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Agronomic performance of beetroot as a function of silicon application[1]

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ABSTRACT - Beetroot, when cultivated in hot regions such as the Brazilian semi-arid, is subjected to various stressful environmental factors that can negatively impact its productivity and quality. Silicon is an element known for its ability to mitigate damage caused by both abiotic and biotic stressors and is recognized as a productivity and quality enhancer in agricultural crops. Therefore, this study aimed to evaluate the effects of silicon application on the agronomic performance of the beet crop. The experimental design used was a randomized block design in a 5 x 2 factorial arrangement with four replications, comprising five silicon doses (0.0; 0.9; 1.8; 2.7, and 3.6 kg ha^{-1}) and two table beet cultivars (Fortuna and Maravilha). The assessed variables included plant height, number of leaves per plant, polar and equatorial diameter of the tuberous root, tuberous root, shoot and total dry matter mass, commercial, non-commercial, and total productivity, as well as quality assessment of the root with determinations of pH, vitamin C, titratable acidity, and total soluble sugars. A silicon dose of 2.56 kg ha^{-1} promoted optimal root development in the Fortuna cultivar; however, silicon application at all tested doses reduced the levels of soluble sugars, while a dose of 3.6 kg ha^{-1} increased total titratable acidity. In contrast, silicon did not influence root development in the Maravilha cultivar, but an application of 3.13 kg ha^{-1} increased the total soluble sugar content by 86.13%.

Key words: *Beta vulgaris* L. Climate conditions. Abiotic stress. Beneficial elements.

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INTRODUCTION

Beetroot (*Beta vulgaris* L.) is a functional food that holds nutraceutical properties within the agricultural sector. It is composed of both essential nutrients and bioactive compounds, offering both nutritional and health benefits. Besides being consumed in its natural form as a raw or cooked salad ingredient, beetroot is also utilized in the agricultural industry as a natural colorant and preservative, serving as an alternative to artificial additives (NEMZER *et al*., 2011; SLIMEN; NAJAR; ABDERRABBAM, 2017; DOMÍNGUEZ *et al*., 2020).

In hot climate regions, beetroot production and quality are hindered by various abiotic and biotic stresses the plant encounters, including drought, salinity, elevated temperatures, pathogens, and insects. Among these, high temperature is often the primary limiting factor for production, as most cultivars perform optimally at temperatures around 20 °C. Consequently, a considerable proportion of consumed beetroot is sourced from areas with more favorable growing conditions. However, this increases product cost and compromises quality due to the expenses and damages incurred during transportation (NEELWARNE; HALAGUR, 2013; FILGUEIRA, 2008; TIVELLI *et al*., 2011; SOUZA; RESENDE, 2014; ZHU, 2016; FRANCO *et al*., 2021).

Silicon (Si) is an element that, while not essential, can enhance the vegetative growth and reproductive performance of plants. It mitigates damages caused by abiotic and biotic stresses, improves nutritional status, and boosts antioxidant enzymes. Silicon also plays a role in several defense mechanisms against pathogens and insects, leading to more efficient crops, increased food productivity and quality, and reduced reliance on fertilizers and pesticides. As a result, it can be applied in sustainable food production, contributing to food security, especially in regions facing environmental challenges for agriculture (REYNOLDS *et al*., 2016; MIR *et al*., 2022).

In sugar beet, studies under various experimental conditions have highlighted the benefits of Si application, both foliar and via soil, leading to enhanced production and quality of harvested roots (KULIKOVA *et al.*, 2020; ARTYSZAK *et al.*, 2021). However, research examining the impact of Si on table beet is limited. To fully realize the benefits of Si and promote its widespread use, further research, especially field trials, is crucial. Field trials allow for the observation of Si's effects on the crop under specific climate and soil conditions, enabling the fine-tuning of appropriate application rates (GUO-CHAO *et al.*, 2018).

Considering these factors, this study aimed to evaluate the influence of silicon application on the growth, productivity, and quality of beetroot crops.

MATERIAL AND METHODS

The experiment was conducted at the Rafael Fernandes Experimental Farm, owned by the Federal Rural Semi-Arid University (UFERSA), located in the rural area of the municipality of Mossoró-RN (5° 3'25.34"S, 37°23'49.45"W, and 79 m altitude). According to the Köppen classification, the climate of the region is classified as BSh semiarid, with an average annual temperature of 26.5 °C (ALVARES *et al*., 2014). During the experimental period, the region experienced the corresponding climatic conditions (Figure 01).

The soil in the experimental area is classified as Typic Rhodustults (REGO *et al*., 2016). Table 1 shows the characterization of soil chemical properties in the 0-20 cm depth layer, following the methods of Silva (2009).

