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FOLIAR SILICON IN TOLERANCE TO WATER DEFICIT IN BEANS

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ABSTRACT: Common bean (*Phaseolus vulgaris*) is sensitive to water deficit and silicon might promote better tolerance to this abiotic stress. In order to test this hypothesis, foliar silicon doses were used to evaluate the drought tolerance in common bean plants. The experiment was conducted in greenhouse, following a completely randomized block design in a 6 x 2 factorial, with 4 replicates. Six different silicon doses were used (0; 0,5; 1,0; 1,5; 2,0; 2,5 kg Si ha^{-1}) with or without water deficit in the flowering period. Two-liter pots were filled with sandy loam typic paleudalf soil, with automatic irrigation system. Forty-two days after sowing, leaf temperature (LF) was daily analyzed, and at the end of the cycle, parameters such as silicon content in soil and in trifoliate leaves, plant height, shoot dry mass (SDM), shoot fresh mass (SFM), root fresh mass (RFM) and root dry mass (RDM), grain yield per plant, grain yield per pod, pod yield per plant, pod length, fresh and dry grain mass, were evaluated. After stress, absolute integrity percentage (AIP) and relative water content (RWC) were determined. The water condition decreased the number of grains /plants, pods / plant, fresh and dry grain mass and AIP, and increased RWC and LT. Silicon doses did not affect tolerance to water deficit applied to bean plants.

KEYWORDS: *Phaseolus vulgaris*, sustainability, abiotic stress, water stress.

SILÍCIO FOLIAR NA TOLERÂNCIA AO DÉFICIT HÍDRICO NO FEIJÃO

RESUMO: O feijoeiro comum, *Phaseolus vulgaris*, é sensível à deficiência hídrica, e o silício pode promover maior tolerância a esse estresse abiótico. Para testar essa hipótese, objetivou-se avaliar doses de silício foliar na tolerância ao déficit hídrico em feijão. O experimento foi conduzido em casa de vegetação, com delineamento experimental de blocos inteiramente casualizados em esquema fatorial 6 x 2 com quatro repetições. Utilizou-se seis doses de silício (0; 0,5; 1,0; 1,5; 2,0; 2,5 kg Si ha^{-1}) com e sem deficiência hídrica na floração. Os vasos com capacidade de 2 L foram preenchidos com Argissolo Vermelho distrófico, mantidos com irrigação automática. A partir dos 42 dias após a semeadura, analisou-se diariamente a temperatura foliar (TF) e no final do ciclo determinou-se o teor de silício no solo e nos trifólios, a altura das plantas, a massa fresca e seca da parte aérea e raízes, o número de grão/planta, de grãos/vagem, de vagens/planta, o comprimento de vagens e a massa fresca e seca de grãos. Após o estresse, determinou-se a porcentagem de integridade absoluta (PIA) e o conteúdo relativo de água (CRA). A condição hídrica diminuiu o número de grãos/planta, vagens/planta, massa fresca e seca dos grãos e PIA, e aumentou o CRA e TF. O silício não influenciou na tolerância a deficiência hídrica aplicada às plantas de feijão.

PALAVRAS CHAVE: *Phaseolus vulgaris*, sustentabilidade, estresse abiótico. estresse hídrico.

INTRODUCTION

Common bean, *Phaseolus vulgaris*, is one of the most important grains in Brazilian agriculture, with production in the 2019/2020 harvest of 3,229.8 million tons (Conab, 2020). In addition to its economic importance, it has also cultural and social importance, being present in the daily diet of most Brazilian families. Brazilian *per capita* bean consumption is 200.8 g day^{-1} (Bezerra et al., 2013).

The average Brazilian productivity is 1,104 kg ha^{-1} (Companhia Nacional de Abastecimento, 2020), while it can reach over 3,000 kg ha^{-1} in irrigated crops (Silva et al., 2011). However, it is still below its productive potential. Among the factors that limit productivity, abiotic stresses, such as water deficit, stand out (Aguiar et al., 2008). Climatic oscillations, especially dry seasons and poor rainfall distribution, have frequently occurred in the state of Rio Grande do Sul. Out of every ten years, seven are water-deficient. Therefore, there is a need to use alternatives to continue with the cultivation of beans in a sustainable way (Secretaria da Agricultura, Pecuária e Agronegócio, 2014).

