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Silicon application for the production and quality of raspberry fruit in a subtropical region

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Abstract – The objective of this work was to evaluate the effect of silicon (Si) on the cultivation and quality of raspberries (*Rubus idaeus*). The experiment consisted of seven treatments and four blocks located in a subtropical region. Each plot consisted of three pots with one seedling of 'Batum' raspberry. In each pot, the treatment consisted of Si doses at 0, 50, 100, 200, 400, 800, or 1600 mg dm^{-3}, which were applied to the soil 15 days after the transplanting of the seedlings. Field analyses were performed by measuring chlorophyll a and b, water potential, and production. Fruit were analyzed for color, firmness, respiratory rate, soluble solids, and pH. Fertilization with Si stimulates the increase of fruit number and of the raspberry production per plant. The Si application increases the fruit production and fruit firmness; however, it reduces the water potential and respiration rate.

Index terms: *Rubus idaeus*, abiotic stresses, plant nutrition.

Aplicação de silício para a produção e qualidade de frutos de framboesa em região subtropical

Resumo – O objetivo deste trabalho foi avaliar o efeito do silício (Si) sobre o cultivo e a qualidade de framboesa (*Rubus idaeus*). O experimento consistiu de sete tratamentos e quatro blocos em região de clima subtropical. Cada parcela foi composta de três vasos com uma muda da framboeseira 'Batum'. Em cada vaso, o tratamento consistiu de doses de Si a 0, 50, 100, 200, 400, 800 ou 1600 mg dm^{-3}, que foram aplicadas ao solo 15 dias após o transplante das mudas. As análises de campo foram realizadas pela medição de clorofilas a e b, potencial hídrico e produção. Os frutos foram analisados quanto à cor, firmeza, taxa respiratória, sólidos solúveis e pH. A adubação com Si estimula o aumento do número de frutos e da produção de framboesa por planta. O silício promove o aumento da produção e a firmeza dos frutos, no entanto, reduz o potencial hídrico e a taxa de respiração.

Termos para indexação: *Rubus idaeus*, estresse abiótico, nutrição vegetal.

Introduction

Fruit trees of the genus *Rubus* are highly appreciated for their organoleptic characteristics (Guedes et al., 2014; Raseira et al., 2020). More recently, they have also been valued for their health benefits that result from their high levels of antioxidants, vitamins, minerals, fibers, and folic acid, among others (Guedes et al., 2013; Maro et al., 2013, 2014).

Raspberry *(Rubus idaeus* L.) stands out among the fruit species of the genus *Rubus* for its good marketing ability and use in the agroindustry. Raspberry is a species traditionally exploited in temperate regions, mainly in North America, Europe, and Asian countries (Pio et al., 2019).

In the last 10 years, the exploitation of raspberry tree began to advance to subtropical regions. Several studies have been done on the selection of cultivars adapted to the subtropical climate and on the adaptation of their cultural management (Moura et al., 2012; Curi et al., 2014). In the subtropical regions where raspberry trees have been grown, the temperatures are higher in the spring and summer than in their natural habitat (Souza et al., 2014; Rizzi et al., 2020). Their productive performance in subtropical areas is encouraging because the production of raspberry concentrates between November and June, with some cultivars producing large amounts of fruit, as is the case of the Batum cultivar (Campagnolo & Pio, 2012b; Moura et al., 2012). Since temperatures in the subtropical regions are high during the harvest of raspberry trees, it is necessary to develop technologies to increase the production and decrease the respiratory rate of raspberries, aiming to increase their durability after harvest.

In recent years, Si has attracted interest from researchers, due to the benefits that this element brings to some agricultural crops. Among the advantages of Si are the ways that this element modifies the physiology of the plant, in the form of compounds that are deposited in the tissues and form a structure of silicon, which reduces the water consumption by the plant and the losses related to the incidence of pests and diseases, due to the difficulty of pests to penetrate the tissues (Silva et al., 2013).

Silicon can act to reduce transpiration, favor the photosynthetic rate of plants by improving the leaf architecture, and reduce the respiratory activity of fruits (Silva et al., 2013). It can provide a greater tolerance to lodging and greater structural rigidity of tissues, as well as protection against abiotic stresses, such as by reducing the toxicity of manganese, iron, and sodium, and greater resistance to excess aluminum. In addition, silicon increases the thickness of the leaf blade tissues and the deposition of epicuticular wax (Braga et al., 2009). This element optimizes the plant-environment system, since it can help plants withstand climatic, edaphic, and biological adversities. Silicon acts as an inhibitor of natural stresses by mitigating, for instance, the impacts caused by extreme temperatures (Braga et al., 2009). Silicon can also lead to increased postharvest fruit quality by promoting changes in the concentrations of anthocyanins, soluble solids, and titratable acidity, which can translate into higher market quality (Silva et al., 2013).

