlant, Telêmaco Borba, PR, Brazil) with 16 mg dm^{-3} Si. After 35 days, the seedlings were transplanted to 3.0×0.5 m beds, each with six plants, and the useful portion consisted of the three central plants. The soil of the beds was characterized as a Nitossolo Vermelho distroférrico (Santos et al., 2018), corresponding to a Nitosol (IUSS Working Group WRB, 2015) or an Ultisol (Soil Survey Staff, 2014), with a very clayey texture, with 720 g kg^{-1} clay, 160 g kg^{-1} silt, 70 g kg^{-1} fine sand, and 50 g kg^{-1} coarse sand. The Si content ($CaCl_2$ 0.01 mol dm^{-3}) before cultivation was 15.7 mg dm^{-3}. Soil chemical characterization is presented in Table 1. The soil showed an average density of 1.09 Mg m^{-3}, with

Table 1. Chemical characterization of the soil used in the cauliflower (*Brassica oleracea* var. *botrytis*) seedling beds.

Parameter[(1)]	Value
pH in $CaCl_2$	6.70
pH SMP	7.10
Al (cmol$_c$ dm^{-3})	0.00
Hydrogen (cmol$_c$ dm^{-3})	2.17
Ca (cmol$_c$ dm^{-3})	12.31
Mg (cmol$_c$ dm^{-3})	2.70
K (cmol$_c$ dm^{-3})	0.92
CEC at pH 7.0 (cmol$_c$ dm^{-3})	18.10
Effective CEC (cmol$_c$ dm^{-3})	15.93
Soil organic matter (%)	1.99
P (mg dm^{-3})	98.88
Remaining P (mg dm^{-3})	18.96
S (mg dm^{-3})	129.70
B (mg dm^{-3})	0.06
Cu (mg dm^{-3})	14.70
Fe (mg dm^{-3})	71.16
Mn (mg dm^{-3})	150.18
Zn (mg dm^{-3})	9.66

[(1)]CEC, cation exchange capacity. Source: AgriSolum Análises Agronômicas, Maringá, PR, Brazil.

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a base fertilization of 30 kg ha^{-1} N, 250 kg ha^{-1} P_2O_5, 100 kg ha^{-1} K_2O, and 4.0 kg ha^{-1} B, according to the recommendations for the crop (Pauletti & Motta, 2017).

Daily ETc was estimated with lysimeters with a constant water table with compensation inside the greenhouse, according to the methodology adopted by Lozano et al. (2018). Water replacement was performed with a polyethylene tube with drippers spaced 0.25 m apart, with a flow of 5.0 L h^{-1}, a service pressure of 20 m, and Christiansen's uniformity coefficient equal to 94%. In the beds with 100% replacement of ETc, soil water tension was monitored using digital tensiometers (Hidrodinâmica Irrigação, Piracicaba, SP, Brazil) installed at 0.05 and 0.15 m depths, and water replacement was performed when the tension was close to 30 kPa (Marouelli, 2008). The water used for irrigation was semi-artesian, with pH 7.78, conductivity of 158.55 μS cm^{-1}, and 45.94 mg L^{-1} dissolved silica (SiO_2). During the cycle, 32.35, 56.61, and 80.87 L, respectively, were used for the water replacements of 40, 70, and 100% ETc.

To supply the plants with Si, silicon oxide was used, being obtained from the product Agrisil with 98% SiO_2 (AgriSil, Agrobiológica: Soluções Naturais, Leme, SP, Brazil). The product diluted in 2.0 L water was added to soil surface, and its volume was discounted in irrigation. The rate was applied three times: in the initial, intermediate, and final development stages of the plants (Allen et al., 1998).

To determine Si content in the soil, samples were collected from plants from the useful area before and after cauliflower cultivation, and calcium chloride (0.01 mol dm^{-3}) was used as an extractor, following the method described by Korndörfer et al. (2004). At crop harvest, samples of root, stem, leaf, and inflorescence were collected to determine the accumulation of dry matter and the concentration of Si in the plant tissues according to Silva (2009). The data were subjected to the analysis of variance by the F-test, with 5% significance, and to the regression analysis. For the statistical analysis, the Sisvar software was used (Ferreira, 2019).