Silicon (Si) is not considered an essential element for most plants, as species complete their life cycle without it. Still, some plants accumulate this element in their cell walls, contributing to resistance to pathogens, insects and abiotic stresses, increasing crop yields and reducing heavy metal toxicity (Eneji et al., 2008; Shen et al., 2010; Taiz and Zeiger, 2013; Teodoro et al., 2015). Si is deposited below the cuticle of leaves, forming a double layer that reduces transpiration, leading the plant to better tolerate water deficit (Ma et al., 2001). There is no evidence demonstrating the involvement of this element in plant metabolism. Therefore, its function is probably mechanical and the effects are more visible under conditions of biotic and abiotic stresses (Ma et al., 2001). Si concentration in plants varies between species and generally monocotyledonous accumulate more than dicotyledonous. However, soybean has already been defined as a Si accumulating plant (Hodson et al., 2005).

The study on silicate fertilization in bean production is essential to elucidate the rural producer about its possible benefits under water stress conditions. Thus, the aim of this study was to evaluate the effects of foliar silicon doses on water deficit tolerance in common beans.

MATERIAL AND METHODS

The experiment was carried out in greenhouse at the State University of Rio Grande do Sul, located in Cachoeira do Sul/RS, from January to April 2017. The 'Minuano' cultivar, from Embrapa, belonging to the commercial group of black beans widely cultivated by farmers in the region, was used. The experimental design used was completely randomized blocks, in a 6 x 2 factorial scheme with four replicates. Plots were conducted with single foliar application of six silicon doses (Si): 0; 0.5; 1.0; 1.5; 2.0; 2.5 kg Si ha^{-1}, with and without water deficit at flowering, applied in the morning on the same day as the beginning of water deficit. As source of Si, the Potency product with 68.1% silicon, 6% calcium, 5.7% phosphorus, 5.2% potassium, 4.4% magnesium, 4% iron, 2% molybdenum, 2% zinc and 1% cobalt was used. The concentrations of the other nutrients present in the product, applied in treatments, were corrected in each plot.

The substrate used was the dystrophic Red Argisol, whose characteristics were determined by chemical analysis, showing 1.5 mg dm^{-3} of P; 34 mg dm^{-3} of K; 0 cmolc dm^{-3} of Al; 6.2 cmolc dm^{-3} of Ca; 3.1 cmolc dm^{-3} of Mg; 2.2 cmolc dm^{-3} of H+Al; 11.6 cmolc dm^{-3} CEC; pH = 7.9; 4 cmolc dm^{-3} of effective CEC; 2.4% organic matter; 30% clay and pH 6.5 and corrected according to recommendations from the Fertilization and Liming Manual (Cqfs-RS/SC, 2016). The soil was collected in the 0-25 cm layer, air dried, sieved in a 5 cm mesh and placed in 2-L PET bottle pots, coated with black paint, which constituted the plots.

Irrigation was automatic, controlled by Arduino with soil moisture sensors. The command tension was defined from the soil water tension curve (Knies, 2010). Plots corresponding to the absence of water deficit were irrigated according to the crop needs throughout the cycle. Plots corresponding to the presence of water deficit were irrigated as needed until flowering (R6), when water deficit was imposed up to 42.81 mm of accumulated reference evapotranspiration (ETo), daily calculated through data from the Automatic Station A803 of the National Institute of Meteorology using the SMAI software. The water deficit lasted 13 days, from 03/11/2017 to 03/23/2017. After this period, irrigation was resumed as needed by the crop until the end of the cycle.