Kowal et al. (2020) studied strawberry plants and reported higher productivity, increased sugar content, and changes in internal and external color of strawberries exposed to different Si doses. Silva et al. (2013) evaluated the effect of Si on the production and quality of strawberry fruit and reported that Si increased fruit production and promoted improvements in strawberry fruit quality, regardless of the application method (soil or leaf).

The objective of this work was to evaluate the effect of Si on the cultivation and quality of raspberry.

Materials and Methods

The experiment was conducted in the state of Minas Gerais, Brazil, at 21°14'S, 45°00'W at 918 m above sea level. According to the Köppen-Geiger's classification, the climate of the region is of the Cwb type, that is, tropical high altitude (mesothermal), with dry winters and concentrated rains from October to March (Alvares et al., 2013). The climate data for the experimental period are presented (Figure 1).

The experiment was carried out in 11 L plastic pots, which were filled with 10 L of clay soil sieved through a 4 mm mesh sieve. The chemical and physical attributes (Table 1) were determined from soil analyses. Soil liming was performed to increase base saturation to 80%, by applying 2,465 kg of lime to 1 m^3 soil, with 36% CaO and 12% MgO contents. The limestone was mixed with the soil until a homogeneous mixture was attained. After homogenization, the soil was distributed in the pots and incubated for 90 days with moisture at field capacity. Based on the soil analysis, the planting fertilization was performed on the day the seedlings were planted, using 8 g of N-P_2O_5-K_2O of the formula 04-14-08 per pot. For the correction and fertilization of raspberry growing, recommendations were followed according to Pio (2018).

Each pot received one raspberry seedling of 'Batum' raspberry produced by using root cuttings

(Campagnolo & Pio, 2012a) in a greenhouse. Before being taken to the field, the 20 cm seedlings were selected and acclimatized according Pio (2018). Irrigation was performed daily, using drippers in pots for water supply.

The experimental design was randomized blocks with four replicates. The treatments consisted of six Si doses, applied to the soil, and one control treatment (without Si application). The Si doses were 0, 50, 100, 200, 400, 800, and 1,600 mg dm^{-3} of soil. The source of Si was AgriSil (Agrobiológica: Soluções Naturais, Leme, SP, Brazil), at 98% SiO_2 concentration. The Si concentrations in the treatments were applied by surface incorporation to the soil 15 days after transplanting the seedlings.

Crop treatments normally required for the cultivation of raspberry were performed throughout the experiment, such as weed control, monitoring for possible attacks of pests and diseases, and topdressing fertilization (Moura et al., 2012; Curi et al., 2014). Three topdressing applications were performed at 30-day intervals, and 2 g of urea (45% N) and 2 g of potassium chloride (58% K_2O) were used for each application. All crop treatments, such as topdressing fertilizer application, were performed in all pots of the experiment.

At 90 days after transplanting the seedlings, which corresponded to the beginning of fruit production, the chlorophyll a and b concentrations were measured in the treatments on the 3rd and 4th newly developed leaves, in each pot. Readings were performed in the three plants in the plot, and their mean values were used. Levels of chlorophyll content indexes a and b were determined using a SPAD-502 portable chlorophyll meter (Minolta Camera Co., Osaka, Japan), which non-destructively and instantaneously measures the light transmittance through the leaf, in wavelengths with one peak at 650 nm, a region of high absorbance by chlorophyll molecules, and another peak at 940 nm, in which the absorbance by the leaf is low, serving as a correction factor for the water content or leaf thickness. Total chlorophyll was calculated by adding chlorophyll a and b.