Results and Discussion

Water replacement did not have a significant effect on Si levels in the soil after cauliflower cultivation (Figure 1). The water used for irrigation can add or remove Si and other nutrients in the soil. In the case of the present study, the amount of total Si added through the water was considered low since the used Si rates were of 50, 100, and 150 kg ha^{-1}.

Although Si can be leached into the soil (Menegale et al., 2015; Kaushik & Saini, 2019) and irrigation with criteria only allows the replacement of the amount lost by evapotranspiration, the losses of the element were minimal even in treatments with 100% ETc replacement, being even lower under water deficit conditions. In a study on a Latossolo Vermelho distroférico, corresponding to an Oxisol, in an area without the application of Si sources, the maximum content of the element was 21.84 mg dm^{-3} (Gutierrez et al., 2011), which is similar to that obtained in the present study in the treatment without Si application (Figure 1).

The application of silicon oxide increased the content of Si in the soil by 128.19, 165.33, and 232.81%, respectively, at the rates of 50, 100, and 150 kg ha^{-1} (Figure 1). This increase led to a significant increase in the content of the element in cauliflower roots, stem, leaves, and inflorescence. Therefore, the Si content in the soil directly influences the absorption of the

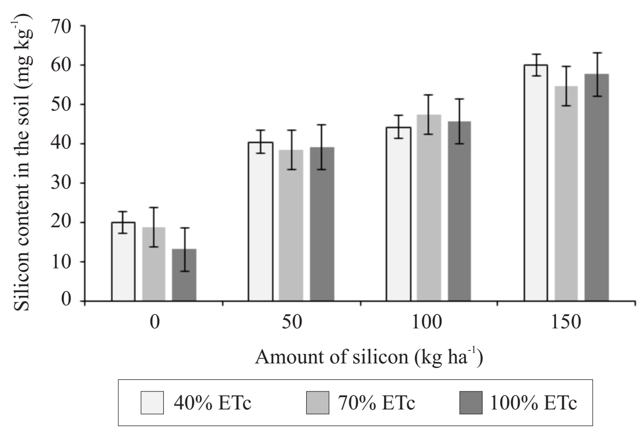

Figure 1. Silicon content in the soil – a Nitossolo Vermelho distroférrico, corresponding to a Nitosol or an Ultisol – of the experimental area after the cultivation of cauliflower (*Brassica oleracea* var. *botrytis*) under different water replacement conditions (40, 70, and 100% evapotranspiration, ETc) and Si rates (0, 50, 100, and 150 kg ha^{-1}).

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element by the plants, and Si extraction by calcium chloride allows determining the amount available (Gutierrez et al., 2011).

In cauliflower vegetative tissues, the highest levels of Si accumulation were found in the roots (0.5 to 2.19) and the lowest ones in the leaves (0.29 to 0.9) (Figure 2). The distribution of nutrients in plant components is associated with nutrient mobility and plant metabolism (Cardoso et al., 2016). In the initial period of plant development, macro- and micronutrients accumulate in the stem, and, at the beginning of the reproductive period, the nutrients are drained to the inflorescence, from where they are redistributed to the other plant components (Alves et al., 2011). Although the inflorescence stands out in the process of nutrient redistribution, the plant tissue can show a rapid polymerization of Si, especially in older cells, where the element was redistributed to mainly from new tissues with active cells (Bauer et al., 2011). Therefore, since remobilization occurs chiefly in the leaves of the inflorescence, the presence of higher