At 42 days after sowing, water deficit was started and leaf temperature was daily measured at 12h (±1h) until the end of the plant cycle, using infrared thermometer in the central leaflet of the trifoliate leaf located in the upper third of the plant. Protoplasmic tolerance (Vasquez-Tello et al., 1990) and relative water content (Barrs and Weatherley, 1962) were evaluated in random trifoliate leaves in the plant on the last day of water deficit (beginning of the R7 stage - pod formation). At the end of the cycle (99 days after sowing), plants were evaluated for height, shoot and root fresh and dry mass, number of grains/plant, number of grains/pod, pod length and fresh and dry grain mass. Si content was determined in trifoliate leaves of the middle third of bean plants and in the soil (Korndörfer et al., 2004), in the Laboratory of the Department of Soils and Environmental Resources of the Faculty of Agricultural Sciences of UNESP, Botucatu/SP.

Results were submitted to analysis of variance (ANOVA) and the interaction between Si doses and water conditions was analyzed, when significant. The effects of Si doses were submitted to regression analysis, testing the linear and quadratic models and the effects of water deficit were submitted to the F test at 0.05 error probability, using the Sisvar statistical software (Ferreira, 2011). Pearson's linear correlation was also determined using the Excel version 2007 software.

RESULTS AND DISCUSSION

The water condition significantly affected the relative water content (RWC) of beans, with higher values under water deficit, while Si doses did not differ significantly (Table 1). Trifoliate leaves have the ability to absorb water through the relative air humidity, and the collection of trifoliate leaves for analysis at dawn may not be recommended, which resulted in higher RWC in plants under water deficit. RWC is considered an indicator of the plant's water conditions, which corresponds to the amount of water in its tissues at a given moment, compared to the maximum amount of water it can retain (Angelocci, 2002). Plants under water deficit have lower photosynthetic rates due to the closing of stomata to withstand water scarcity, which reduces the production of photoassimilates, confirmed by the lower number of grains per plant (Table 2). The random collection of trifoliate leaves for analysis may have influenced higher RWC in plants under water deficit. In a study carried out by Mariano et al. (2009), it was observed that the collection of leaves in different thirds of plants can result in greater or lesser RWC, thus, random collection is not the indicated methodology.

Table 1. Relative water content (RWC), absolute integrity percentage (AIP) at the R7 stage in beans, plant height, root length (CR), shoot and root fresh and dry mass (MFPA, MSPA, MFR, MSR) at the end of the bean cycle.

Water Condition	RWC	AIP	Height	CR	MFPA	MSPA	MFR	MSR
	%	%	cm	cm	g	g	g	g
No water deficiency	49.71 B	0.75 A	114.29	19.65	4.83	1.87	2.96	1.03
Water deficiency	56.61 A	0.65 B	80.13	20.27	4.46	1.65	2.80	1.04
CH	*	*	ns	ns	ns	ns	ns	ns
D	ns	ns	ns	ns	ns	ns	ns	ns
CH*D	ns	*	ns	ns	ns	ns	ns	ns
CV (%)	24.77	15.87	62.11	16.04	38.18	23.86	41.80	42.72

F test for water condition (CH), for doses (D) and for interaction between water condition and doses (CH*D). Capital letters in averages mean significant difference between water conditions ns: not significant at 0.05 error probability level. * significant at 0.05 error probability level.

Table 2. Pod length (CV), beans per plant (G/P), beans per pod (G/V), fresh and dry mass of beans (MFG, MSG), pods per plant (V/P), silicon content in leaf tissue (SI TF) in g kg -1 and in % and silicon content in soil.

Water Condition	CV	G/P	G/V	MFG	MSG	V/P	Si TF	Si TF	Si solo
	cm	un	un	g	g	un	g kg^{-1}	%	mg dm^{-3}
No water deficiency	9.44	33.17A	4.7	8.17A	7.30A	7.21A	17.55	1.76	12.09
Water deficiency	9.50	23.83 B	5.02	5.38B	4.68B	4.79B	18.56	1.85	11.60
CH	ns	*	ns	*	*	*	ns	ns	ns
D	ns	ns	ns	ns	ns	ns	ns	ns	ns
CH*D	ns	ns	ns	ns	ns	ns	*	*	ns
CV (%)	12.05	29.33	16.33	40.58	40.32	30.87	13.01	12.7	8.06

F test for water condition (CH), for doses (D) and for interaction between water condition and doses (CH*D). Capital letters in averages mean significant difference between water conditions ns: not significant at 0.05 error probability level. * significant at 0.05 error probability level.