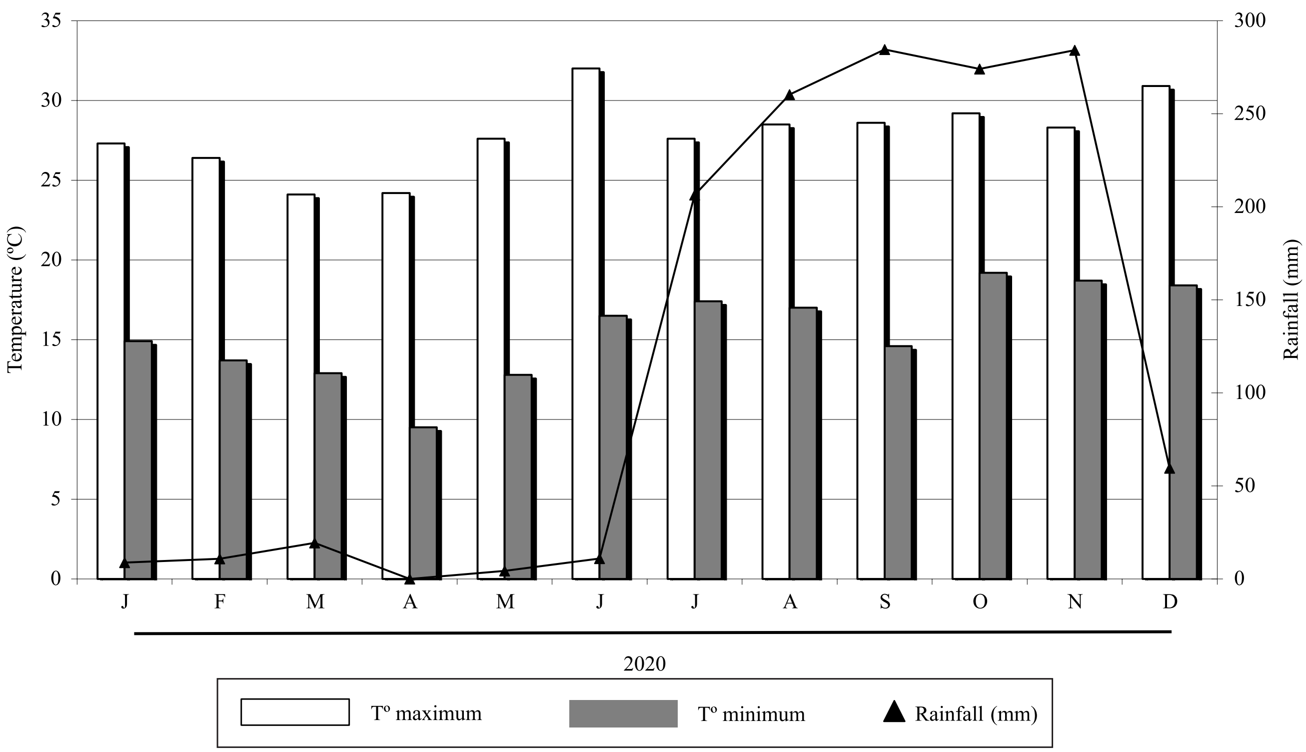

Figure 1. Mean maximum and minimum temperatures and mean monthly cumulative rainfall between January 2020 and December 2020.

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At 100 days after the seedling transplanting, leaf water potential was measured using a pressure chamber Scholander pump (PMS Instrument Company, Albany, OR, USA). Twelve leaves, immediately below the panicles, were collected for each treatment, and the mean of the readings was calculated. The measurements were performed when plants were already at the beginning of production. The measurements were performed in the morning, between 1:00 h and 6:00 h, when leaves would have their stomata closed, due to the low light intensity, which was considered the baseline potential.

Fruit were harvested three times a week throughout the experiment, time at which they were counted and weighed. At the end, the total production was calculated by adding all harvests performed throughout the production cycle.

Fruit were taken to the laboratory for color analysis, which was performed at three different points of the fruit using the CR-400 Minolta Colorimeter (Minolta Camera Co., Osaka, Japan) in CIE mode, by determining the color (L*), chromaticity (C*), and hue angle (hue*). The respiratory rate was analyzed using glass containers with one fruit of known mass, after the aliquots of the internal sample were removed with the aid of the PBI Dansensor gas analyzer (Ametek Mocon, MIN, USA). The results, which are expressed as percentage of CO_2, were converted to mL CO_2 kg^{-1} h^{-1}, considering the volume of the container, the mass and volume of fruit in each container, and the time that such containers remained closed. Firmness was measured by a manual digital fruit hardness tester (Instrutherm, PTR-300, São Paulo, Brazil), with a 3 mm diameter probe. The evaluations were performed at the center of the fruit surface, and the results were expressed in newtons (N). The content of total soluble solids (% °Brix) was determined in a digital refractometer according to the AOAC method (AOAC International, 2023). pH was determined with a Schott Handylab pH meter, according to the AOAC technique (Latimer Jr., 2023).