Figure 1 - Maximum (Tmax), minimum (Tmin), and mean (Tmean) air temperatures, and monthly rainfall from January 2021 to December 2021 in the municipality of Mossoró-RN, Brazil

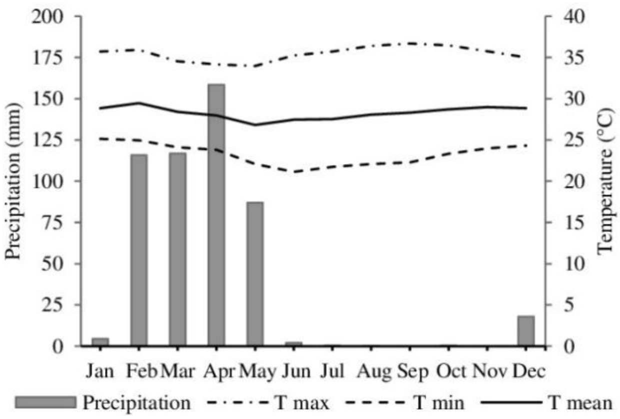


Table 1 - Chemical characterization of the soil in the experimental area, Mossoró-RN, Brazil, 2021

pH (H_2O)	Si	Ca	Mg	H+A	SB	CTC	V	M.O	Fe	Mn	B	Cu	Zn	P	K
	mg kg^{-1}	------------- cmolc dm^{-3} -------------					%	g dm^{-3}	--------------------- mg dm^{-3} ---------------------						
5.2	56.49	0.66	0.08	2.84	0.84	3.69	23	14.9	163.0	15.8	0.77	0.33	0.64	1.9	39

The experimental soil was corrected and fertilized based on the chemical analysis. Lime was applied at a rate of 1000 kg ha^{-1}, incorporated to a depth of 20 cm, and applied 150 days before the experiment's implementation. The soil was prepared via plowing and harrowing, followed by bed formation. For planting fertilization, 190 kg ha^{-1} P_2O_5 was used in the form of single superphosphate, as recommended by Silva *et al.* (2019). Topdressing fertilization, according to Traini (2013), was done through weekly split fertigation, totaling nine applications from 11 days after sowing (DAS) to 74 DAS. The following nutrients were applied: 128.8 kg ha^{-1} N, 171.9 kg ha^{-1} K_2O, 54.2 kg ha^{-1} Ca, 13.8 kg ha^{-1} Mg, and 24.0 kg ha^{-1} S. Additionally, 0.210 kg ha^{-1} B, 0.036 kg ha^{-1} Cu, 0.266 kg ha^{-1} Fe, 0.248 kg ha^{-1} Mn, 0.036 kg ha^{-1} Mo, and 0.338 kg ha^{-1} Zn were also applied in two applications at 47 and 57 DAS. The fertilizers used were urea, potassium chloride, potassium nitrate, magnesium sulfate, calcium nitrate, zinc sulfate, boric acid, copper sulfate, and Rexolin®.

The experimental design was a randomized complete block design, using a 5 x 2 factorial scheme with four replications. The treatments consisted of five silicon (Si) doses (0, 0.9, 1.8, 2.7, and 3.6 kg ha^{-1}) applied via foliar spray, and two table beet cultivars (Fortuna and Maravilha). Each experimental unit was a bed measuring 3.0 x 1.5 m, totaling 4.5 m^2, with six rows of plants spaced at 0.25 x 0.10 m, at a population density of 240,000 plants ha^{-1}. The four central rows were considered the useful area, excluding one plant from each end, yielding a useful area of 2.8 m^2.

The Si doses were split into three applications at 30, 37, and 44 DAS, using calcium silicate in the form of the commercial product Barrier (Cosmocel®). A pressurized backpack sprayer with a flat fan nozzle was used, calibrated for a constant flow rate, delivering a spray volume equivalent to 533 L ha^{-1}.

Sowing was done manually on 02/08/2021, using two to three glomerules per planting hole. Thinning was done at 24 DAS, leaving one plant per hole. The irrigation system used was micro-sprinkling until 18 DAS, then drip irrigation with three drip tapes per bed, spaced at 0.50 m, and self-compensating emitters with an average flow rate of 1.5 L h^{-1}, spaced at 0.30 m, was employed. Irrigations were done daily, applying water depths based on the crop's evapotranspiration balance, totaling 543.81 mm (ALLEN *et al.*, 2006). The irrigation water came from a deep tube well in the Açu sandstone aquifer. It presented the following characteristics: pH = 7.1; electrical conductivity (EC) = 0.61 dS m^{-1}; contents of K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}, and HCO_3 of 0.65, 1.73, 2.50, 1.90, 1.60, 0.0, and 4.00 mmolc L^{-1}; and a sodium adsorption ratio (SAR) of 1.2.

Weed control was manual, and pest and disease management used commercial products based on Metiram, Pyraclostrobin, Azoxystrobin, Difenoconazole, Triazinamine, and Antranilamide. Harvesting was at 77 DAS.