Table 3. Leaf temperature of bean plants during water deficit (CDH) and after water deficit suspension (SDH).

Water Condition	**Leaf temperature**				
	1st week CDH	**2nd week CDH #**	**1st week SDH**	**2nd week SDH**	**3rd week SDH ¨**
No water deficiency			ºC		
	20.82	20.93	22.62 B	23.37 B	22.02 B
Water deficiency	23.83	24.32	24.90 A	24.65 A	22.83 A
CH	*	*	*	*	*
D	ns	ns	ns	ns	ns
CH*D	*	*	ns	ns	ns
CV (%)	8.4	7.95	5.27	6.67	4.45

F test for water condition (CH), for doses (D) and for interaction between water condition and doses (CH*D). Capital letters in averages mean significant difference between water conditions ns: not significant at 0.05 error probability level. * significant at 0.05 error probability level.

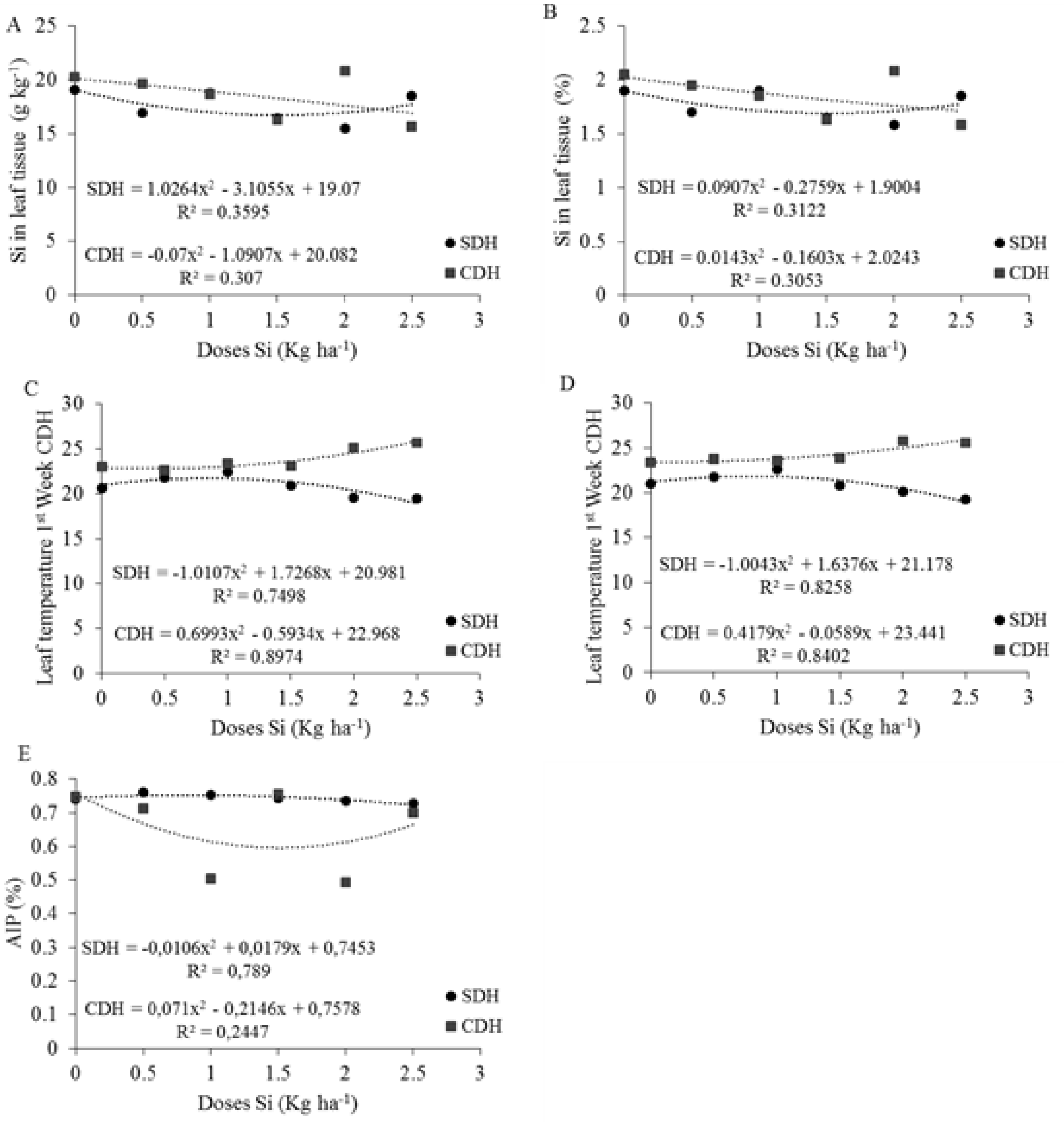
In plants with water deficit, Pearson's correlation for parameters RWC and number of grains plant-1 was 0.61 (Table 4). However, stressed plants showed lower productivity (Table 2). There was no statistical difference for plant mass, which may have occurred because Si was applied in pre-flowering and stress started at flowering, so the morphological conditions of plants were already established, unlike productive characteristics, such as the number of grains per plant (Table 2).