The results were subjected to the analysis of variance by the F-test, at 5% probability. When significant, a regression analysis was performed by the F-test, at 5% probability, using the statistical program R.

Table 1. Chemical and physical characteristics of the soil used in the experiment.

Characteristic	Unit	Result
pH in water - 1:2.5 ratio		4.4
Potassium (Mehlich-1)	mg dm^{-3}	59.18
Phosphorus (Mehlich-1)	mg dm^{-3}	0.61
Calcium (1 mol L^{-1} KCl)	$cmol_c$ dm^{-3}	1.08
Magnesium (1 mol L^{-1} KCl)	$cmol_c$ dm^{-3}	0.20
Aluminum	$cmol_c$ dm^{-3}	0.53
Hydrogen + aluminum (extractor: SMP)	$cmol_c$ dm^{-3}	6.52
BS = sum of exchangeable bases	$cmol_c$ dm^{-3}	1.43
CEC (t) – effective cation exchange capacity	$cmol_c$ dm^{-3}	1.96
CEC (T) – CEC at pH 7.0	$cmol_c$ dm^{-3}	7.95
V – base saturation index	%	18.01
m – aluminum saturation index	%	27.04
Organic matter	g kg^{-1}	2.95
Remaining phosphorus	mg L^{-1}	10.0
Zinc (Mehlich-1)	mg dm^{-3}	0.72
Iron (Mehlich-1)	mg dm^{-3}	71.27
Manganese (Mehlich-1)	mg dm^{-3}	43.75
Copper (Mehlich-1)	mg dm^{-3}	3.05
Boron (hot water extractor)	mg dm^{-3}	0.06
Sulfur (monocalcium phosphate in acetic acid)	mg dm^{-3}	20.24
Si	mg kg^{-1}	9.95
Clay	g kg^{-1}	61
Silt	g kg^{-1}	23
Sand	g kg^{-1}	16
Texture	Soil type 3, clayey texture	

Results and Discussion

The ratio of chlorophyll a and b was not affected by increasing Si doses applied to the soil. However, the Si doses significantly affected the leaf water potential (Table 2). Leaf water potential decreased with the increase in the first Si dose (Figure 2 A). The lowest leaf water potential (2.06 MPa) was obtained with at 800 mg dm^{-3} Si dose.

The Si doses significantly influenced the harvest parameters, such as production, number of fruit, and mean fruit mass (Table 2). An important way by which Si could have contributed to the harvest parameters is related to the effect that this element has on other chemical elements that are key to plant nutrition and that are absorbed from the soil, such as phosphorus (Greger et al., 2018). The occurrence of this reaction throughout the crop cycle provides a significant amount of phosphorus to the plants, which leads to increased production. In a research carried out with physalis, the presence of silicon provided the improvement of leaf structures of seedlings of physalis (*Physalis peruviana* L.), and improved also other phytotechnical characteristics (shoot length, root length, stem diameter, number of leaves, and number of shoots) (Lazzarini et al., 2020).

The leaf water potential reduction is another factor that may have contributed to the increased production in the treatments with Si doses (Table 2), as it reduced leaf transpiration. It is likely that this saving of untranspired water was used by plants in their various metabolic pathways, increasing their productive potential.

Table 2. Analysis of variance on chlorophyll a (Ca), chlorophyll b (Cb), total chlorophyll (CT), leaf water potential (WP), number of fruit (NF), mean fruit mass (FM) and production (P) of 'Batum' raspberry (*Rubus idaeus*) grown in a subtropical region as a function of Si dose.

Source of variation	DF	Mean square						
		Ca	Cb	CT	WP (MPa)	NF	FM (g)	Production (g)
Treatments	6	6.64ns	3.36ns	16.92ns	0.69*	1,495.56*	0.59*	2,558.20*
Blocks	3	13.74	15.20	53.47	0.04	2.18	0.00	3.82
Residual	18	9.47	6.25	29.23	0.03	9.69	0.00	10.30
CV (%)	-	10.92	21.40	13.56	5.69	3.43	3.14	1.71
Mean	-	28.20	11.80	39.90	2.80	90.88	1.96	188.21

*Significant at 5% probability. nsNonsignificant by the F-test.