At harvest, growth, root yield, and tuber root quality parameters were assessed. From the useful area of each plot, ten plants were randomly selected for evaluation. Plant height was determined by measuring from the crown to the tip of the tallest leaf with a ruler. Leaf counts were taken individually. Using a digital caliper, the polar (longitudinal) and equatorial (transverse) diameters of roots were gauged. Finally, shoot, root, and total dry masses were obtained by drying them in a forced-air circulation oven at 65 °C until reaching a consistent weight, which was then recorded.

Root yield was classified into commercial and non-commercial categories. Commercial yield encompassed roots with an equatorial diameter greater than 5 cm and no evident lesions or deformations (HORTBRASIL, 2006). In contrast, non-commercial yield consisted of roots falling outside these criteria. Total productivity was derived by combining both commercial and non-commercial yields.

To understand the quality of the tuberous roots, we extracted juice from ten representative commercial roots from each experimental plot. We measured the pH using a standard benchtop pH meter. The vitamin C content was determined through a titration method following the approach described by STROHECKERN and HENNING (1967). Titratable acidity was evaluated using the electrometric method based on the protocol provided by the INSTITUTO ADOLFO LUTZ (1985). Lastly, the total soluble sugars were assessed in triplicate using the Anthrone method as detailed by YEMM and WILLIS in (1954).

The collected data underwent variance analysis using the F-test. In instances where the cultivar factor showed significant variance, mean values were compared using the Tukey test with a 5% level of significance. For variations in Si doses, a regression analysis was conducted utilizing the SISVAR software v5.3 (FERREIRA, 2011).

RESULTS AND DISCUSSION

In terms of growth variables, only the root dry mass (RDM) showed a significant interaction between the cultivar and Si dose factors. The Si dose factor notably impacted the number of leaves (NL) and root polar diameter (RPD). Conversely, the cultivar factor significantly influenced plant height (PH) and root equatorial diameter (RED). However, total plant dry mass (TPDM) remained unaffected by either factor, as presented in Table 2.

Table 2 - Analysis of variance and mean values by dose for beet cultivars considering various parameters: number of leaves (NL), plant height (PH), polar root diameter (RPD), root equatorial diameter (RED), shoot dry mass (SDM), root dry mass (RDM), and total dry mass (TDM) in response to foliar silicon application. Mossoró-RN, Brazil, 2022. ** indicates significance at the 1% level, * at the 5% level, and (ns) no significance at the 5% level

VF	DF	Mean squares						
		NL	PH	RPD	RED	SDM	RDM	TDM
Block	3	0.22^{ns}	0.16^{ns}	79.73**	3.08^{ns}	0.71^{ns}	1.40^{ns}	0.75^{ns}
Cultivar (C)	1	0.42^{ns}	324.73**	51.48^{ns}	194.21*	51.08**	13.88*	11.74^{ns}
Si Dose (D)	4	1.93**	15.14^{ns}	54.71**	21.01^{ns}	1.01^{ns}	6.19*	10.93^{ns}
C x D	4	0.56^{ns}	13.94^{ns}	25.64^{ns}	65.05^{ns}	0.30^{ns}	6.98*	7.54^{ns}
Error	27	0.38	10.90	13.05	30.29	1.74	2.26	5.86
CV (%)	-	6.41	10.18	6.56	9.71	27.38	14.04	15.58
Dose		NL	PH (cm)	RPD (mm)	RED (mm)	SDM (g)	RDM (g)	TDM (g)
----- Cultivar Fortuna -----								
0		9.25	27.47	54.32	57.12	3.11	8.95	12.06
0.9		9.85	27.94	55.75	57.49	3.36	11.36	14.72
1.8		10.45	31.27	56.22	57.86	4.54	11.51	16.05
2.7		9.40	30.86	54.61	61.34	3.73	12.98	16.71
3.6		8.90	30.45	60.08	60.68	3.70	11.74	15.44
Mean values		9.57	29.60	56.19	58.90	3.69	11.31	14.99
Regression analysis		**	ns	ns	ns	ns	*	*
----- Cultivar Maravilha -----								
0		9.85	34.20	51.81	56.15	5.79	10.32	16.11
0.9		9.55	37.07	48.33	54.22	5.89	9.29	15.18
1.8		10.55	37.44	57.80	60.20	6.24	11.75	17.99
2.7		9.13	35.27	55.20	53.19	5.79	10.28	16.07
3.6		9.80	32.52	56.49	48.70	6.02	9.02	15.04
Mean values		9.78	35.30	53.93	54.49	5.95	11.13	16.08
Regression analysis		ns	**	**	ns	ns	ns	ns

Root dry mass (RDM) increased with Si doses in the Fortuna cultivar, following a quadratic model. The optimal RDM was estimated at 12.46 g per plant with a Si dose of 2.56 kg ha^{-1}, marking an 11.69% increase compared to the control without Si application. Conversely, the Maravilha cultivar showed no response to Si, maintaining an average RDM of 10.13 g $plant^{-1}$, and no model equation was fitted for it (Figure 2A). Notably, at Si doses of 2.7 and 3.6 kg ha^{-1}, the RDMs of Maravilha and Fortuna cultivars were statistically different, with Fortuna outperforming Maravilha.