Table 4. Pearson correlation between response variables relative water content (RWC), absolute integrity percentage (AIP), height, root length (CR), shoot (MFPA, MSPA) and root (MFS, MSR) fresh and dry mass, pod length (CV), beans per plant (G/P), beans per pod (G/V), fresh and dry mass of beans (MFG, MSG), pods per plant (V/P), foliar (Si TF) and soil (Si soil) silicon content in the water condition without water deficit (SDH) and with water deficit (CDH).

SDH/CDH	RWC	AIP	Height	CR	MFPA	MSPA	MFR	MSR
RWC	-	-0.08/0.73	0.25/0.02	-0.28/-0.26	0.28/0.66	-0.24/-0.10	0.68/0.32	0.59/0.67
AIP	-	-	0.15/-0.25	0.15/-0.68	0.32/0.49	0.80/0.12	0.28/0.11	0.59/0.41
Height	-	-	-	-0.44/0.76	-0.60/-0.29	0.13/0.45	-0.30/-0.56	-0.21/-0.59
CR	-	-	-	-	0.66/-0.24	0.62/-0.09	0.00/-0.56	0.06/-0.45
MFPA	-	-	-	-	-	0.41/-0.23	0.64/0.26	0.73/0.57
MSPA	-	-	-	-	-	-	-0.02/-0.10	0.29/-0.64
MFR	-	-	-	-	-	-	-	0.88/0.68
MSR	-	-	-	-	-	-	-	-
CV	-	-	-	-	-	-	-	-
G/P	-	-	-	-	-	-	-	-
G/V	-	-	-	-	-	-	-	-
MFG	-	-	-	-	-	-	-	-
MSG	-	-	-	-	-	-	-	-
V/P	-	-	-	-	-	-	-	-
Si TF	-	-	-	-	-	-	-	-
Si soil	-	-	-	-	-	-	-	-
SDH/CDH	CV	G/P	G/V	MF grains	MS grains	V/P	Si TF	Si soil
RWC	-0.55/0.26	-0.21/0.61	0.08/0.16	-0.52/0.81	-0.57/0.78	-0.23/0.47	0.43/0.21	-0.28/-0.36
AIP	0.71/-0.07	-0.32/0.29	-0.87/0.00	0.09/0.69	0.15/0.64	0.59/0.43	-0.62/-0.4	-0.61/-0.09
Height	0.09/0.71	-0.07/0.63	0.31/0.62	0.10/0.43	-0.09/0.42	0.17/0.59	-0.08/-0.17	-0.15/0.58
CR	0.11/0.40	0.77/0.29	-0.23/0.21	0.76/0.00	0.85/0.04	0.75/0.20	-0.63/0.22	-0.04/0.12
MFPA	-0.12/-0.47	0.16/0.51	-0.60/-0.60	0.05/0.54	0.19/0.62	0.36/0.45	-0.31/0.31	-0.23/-0.59
MSPA	0.57/0.24	0.27/0.43	-0.63/0.39	0.64/0.26	0.66/0.26	0.94/0.51	-0.92/-0.53	-0.38/0.90
MFR	-0.04/-0.07	-0.31/-0.14	-0.44/-0.04	-0.54/-0.20	-0.42/-0.21	-0.09/-0.42	0.33/0.62	-0.67/-0.37
FSR	0.04/-0.12	-0.43/-0.08	-0.74/-0.21	-0.45/0.13	-0.35/0.11	0.11/-0.28	-0.04/0.60	-0.02/-0.65
CV	-	-0.11/0.31	-0.51/0.96	0.28/0.30	0.35/0.20	0.48/0.15	-0.40/0.04	-0.61/0.38
G/P	-	-	0.41/0.19	0.84/0.85	0.83/0.90	0.57/0.91	-0.34/0.02	0.14/0.20
G/V	-	-	-	0.11/0.21	-0.02/0.10	-0.36/0.09	0.50/0.14	0.43/0.55
MFG	-	-	-	-	0.97/0.99	0.81/0.88	-0.73/0.22	0.10/0.07
MSG	-	-	-	-	-	0.83/0.91	-0.73/-0.18	0.02/0.04
V/P	-	-	-	-	-	-	-0.86/-0.36	-0.36/0.34
Si TF	-	-	-	-	-	-	-	-0.02/-0.65
Si soil	-	-	-	-	-	-	-	-