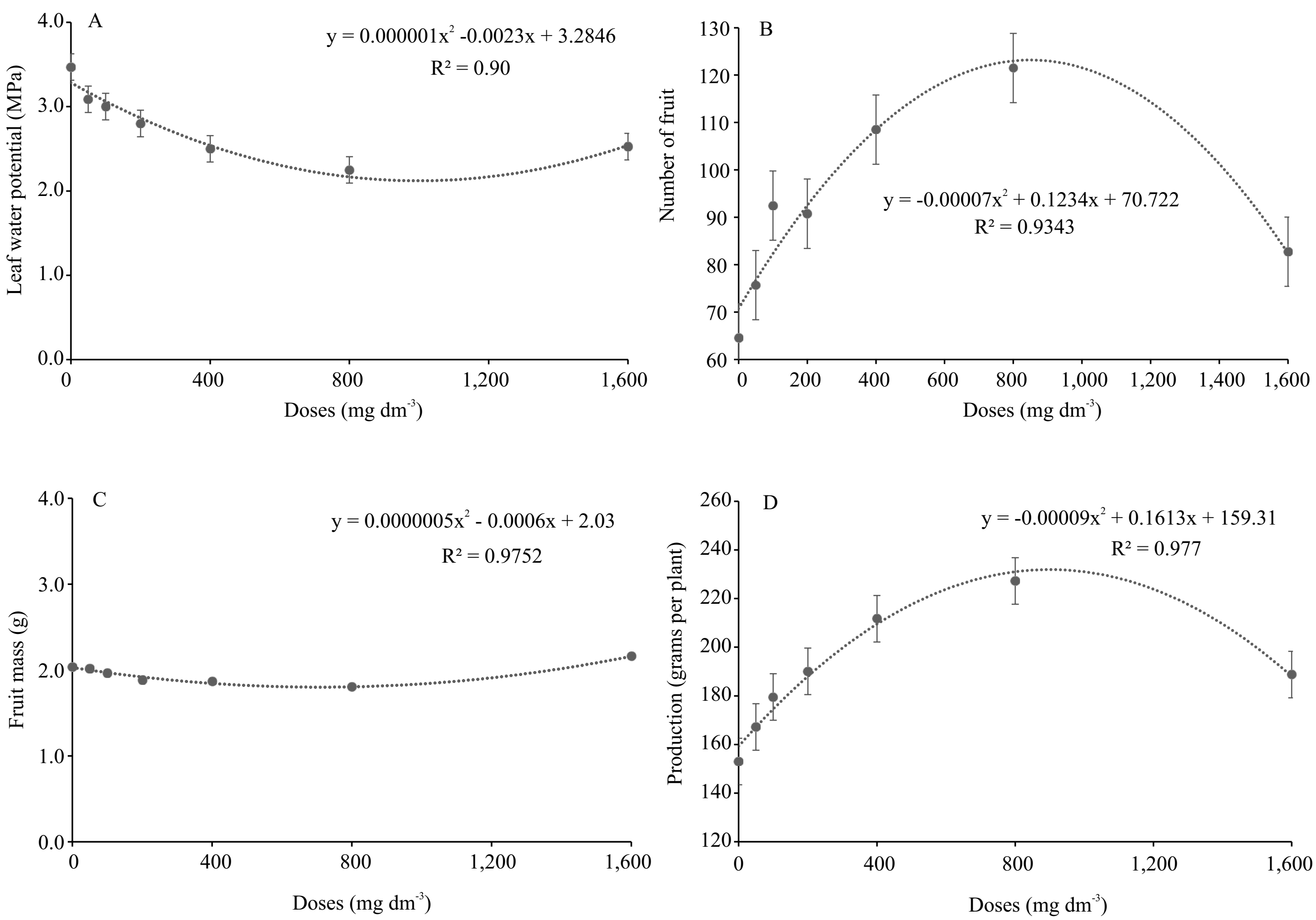

Figure 2. Characteristics of 'Batum' raspberry (*Rubus idaeus*) grown in a subtropical region, as a function of Si dose applications: A, leaf water potential; B, number of fruit per plant; C, mean fruit mass; and D, fruit production.

