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ORIGINAL PAPER

Silicon Application to Soil Increases the Yield and Quality of Table Grapes (*Vitis vinifera* L.) Grown in a Semiarid Climate of Brazil

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Abstract

Purpose Silicon (Si) acts to reduce biotic and abiotic stresses in plants. Herein, we aimed to assess the impact of an amorphous silica-based fertilizer (ASF) applied to soil on the yield, mineral nutrition, chlorophyll fluorescence, and postharvest quality of two cultivars of table grapes grown in a semiarid climate.

Methods The cultivars Arra 15 and BRS Vitoria were submitted to the treatments control, 175 or 350 kg ha^{-1} ASF. Leaf and fruit samples were collected and analyzed for Si, nutrients, and postharvest quality characteristics. Photosynthetic efficiency was assessed by measuring chlorophyll a fluorescence.

Results Both cultivars showed significant responses to Si with the ASF rates of 175 and 350 kg ha^{-1}. The characteristics improved through ASF application compared to the control were: fruit production (6–22%), bunch weight (11%), number of berries (20–34%), berry crunchiness (20%), the content of total soluble solids (13–20%), the titratable acidity (13%), the accumulation of macro and micronutrients (12–45%) and the photosynthetic efficiency (5–33%).

Conclusion Soil-applied Si increases the yield and quality of grapes by improving the plant response to abiotic stresses, being such effects more significant in the dry season.

Keywords Plant nutrition · chlorophyl fluorescence · silicate fertilization · Arra 15

1 Introduction

Table grape (*Vitis vinifera* L.) is the third most exported fruit species in Brazil, with an annual production value of more than US$ 300 million [1, 2]. The development of seedless cultivars adapted to the conditions of the semiarid region of northeastern Brazil made it possible for the area to account for more than 90% of all grapes exported from the country [3]. Although the climate and irrigation in the region allow up to three crops per year, high temperatures, intense sunlight, and water deficit can reduce photosynthetic efficiency, biomass production, and yield [4–6]. Additionally, practices that improve the quality and extend the shelf life of the fruit are necessary due to the time spent in the export process [7].

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Silicon influences the soil-plant system by protecting plants against biotic and abiotic stresses, promoting improvements in soil physical and chemical properties, and increasing nutrient uptake [8–12]. Si can also induce biochemical and physiological changes in the plant that positively affect crop performance [13–15]. Although being widely found in soils in the form of oxides or silicates, Si is absorbed by plants in the form of silicic acid (H_4SiO_4). In this scenario, natural amorphous sources of Si have been recommended for soil application due to the possible higher Si solubility, lower input of contaminants compared to silicate slags, and retention of water and nutrients, contributing to the improvement of soil fertility [16–18].

Sandy soils with neutral to alkaline pH have been shown to be more responsive to Si fertilization in the soils of Northeast Brazil [9, 12]; the soils of this region are generally less clayey and less acidic than those of other regions of the country. In these soils, the low solubility of the primary source of Si (quartz) and the increase in solubility of the element with increasing pH in soils allow Si supplementation to have a better response of crops, especially under light, heat, and water stresses [19, 20]. Previous studies showed that Si reduced damage to the photosynthetic apparatus in grapevines [20, 21]. However, few studies evaluate the Si influence on physiological parameters, such as the chlorophyll fluorescence, particularly in reducing damage caused by high light and temperature. On the other hand, previous field trials have shown that grapevines supplied with Si applied in the soil or foliar significantly increased fruit yield, berry weight and size, bunch weight, total soluble solids to acidity titratable ratio, and fruit firmness. In addition, Si reduced rot incidence and prolonged the fruit shelf life [22, 23]. Furthermore, Nascimento et al., [12], assessing two sources of silicon fertilizer, reported that an amorphous silicon-based fertilizer (ASF) was more efficient in increasing corn and sugarcane plants' biomass than a calcium silicate source. These results were associated with the benefits that ASF provides to soils regarding other sources of silicon.

Abiotic stresses such as drought and heat are major plant stresses in semiarid regions and must be reduced to improve crop performance. Thus, the objective of this study was to assess the potential of soil-applied Si to enhance plant nutrition and increase yield and postharvest quality of the seedless table grape Arra 15 and BRS Vitoria cultivars. The study was carried out for two cropping seasons in a semiarid climate of northeastern Brazil. We hypothesized that Si application has different impacts on the grape cultivars depending on the environmental conditions in the dry and humid seasons and could be integrated into the management of table grapes grown in semiarid settings to ameliorate the multiple plant stresses in such an environment.