The lowest absolute integrity percentage (AIP) values were recorded in plants under water deficit, at Si doses 1 and 2 kg ha^{-1} (Table 1, Figure 1E), thus presenting lower electrolyte retention, not being efficient for protecting cell integrity. There is increase in the release of electrolytes by the plant when submitted to water stress (Pimentel et al., 2002). During water stress, plants show changes in electron transport mediated by superoxide radicals (Taiz and Zeiger, 2013), causing reduction in photosynthetic activities and imbalances in electron transport.

Figure 1. Relationship between Si doses and Si content in leaf tissue (g kg^{-1}) (A), Si content in leaf tissue (%) (B), leaf temperature in the 1st Week CDH (ºC) (C), leaf temperature in the 2nd Week CDH (ºC) (D) and absolute integrity percentage (AIP) (%) (E) in water conditions without water deficit (SDH) and with water deficit (CDH).



The water conditions and silicon doses did not contribute to significant differences in height, root length and shoot and root fresh and dry mass, probably because water deficit was imposed at flowering and lasted only 13 days, thus, the vegetative characteristics were already established (Table 1). Similarly, but without water deficit, Si doses in sunflower did not influence plant height and shoot dry mass (Oliveira et al., 2013).

Discordant results regarding morphological characteristics and water deficit were found in literature. In wheat plants, water deficit at flowering promoted by irrigation suspension caused a decrease in shoot height and dry mass (Santos et al., 2012).

Significant reduction of 28.16% was observed for number of grains per plant, 33.56% for number of pods per plant, 34.15% for fresh weight of grains and 35.89% for the dry weight of grains under water deficit condition compared to condition without water deficit (Table 2). No significant difference between Si doses was observed for these variables. These results are similar to those found for doses of 30 g L^{-1} of rocksil, 20 g L^{-1} of saborsil AC77 and 30 g L^{-1} of potassium silicate, since Si did not provide significant difference in the number of pods per plant and number of grains per pod in common bean plants (Teixeira et al., 2008). Likewise, doses between 0 and 500 kg ha^{-1} also did not significantly increase grain yield and number of seeds per pod in soybean plants (Pereira Júnior et al., 2010).