The maximum fruit production (230.39 g per plant) was obtained with Si supplied at the 793.13 mg dm^{-3}, with about 28% increase over the production without Si application, which was only 180.07 g per plant (Figure 2 D). Curi et al. (2015) evaluated the productivity and quality of 'Batum' raspberry, in a subtropical region, and obtained 10.3 Mg ha^{-1} production. The production of 13.2 Mg ha^{-1} was estimated by using this Si dose. These results are similar to those obtained by Silva et al. (2013), who worked with strawberries, whose fertilizations with Si contributed to the increase of fruit production.

The number of fruit per plant followed the same trend as fruit production (Figure 2 B). The highest number of fruit (125) was obtained with 889.29 mg dm^{-3} Si, which represented 78% increase of the number of fruit, in comparison with treatments without the addition of Si (70 fruit per plant). These results corroborate those found by Silva et al. (2013), who evaluated the effect of Si on the production and quality of strawberry fruit.

However, with the increase of production both in mass (total g per plant) and in number of fruit per plant, there was a reduction of the mean fruit mass (Figure 2 C). This reduction of mass per fruit unit can be explained by the leaf/fruit ratio (source/drainage); by increasing the number of fruit, considered a drainage, and maintaining the number of leaves the same, there was a distribution reduction of photoassimilates (Silva et al., 2013). As the number of fruit increased, the mass decreased as a function of the source/drainage ratio. A significant difference was observed in the respiratory rate of fruit (Table 3). As Si dose increased, the respiratory rate of fruit decreased. This reduction was 59.2% under the dose of 900 mg dm^{-3} Si, in comparison with the control without Si application (Figure 3 A). According to Galati et al. (2015), there was less CO_2 release from lettuce leaves in all treatments with Si than in the treatment without Si addition.

Fruit firmness was another very important characteristic analyzed in the postharvest period, especially for small fruit. Higher fruit firmness was obtained with increasing Si doses (Table 3, Figure 3 B). Since higher Si doses yielded firmer fruit, these fruit may be less sensitive to the attack by pests and diseases (Galati et al., 2015). The findings of the present work are similar to those reported for the increased pulp firmness in the post-harvest quality of 'Xavante' blackberry and 'Albion' strawberry fruit, which resulted from the positive effects of Si applications (Munaretto et al., 2018, 2020). This characteristic may be attributed to the fact that Si is part of the structure of the plant. In the plant cell walls, Si can increase the content of hemicellulose and lignin, thus increasing the rigidity of the cell walls (Munaretto et al., 2018). Silicon is also present in the lumen and intercellular spaces of plants as amorphous silica in the cellular epidermis, stomata, trichomes, and vessel elements, providing greater firmness to plant structures, including the fruit (Munaretto et al., 2018).

Another point to be considered is that firmer fruit tend to promote greater durability postharvest. This is an important factor in the cultivation of raspberry trees in the subtropical region, given that high temperatures at the time of harvest correlate with lower fruit durability. It is assumed that firming up the fruit is a strategy to increase the durability of fruit and the time they last in the postharvest period.

The contents of soluble solids (°Brix) changed significantly because of the Si applications (Table 3), however this reduction was small (Figure 3 C). This

Table 3. Analysis of variance for color (L*), chroma (C*), hue angle (Hue*), fruit respiration rate (FR), firmness (N), soluble solids (SS), and pH of 'Batum' raspberry (*Rubus idaeus*) grown in a subtropical region as a function of Si dose.

Source of variation	DF	Mean square						
		L*	C*	Hue*	FR (mL CO_2 kg^{-1} per hour)	Firmness (N)	SS (°Brix)	pH
Treatment	6	0.79^{ns}	5.08^{ns}	24.34^{ns}	0.08*	0.36*	0.26*	0.08*
Block	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Residual	18	6.64	40.86	159.88	0.00	0.01	0.01	0.00
CV (%)	-	11.66	23.17	45.77	2.68	18.77	1.35	0.49
Mean	-	22.10	27.59	27.63	1.00	0.42	5.49	3.13

*Significant at 5% probability. ^{ns}Nonsignificant by the F-test.