2 Materials and Methods

2.1 Field Experiments

The experiments were conducted for two cropping seasons in Casa Nova, BA state, northeastern Brazil (Fig. 1). During the study, the temperature in the region ranged between 21.5 and 33.0 ºC, the average humidity was 51%, precipitation was 309 mm, and evapotranspiration was 260.8 mm (Fig. 2). Two areas of commercial table grape (*Vitis vinifera*) were evaluated, respectively, with the seedless cultivars Arra 15® (9° 20.593' S, 40° 48.950' W) and BRS Vitoria (9° 25.754' S, 40° 46.483' W), during two seasons: September to December 2020 (humid season) and January to April 2021 (dry season).

BRS Vitoria is the most cultivated table grape in the study area, occupying nearly 1,500 ha. It is a vigorous black cultivar adapted to wide climate settings and has excellent horticultural performance in several regions. The bunches are compact, requiring careful management practices, including growth regulators for elongation and berry thinning with scissors [25, 26]. In its turn, Arra 15® is second to BRS Vitoria regarding the cultivated area in Northeast Brazil. It is a white seedless grape with large, elongated, particularly crunchy berries planted worldwide due to its adaptability to differing climates, outstanding shipping performance, and long shelf life.

The soils of the experimental areas were classified as Ultisol in the cultivation of Arra 15 and Entisol in the cultivation of the Vitoria grape [27]. The physical and chemical characterization of soils at a depth of 0–20 cm was performed according to standard methods described by the Brazilian Agricultural Research Corporation [28] (Table 1). Soil available Si was extracted with 0.01 mol L^{-1} calcium chloride followed by colorimetric determination [29].

2.2 Experimental Design

An experiment was set up in randomized blocks with three replicates for each cultivar. The cultivars BRS Vitoria and Arra 15 were five and four years old, respectively, and cultivated in a trellis-type system with 3.5 × 3.0 m spacing with drip irrigation. Silicon was supplied as a granular fertilizer (2–5 mm) derived from amorphous silica (Agrisilica), containing 23% Si, 2% Ca, 1% Mg, and 1% Fe [9]. The treatments consisted of three rates of ASF (0, 175, and 350 kg ha^{-1}) banded along the row with no incorporation five days after the production pruning in each evaluated crop season. The treatment plots were sized at 10.5 × 100 m, comprising three cultivation lines; the central line was considered the usable plot area for sample collection (Fig. 1).