Although not significantly affected by doses, as indicated by the F-test, TDM still followed a quadratic regression pattern, peaking at an estimated 16.57 g $plant^{-1}$ at a silicon dose of 2.15 kg ha^{-1} (Figure 2B). Notably, SDM differed between the two cultivars, with Maravilha showing significantly higher values at 5.95 g Si $plant^{-1}$ and Fortuna at 3.692 g Si $plant^{-1}$. In a related study by Behtash *et al.* (2010), table beet plants exposed to cadmium showed increased dry mass in both shoot and root sections when treated with silicon. Likewise, Viciedo *et al.* (2019) observed analogous outcomes in sugar beet crops exposed to harmful ammonia levels but mitigated with silicon application.

Further emphasizing the impact of Si, Melo Filho *et al.* (2020) investigated its effects on beet plants under saline stress. They discovered that Si application led to enhanced net photosynthesis and improved carboxylation efficiency. This heightened photosynthetic capability, culminating in increased dry mass generation upon Si fertilization, can likely be traced back to the structural contributions from this element. By influencing biochemical processes, Si enhances the nutritional status of plants. It aids in the absorption of essential nutrients like potassium and nitrogen and diminishes the oxidative damage brought on by challenging abiotic conditions, as supported by findings from ALI *et al.* (2020) and DUANGPAN *et al.* (2022).

Further observations revealed that both NL and PH increase with increasing Si doses. They maxed out at 10.0 leaves per plant and 33.80 cm in height at Si doses of 1.56 and 1.91 kg ha^{-1}, respectively. In comparison to the non-Si treatment, this represented growth spurts of around 5% in leaf count and 10% in plant height (Figure 3A, B). While the cultivars displayed similar leaf counts, there was a disparity in height. Maravilha, standing tall at 35.3 cm, overshadowed Fortuna, which measured 29.60 cm.

In Swiss chard plants, Souza *et al.* (2018) found that foliar application of 0.011 g of Si per plant led to a 10.27% increase in plant height and a 26% increase in aerial part dry mass compared to the non-application. Si can contribute to plant growth improvement through its direct role in enhancing the plant's nutritional status, as mentioned earlier, and by inducing the reduction of damages caused by pathogens and insects, promoting indirect benefits. It also facilitates the elongation of the aerial part without plant lodging, as the deposition of silica in the cell wall helps maintain the stiffness and elasticity of plant stems (ALI *et al*., 2013; MARTIN *et al*., 2017).

Regarding the number of leaves, Si application may have delayed leaf senescence by minimizing the deleterious effects caused by reactive oxygen species (ROS) due to promoting higher activity of enzymes such as superoxide dismutase, peroxidase dismutase, and catalase, as observed in fodder beet by Ali *et al.* (2019), along with improvement in the plant's hormonal balance (MAILLARD *et al*., 2018). There may also have been a mitigation effect on the attack of diseases affecting the leaf area, as Si is effective against foliar pathogens of the crop (WEILAND; KOCH, 2004; DERBALAH; EL-MOGHAZY; GODAH, 2013).

Figure 2 - Variation in root dry mass (RDM) (A) and total dry mass (TDM) (B) of beet in response to foliar silicon application in Mossoró-RN, Brazil, 2022. Within the same dose, data points marked by different letters signify statistical differences at the 5% probability level using the Tukey test. Symbols: ** denotes significance at the 1% probability level; * indicates significance at the 5% level; and (ns) highlights non-significance at the 5% level