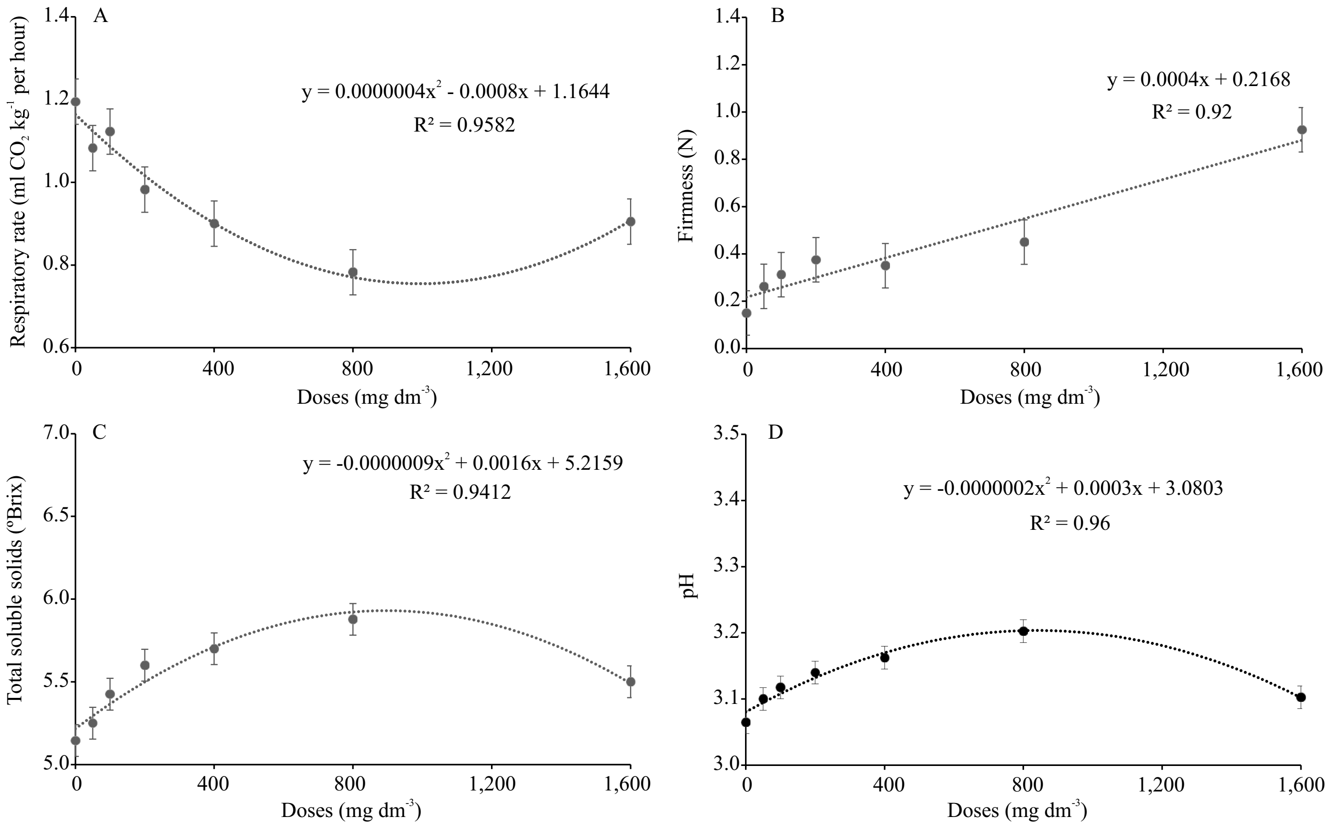

Figure 3. Parameters of fruit of 'Batum' raspberry (*Rubus idaeus*) grown in a subtropical region, as a function of Si doses: A, respiratory rate; B, firmness; C, total soluble solids; and D, pH.

result can be explained by the increase of the number of fruit with the increase in Si, which made for a lower amount of photoassimilates per fruit.

Fruit pH increased as Si increased (Table 3). There was a maximum pH of 3.15 at the 800 mg dm^{-3} Si dose. In general, the pH tends to increase with the increase of soluble solids and the advancement of the maturation stage of fruit.

Conclusions

1. The doses of silicon influence the productive and physicochemical characteristics of 'Batum' raspberry (*Rubus idaeus*) fruit grown in subtropical regions.

2. The dose of 800 mg dm^{-3} Si favors the reduction of leaf water potential, increasing the number of fruit and production of 'Batum' raspberry; in return, there is a reduction of the fruit fresh mass.

3. The dose of 800 mg dm^{-3} Si decreases the respiratory rate of fruit and the total soluble solids content and increases the pH.

4. The gradual increase in silicon doses promotes a greater fruit firmness.

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