Soil Si content did not differ significantly between treatments at mean values of 11.84 mg dm^{-3} (Table 2). Even when Si was applied, levels exceeded those obtained by other authors, such as 5.9 mg dm^{-3} in dystrophic Red Latosol at zero dose (Mauad et al., 2003). Differences like this are associated to the amounts of Si naturally available in the soil. Other researches have shown that there is a linear increase in the Si content in soils with increasing doses applied in Typic Quartzipsamments soil with the wollastonite source in rice (Pereira et al., 2007) and in typical dystrophic Red Latosol with the slag source in sugarcane (Souza et al., 2010), both with soil application. In the present work, the absence of significant difference as a function of Si doses is related to the leaf application, without deposition of this element in the soil. There was positive correlation of 0.9 (Table 4) in plants under water stress in relation to the Si content in the soil and the shoot dry mass, which suggests that the higher the silicon content in the soil, the greater the plant growth. These data corroborate Malavolta (1980), when mentioning Si as a provider of better growth in several monocotyledonous and dicotyledonous plants.

Significant interaction between water condition and silicon doses was observed for Si content and percentage in the leaf tissue (Table 2, Figure 1A, B). The Si dose of 2 kg ha^{-1} resulted in higher foliar content in water deficit than in the normal irrigation regime (Figure 1A, B). Generally, Si-accumulating plants have leaf content above 1% and non-accumulating plants below 0.5% (Mauad et al., 2003). Therefore, beans can be Si accumulators, although this accumulation does not significantly reflect on water deficit tolerance. Nevertheless, plants with water deficit presented RWC 6.9% higher than those without water deficiency. The `Aporé` bean cultivar presented 0.84 mg kg^{-1} of Si in the "wet season" in its trifoliate leaves (Teixeira et al., 2008). In this study, average of 17.55 g kg^{-1} was observed in trifoliate leaves for plants without water restriction and 18.56 g kg^{-1} for plants with water restriction. Therefore, the values obtained are above those recorded for the crop. The correlation indicated negative influence of 0.92 of leaf Si content in relation to shoot dry mass of unstressed plants (Table 4), suggesting that the higher the Si content in leaves, the lower their dry mass. With closed stomata, transpiration and water loss decrease as Si polymerizes in the stomatal cell walls, decreasing their flexibility (Ma et al., 2001). Under these conditions, photosynthesis may decrease due to a decrease in the CO_2 flow into the stomatal chamber (Silva et al., 2015), and by decreasing transpiration, the absorption of nutrients by water mass flow decreases (Taiz et al., 2015). Zeiger, 2013), which can lead to lower development and consequent lower dry mass of unstressed bean plants with Si application.

Water deficit caused significant difference in leaf temperature (Table 3). Si doses of 2 and 2.5 kg ha^{-1} in the first week of water deficit showed significant interaction, these being these doses with the highest average leaf temperatures (Figure 1C). In the second week, Si dose of 1.5 kg ha^{-1} also showed the same behavior (Figure 1D). The results indicate that these doses were not efficient to control the stress of plants caused by water deficiency, not helping in the resistance after regular irrigation return, maintaining high temperatures in plants under water deficiency.

On all evaluation dates, leaf temperature was higher under water deficit conditions (Table 3). As water becomes limiting, transpiration is reduced, increasing leaf temperature as the plant's cooling system becomes limiting (Taiz and Zeiger, 2013). In addition to the direct effect of stomatal resistance to water vapor diffusion of bean plants submitted to water deficit, there is also a decrease in photosynthesis caused by the increase in leaf temperature and consequent stomatal closure, caused by water deficit (Bergamaschi et al., 1988), making the availability of photosyntates for pod filling scarce, as can be observed in production results in Table 2.

Although Si is considered a beneficial element, its effects are usually more expressed when plants are under stress (Ma et al., 2001). However, in this research, Si doses applied to bean plants did not show significant difference in RWC, plant height, root length, shoot and root fresh dry mass, number of grains plant^{-1} and per pod^{-1}, pod length, fresh and dry mass of grains, number of pods plant^{-1} and Si content in the soil after plants were exposed to water scarcity. Thus, under the conditions of this experiment, it could be concluded that foliar Si doses did not influence tolerance to water deficit applied to bean plants and, therefore, further studies are required to evaluate other concentrations and/or number of applications, including periods before exposure to stress.

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