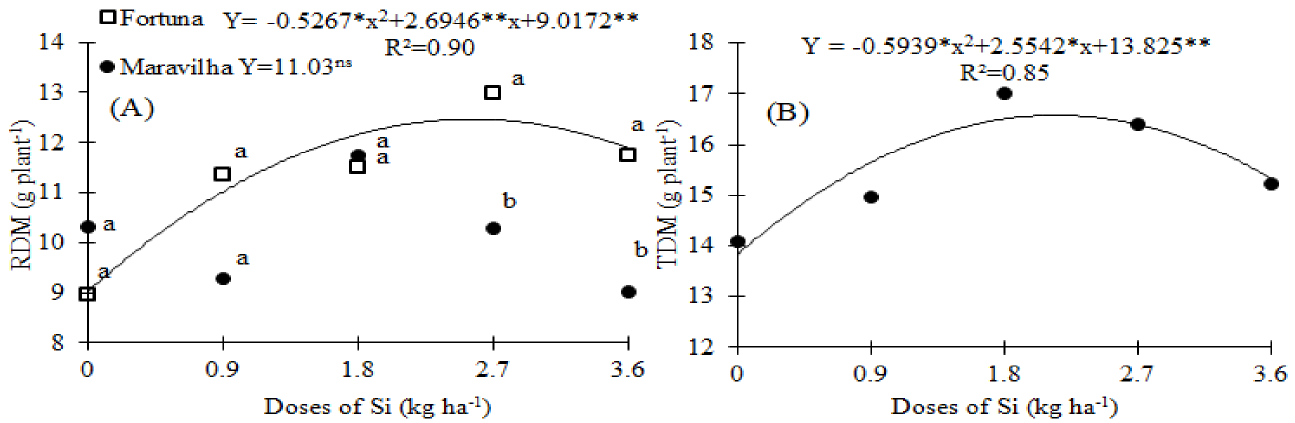
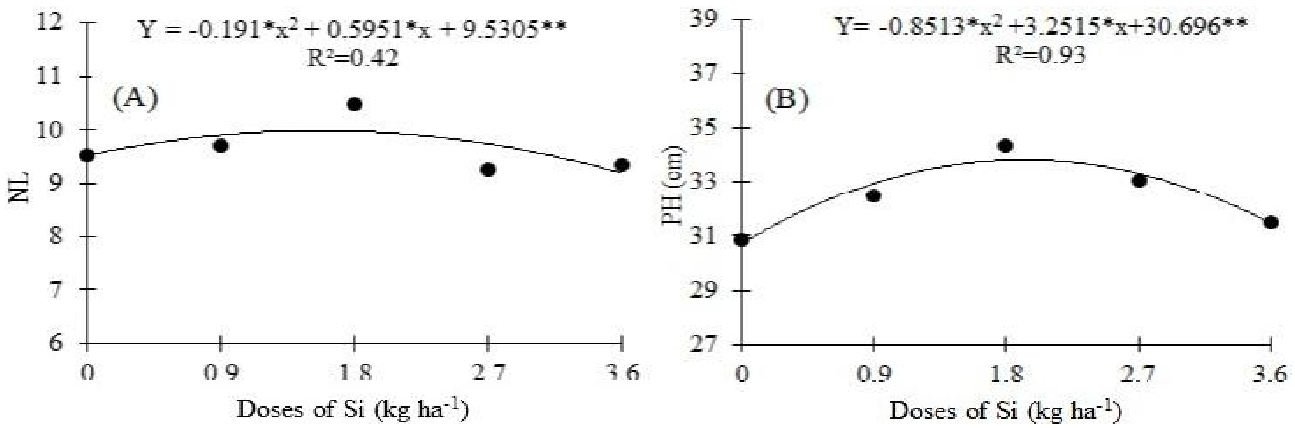


Figure 3 - Number of leaves (NL) (A) and plant height (PH) (B) of beet plants due to foliar silicon application in Mossoró-RN, Brazil, 2022. ** indicates significance at 1% probability, * indicates significance at 5% probability, (ns) indicates not significant at the 5% probability level



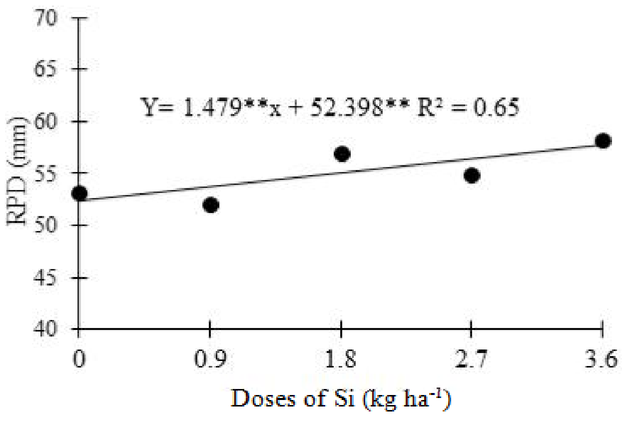
This may have made it possible for the plants to have larger size, with longer-lived leaves, resulting in a higher number of photosynthetically active leaves at the end of the cycle. Larger and more numerous leaves increase the plant's leaf area, which favors light interception and, consequently, higher photosynthetic efficiency, leading to a greater capacity for plant biomass production (BLANCO; FOLEGATTI, 2005).

In addition to the benefits for root production, the increased above-ground growth that Si provides indicates that this element can enhance leaf production in beet cultivation for consumers who consume both the roots and the aerial part of the plant. In these market niches, the whole plant is sold, meaning the tuberous root along with the foliage, or even just the foliage itself, which can be consumed in salads. (PETHYBRIDGE *et al*., 2018; SANTOS *et al*., 2021).

Although beet leaves are more nutritious than the roots themselves, their consumption is limited. However, producing high-quality foliage can encourage the inclusion of this plant part in the human diet. This brings benefits, such as providing a highly nutritious food source and increasing food production within the same crop cycle. Therefore, having a substantial number of healthy leaves with minimal damage is crucial, as damaged, and weak leaves may lead to rejection by consumers (FILGUEIRA, 2008; PETHYBRIDGE *et al*., 2017; PETHYBRIDGE *et al*., 2018).

The application of Si resulted in a linear increase in the polar root diameter, with the maximum dose used providing a 48% increment compared to plants that did not receive Si application (Figure 4). These findings corroborate with Alkahtani *et al.* (2021), who observed an increase in RPD and RED in sugar beet plants subjected to water stress and foliar Si fertilization.