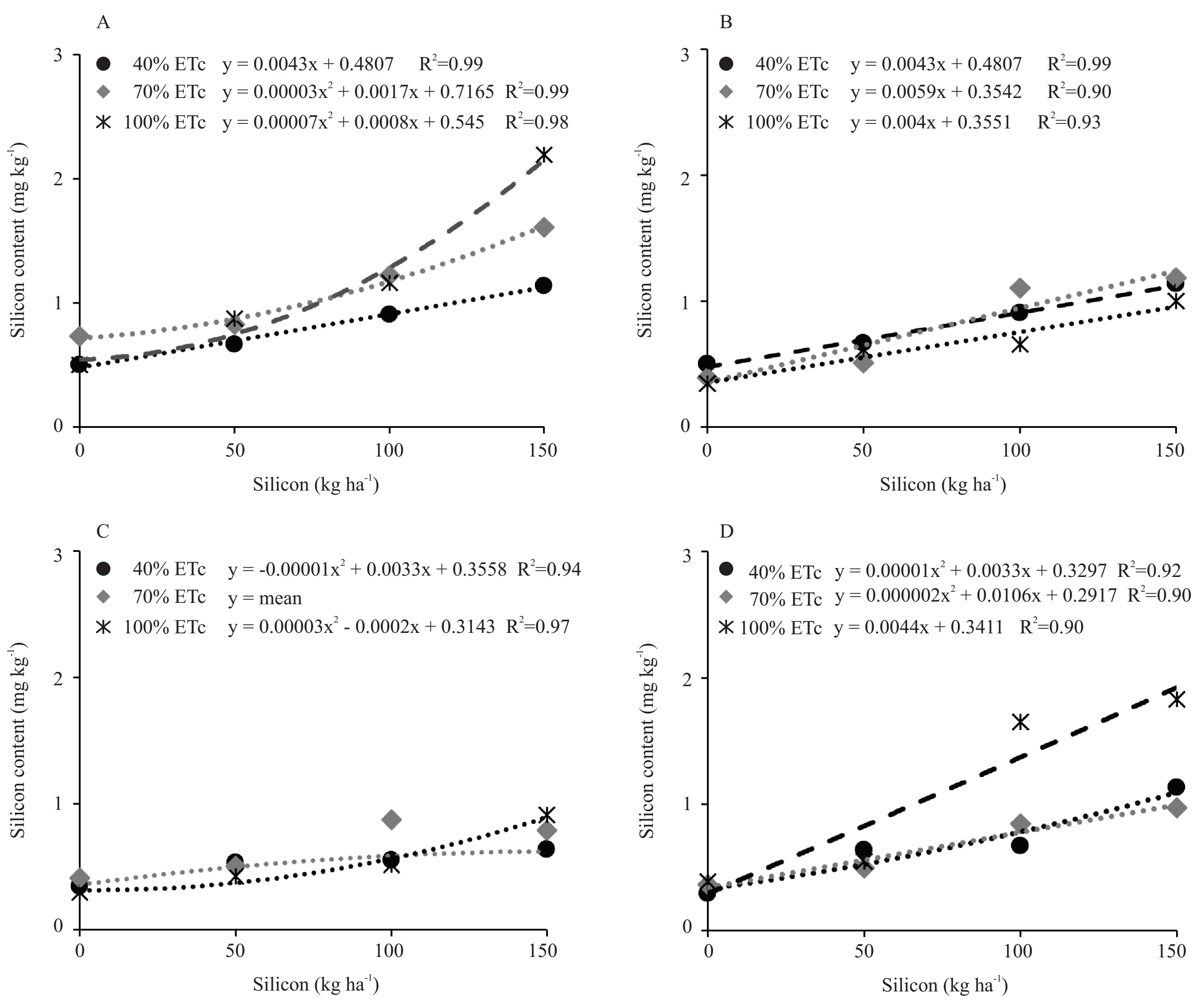

Figure 2. Silicon accumulation due to the addition of the element to the soil in the roots (A), stem (B), leaves (C), and inflorescence (D) of cauliflower (*Brassica oleracea* var. *botrytis*) under different water replacement conditions (40, 70, and 100% evapotranspiration, ETc).

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levels of the nutrient is justified in more lignified tissues, such as roots and stem.

The addition of Si (98% SiO_2) at increasing rates to soil surface did not significantly increase the amount of Si in cauliflower leaves with the water replacement of 70% ETc (Figure 2). However, the increase in the element in the soil due to the added Si rates favored and potentiated the accumulation of Si in the plant components of cauliflower, with higher amounts in the roots and lower ones in the leaves. According to López-Pérez et al. (2018), the increase in Si absorption by vegetables increased their concentration of phytochemicals and antioxidants, and, consequently, the nutritional value of the product.