Figure 4 - Polar diameter of beet tuber root (PDR) as a function of foliar silicon application. Mossoró-RN, 2022. ** significance at 1% probability, * significance at 5% probability, (ns) non-significant at 5% probability level



An exclusive increase in polar diameter of the beetroot results in a more elongated shape, causing an excessive tip. This slight imperfection might render these roots less appealing to consumers (TIVELI *et al*., 2011). The influence of Si in elongating beet roots might be linked to its role as a structural component. When deposited, the element can modify the cell wall's structure and mechanical attributes, enhancing stability and flexibility, which in turn leads to increased root length (HATTORI *et al*., 2003; JIANG *et al*., 2022).

There was no significant interaction between the cultivar and dose factors for non-commercial yield (NCC), commercial yield (CY), and total yield (TY). However, the specific cultivar did significantly affect all yield measures, as detailed in Table 3.

Despite the F-test revealing no significant differences, we observed a trend that Si application potentially boosts CY. Specifically, the Fortuna cultivar experienced a 38.17% yield increase (6.62 t ha^{-1}) with 2.7 kg ha^{-1} of Si. In contrast, the Maravilha cultivar increased yield by 15.56% (2.29 t ha^{-1}) at a Si dose of 1.8 kg ha^{-1}. In research on sugar beet by Artyszak *et al.* (2021), a 20.41% production boost occurred with an Si application of 0.150 kg ha^{-1}. However, at 0.225 kg ha^{-1}, no productivity increase was observed, suggesting there is a threshold for a positive effect of Si. This is mirrored in our study, where, beyond the most effective dose, higher Si doses resulted in diminishing yield gains.

Notably, our findings showed no significant yield reduction. Therefore, under our experimental conditions, no toxic effects were observed up to 3.6 kg ha^{-1} of Si both on the Fortuna and Maravilha cultivars. Interestingly, Si appeared more beneficial for Fortuna than Maravilha, with yield boosts of 38.17% versus 15.56%, respectively. Fortuna peaked at 2.7 kg ha^{-1} Si, whereas Maravilha did at 1.8 kg ha^{-1}. Moreover, for Fortuna, the dose corresponding to the highest yield also improved RDM.

The role of silicon in productivity enhancement seems linked to mitigating abiotic stresses such as temperature, supporting photosynthesis, protein synthesis, and offering structural benefits. Enhanced growth in the above-ground parts of plants, observed through increased NL, PH, and SDM, underscores this yield growth (MUNEER, 2017). Healthy aerial growth translates to a larger photosynthetic area, leading to improved sunlight capture and hence growth. Peixoto *et al.* (2020) reported the role of Si in enlarging leaf area, optimizing light capture and CO_2 absorption, and thereby boosting biomass.

Fortuna outperformed Maravilha in TY (21.29 vs. 16.87 t ha^{-1}) and CY (20.79 vs. 15.28 t ha^{-1}). Yet, for NCY, Maravilha (1.6 vs. 0.49 t ha^{-1}) took the lead (Table 3). These yield outcomes align with the national average for open-pollinated varieties (15 to 20 t ha^{-1}). Moreover, NCY figures hint that Maravilha is more susceptible to hot temperatures, producing more suboptimal roots.

Table 3 - Analysis of variance and average yields by silicon doses for non-commercial yield (NCY), commercial yield (CY), and total yield (TY) across different beet cultivars. Mossoró-RN, Brazil, 2022. ** significance at 1% probability, * significance at 5% probability, (ns) not significant at the 5% probability level

VF	DF	Mean squares		
		NCY	CY	TY
Block	3	0.97*	6.76^{ns}	8.14^{ns}
Cultivar (C)	1	12.21**	304.30**	188.49**
Si dose (D)	4	0.16^{ns}	21.93^{ns}	22.10^{ns}
C x D	4	0.23^{ns}	17.60^{ns}	15.63^{ns}
Error	27	0.30	23.41	21.07
CV (%)	-	52.20	26.83	24.11
Dose (kg ha^{-1})		NCC (t ha^{-1})	CY (t ha^{-1})	TY (t ha^{1})
---------- Cultivar Fortuna ----------				
0		0.65	17.34	17.98
0.9		0.48	19.33	19.80
1.8		0.54	21.25	21.78
2.7		0.55	23.96	24.15
3.6		0.25	22.10	22.36
Mean values		0.49	20.79	21.29
Regression analysis		ns	ns	ns
---------- Cultivar Maravilha ----------				
0		1.33	14.72	16.05
0.9		1.54	15.75	17.29
1.8		2.05	17.01	19.06
2.7		1.44	16.53	17.96
3.6		1.63	12.38	14.00
Mean values		1.60	15.28	16.87
Regression analysis		ns	ns	ns

In terms of root quality, significant interactions between cultivar and Si dose were observed for total soluble sugars (TSS) and total titratable acidity (TTA). Yet, vitamin C (Vit C) and pH levels remained consistent across the studied factors (Table 4).

For both cultivars, TSS levels exhibited a quadratic regression pattern (Figure 5A). The Maravilha cultivar experienced an 86.37% surge in TSS content with Si application, peaking at 7.83% with the 3.13 kg ha^{-1} Si dose compared to the control. Conversely, the TSS content of Fortuna cultivar decreased with Si application. Such a decline bottomed at 4.91% for the 2.28 kg ha^{-1} Si dose, which is 28.10% lower than without Si and 11.61% less than the highest tested dose.

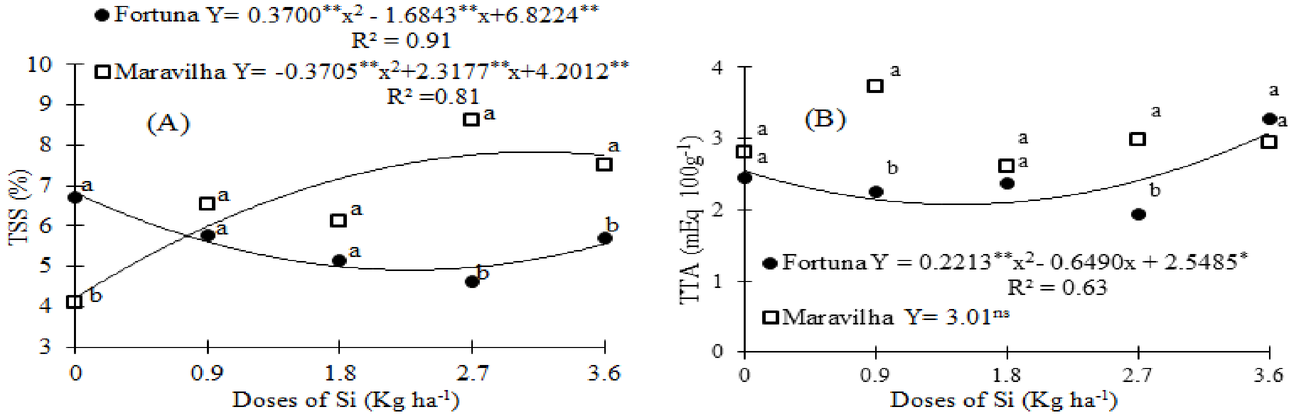
Our findings showed that all Si doses yielded different TSS contents between the cultivars Maravilha and Fortuna. The former positively responded to Si in terms of TSS, while the latter exhibited a decline within the observed dose range. In temperate climates, Artyszak *et al.* (2021) found a 21.92% increase in sugar content in sugar beets with Si application (0.15 kg ha^{-1} Si), while Venâncio *et al.* (2022) observed heightened TSS in onion bulbs under saline stress in the Brazilian semiarid region. These authors noted that the effect was more evident 20 days after harvest. Therefore, Si application may improve post-harvest quality.

A contrasting effect of Si on RDM and TSS was evident between the cultivars evaluated (Figures 2A and 5A). For Fortuna, RDM improved with Si application, peaking at a 2.56 kg ha^{-1}, while its TSS dropped at 2.28 kg ha^{-1}. Conversely, Maravilha displayed a rise in TSS but no distinct RDM improvement with Si application. Likewise, Zhu *et al.* (2016) found that the effects of Si on carbohydrates varied across cucumber cultivars. They noted that the more stress-susceptible cultivar showed increased soluble carbohydrates with Si application, while the more resilient one showed a reduction.

Table 4 - Analysis of variance and average values for vitamin C (Vit C), total soluble sugars (TSS), pH, and total titratable acidity (TTA) across different beet cultivars and silicon application doses. Mossoró-RN, Brazil, 2022. ** significance at 1% probability, * significance at 5% probability, (ns) not significant at the 5% probability level

VF	DF	Mean squares			
		Vit C	TSS	pH	TTA
Block	3	21.67^{ns}	1.53^{ns}	0.006^{ns}	0.14^{ns}
Cultivar (C)	1	119.09^{ns}	9.68**	0.017^{ns}	3.12**
Si dose (D)	4	117.18^{ns}	2.39**	0.003^{ns}	0.72^{ns}
C x D	4	86.17^{ns}	11.36**	0.010^{ns}	1.00*
Error	27	94.67	0.59	0.018	0.34
CV (%)	-	13.91	12.63	2.27	21.19
Dose Kg (ha^{-1})		Vit C mg 100^{-1}	TSS (%)	pH	TTA (mEq L^{-1})
---------- Cultivar Fortuna ----------					
0		66.07	6.72	5.87	2.45
0.9		74.99	5.76	5.83	2.26
1.8		76.18	5.14	5.83	2.37
2.7		67.85	4.61	5.83	1.93
3.6		73.21	5.71	5.78	3.28
Mean values		71.66	5.59	5.83	2.46
Regression analysis		ns	**	ns	*
---------- Cultivar Maravilha ----------					
0		62.50	4.11	5.88	2.81
0.9		66.07	6.51	5.87	3.73
1.8		73.21	6.13	5.81	2.60
2.7		74.99	8.61	5.85	2.98
3.6		64.28	7.49	5.94	2.95
Mean values		68.21	6.57	5.87	3.01
Regression analysis		ns	**	ns	ns