For flower crops, Si supplementation increased the accumulation of the element in the leaves from 13 to 145% in relation to the control (Mattson & Leatherwood, 2010). In melon (*Cucumis melo* L.), the application of Si increased nutrient absorption and yield, and the range considered ideal was from 52 to 104 kg ha^{-1} (Nascimento et al., 2020).

At the end of the cycle of the cauliflower plants grown without the application of silicon oxide and with 40% ETc water replacement, the total accumulation of Si in the shoot was between 40 and 51%, lower than that with the water replacements of 70 and 100% ETc (Figure 3) due to the lower water translocation caused by water restriction. Considering the total accumulation of Si in the aerial part of the plant, the addition of the element to the soil increased total extraction in all conditions of water replacement, with an accumulation of 299.5 mg per plant in the shoot when using 100% ETc and 150 kg ha^{-1} Si. This result is indicative that the Si contents added to the soil were exported to the plants (Figure 1), being absorbed by the roots and transported by the xylem to the stem, leaves, and inflorescence.

Although the application of Si has improved the post-harvest quality of leafy green vegetables (Guerrero et al., 2011; Galati et al., 2015), it is still unclear what are the possible implications for plant metabolic processes due to the interference of the Si accumulated in plant parts and what are the interactions and/or competition between nutrients and Si.

Regardless of the imposed water deficit, the application of increased Si rates also led to an increase in the dry mass of cauliflower plants (Figure 3). This Si benefit in plant biomass reflects the increase in the amount of the element in cauliflower roots and inflorescence (Figure 2), which suggests that the action of Si on the content of reactive oxygen species may have neutralized the stress imposed on the plant.

As for the increase in Si content in the aerial part of cauliflower, positive effects have been reported, including an increased yield and tolerance to physicochemical stress (Barreto et al., 2017). The action of the element is linked to adjustments in water potential, with a relative increase in leaf water contents, photosynthesis, antioxidant defense, and yield potential (Ahmed et al., 2013).

The quantification of Si content in horticultural plants as affected by the application of the element allows to determine the efficiency of the different sources and rates applied, taking into account the known benefits for the crop (Curvelo et al., 2019) and the growing demand for the element in horticulture (Savvas & Ntatsi, 2015).

The obtained results are indicative that cauliflower is responsive to the accumulation of processed Si in the soil and that the extraction of the element is influenced by the water management of the crop. New researches are important, both in cauliflower and in other species of interest, to analyze the efficiency of the application of Si through different methods and of different sources.

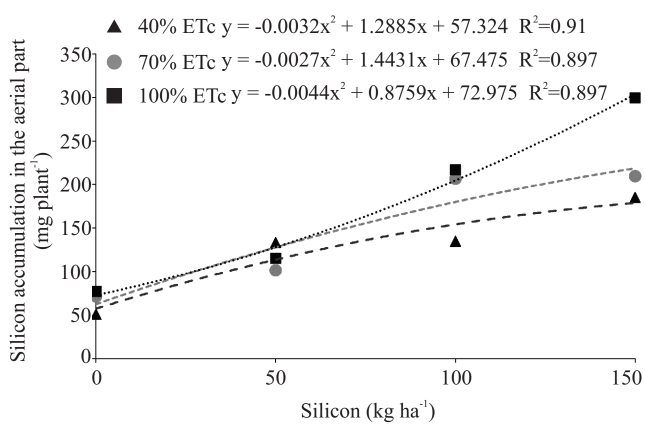

Figure 3. Total silicon accumulation in shoots of cauliflower (*Brassica oleracea* var. *botrytis*) under different water replacement conditions (40, 70, and 100% of evapotranspiration, ETc) and Si rates (0, 50, 100 and 150 kg ha^{-1}) added to the soil.

Conclusions

1. Water replacement influences the accumulation of silicon in cauliflower (*Brassica oleracea* var. *botrytis*) plant tissues, with lower amounts of the element under water deficit conditions.
2. The addition of Si to the soil increases the content of the element in cauliflower plant components, especially in the roots.
3. Water replacement does not influence Si content in the soil.

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