Figure 5 - Changes on total soluble sugars (TSS) (A) and total titratable acidity (TTA) (B) of two beet cultivars as a function of foliar silicon application dose. Mossoró-RN, Brazil, 2022. Data points followed by different letters for the same dose differ statistically from each other at the 5% probability level by the Tukey's test. ** significance at 1% probability, * significance at 5% probability, (ns) not significant at the 5% probability level



The varying effects of silicon on RDM and TSS in the two beet cultivars can be linked to their unique reactions to their environment. The Fortuna cultivar appears more resilient to higher temperatures, whereas the Maravilha is more temperature-sensitive. During the study, the peak average temperature reached 36.5 °C, which for the Maravilha exceeded the advised maximum by 1.5 °C and was 7.5 °C hotter than its ideal conditions (ISLA, 2022).

Under water and salt stress, Pei *et al.* (2010) and Yin (2013) found that Si application increases soluble sugar levels in plants. The Maravilha cultivar, being more temperature-sensitive, used silicon to counteract abiotic stresses, increasing the production of osmolytes such as soluble sugars to reduce stress impacts and stabilize cells. Instead of favoring long-chain carbon compound synthesis which boosts RDM, this cultivar prioritized increasing TSS levels (ALZAHRANI *et al.*, 2018; AMARAL *et al.*, 2020).

In the Fortuna cultivar, Si may have mitigated abiotic stresses via enhancing antioxidant enzyme activity, eliminating the need to produce osmolytes. This improved hydration and nutrient absorption, boosted photosynthesis, and prompted the creation of long-chain carbon molecules, ensuring starch synthesis remained balanced and reduced conversion to soluble sugars.

Previous research has shown that Si promotes starch storage in roots drawn from leaves, amplifying energy storage and boosting root growth over aboveground growth. This correlates with the increase in RDM observed in the Fortuna cultivar after Si application (ZHU *et al.*, 2016; DAS and BISWAS, 2022).

In the Fortuna cultivar, Si application significantly impacted TTA levels, showing a quadratic relationship. A dose of 1.46 kg ha^{-1} of Si resulted in the lowest TTA level (2.07 mEq. 100 g^{-1}), whereas a dose of 3.6 kg ha^{-1} recorded a TTA value of 3.08 mEq 100 g^{-1}. This latter value was notably higher than no Si application (20.86%) and the dose that promoted the minimum TTA observed (39.512%). In contrast, the Maravilha cultivar responded inconsistently and had no clear regression pattern regarding Si doses on TTA.

Both TSS and TTA displayed similar reactions to varying Si doses in the Fortuna cultivar, owing to their shared role in reducing oxidative stress in plants. At lower Si doses, a decrease in both TSS and TTA was evident, suggesting that minimal Si availability prompts the plant to work with other stress-reducing mechanisms. However, as the Si dose increased, a heightened synthesis of TSS and TTA was observed. Interestingly, while the TSS content in Fortuna cultivar started increasing at 2.28 kg ha^{-1} Si, TTA began to rise even at the lower 1.46 kg ha^{-1} Si dose. This suggests that in low Si conditions, the plant prioritizes organic acid synthesis before boosting soluble carbohydrate production.

Assorted studies have noted the potential of Si to modulate TTA content. Lemos Neto *et al.* (2020) found increased TTA levels in hydroponically-grown lettuce due to Si addition. Likewise, foliar Si application in strawberries enhanced TTA levels (FIGUEREDO *et al.*, 2010), whereas fertigation with Si showed the opposite effect (HAJIBOLAND *et al.*, 2017). The findings from Figueiredo *et al.* (2010) and Hajiboland *et al.* (2017) underscore the nuanced interactions between Si and plant metabolic processes. Different plant species, or even cultivars within a species, can manifest varying reactions to Si applications. This variability is often rooted in a plant's inherent adaptability and its specific metabolic adaptations to regional conditions. As a result, while some cultivars utilize Si primarily to bolster their basic metabolic functions, others might leverage Si more towards enhancing resilience against environmental stresses.

CONCLUSIONS

1 **-** Foliar application of silicon enhanced the aboveground growth in both cultivars;

2 **-** For the Fortuna cultivar, the optimal root development was achieved with a dose of 2.56 kg ha^{-1} of silicon. However, all tested doses of silicon reduced soluble sugar levels, while the 3.6 kg ha^{-1} dose led to an increase in total titratable acidity;

3 **-** For the Maravilha cultivar, silicon had no significant impact on root development. However, the application of 3.13 kg ha^{-1} of silicon resulted in an 86.13% increase in total soluble sugar content.

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