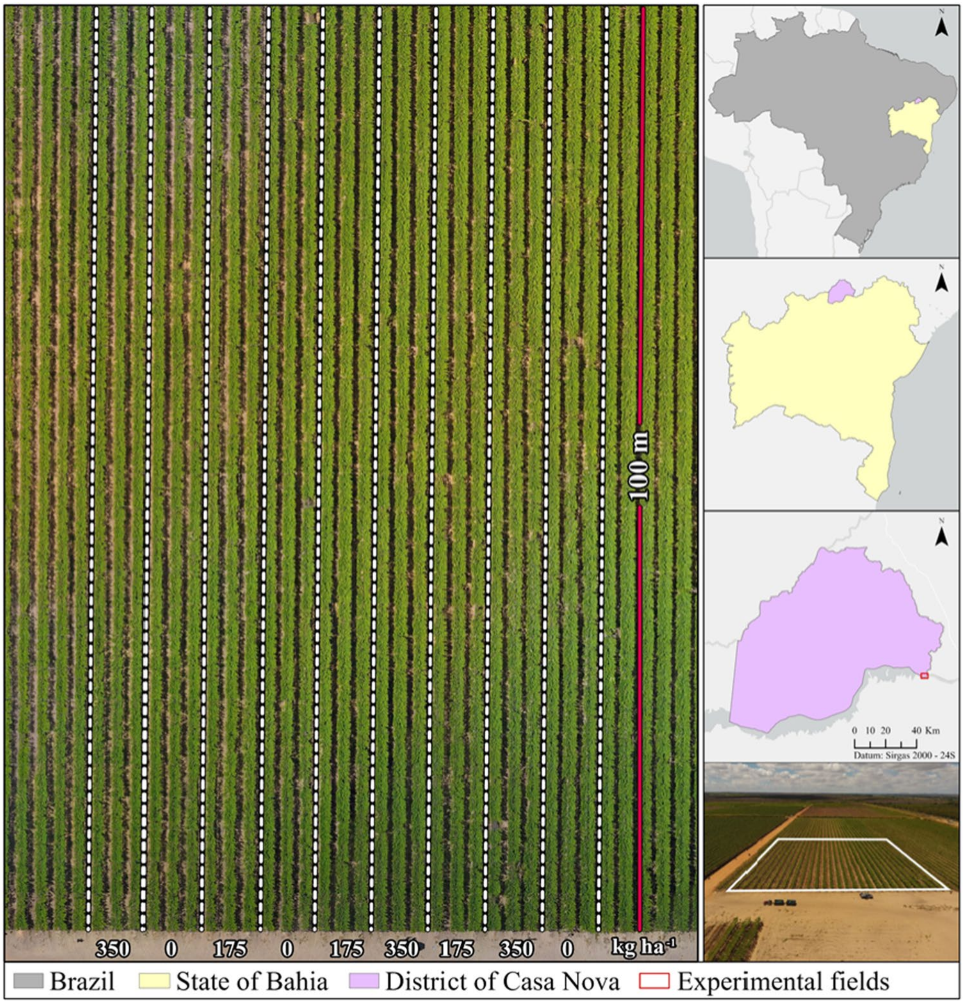


Fig. 1 Schematic representation of the experimental area and arrangement of treatments applied

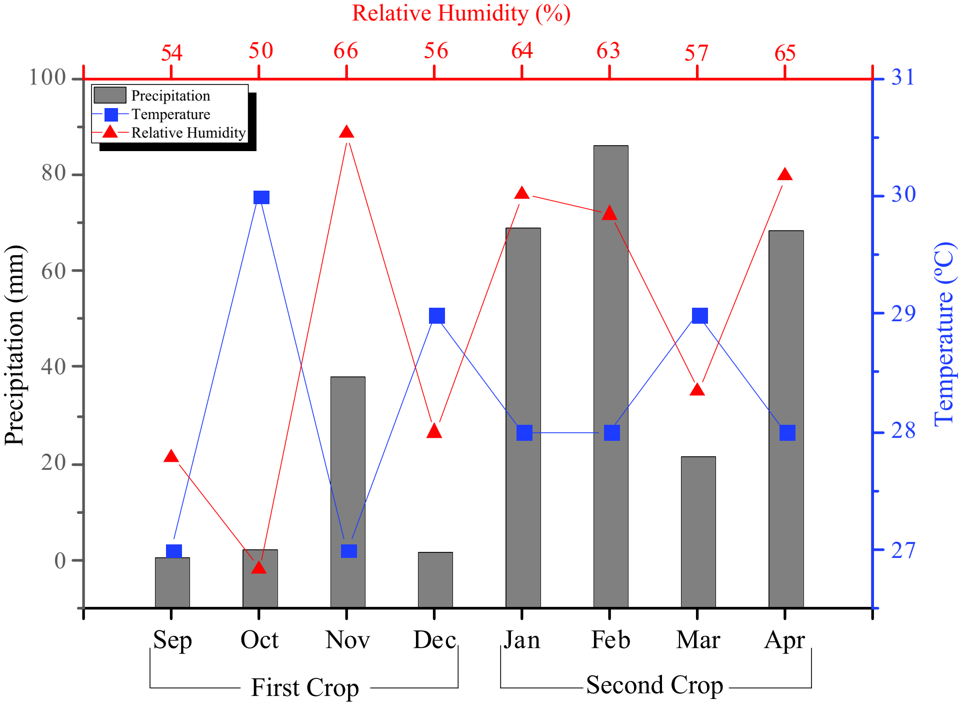


Fig. 2 The changes of mean air temperature, relative humidity and precipitation in two crops (2020–2021) [24]

Table 1 Chemical and physical characteristics of the soils in the experimental areas

Soil Group[a]	pH (H_2O)	H + Al	Ca	Mg	Al	Na	K	P	Si[b]	SOC[c]	Sand	Silt	Clay
	1:2.5	$cmol_c\ dm^{-3}$						mg dm^{-3}		g kg^{-1}			
Ultisol	6.9	0.4	4.7	0.4	0.0	0.07	0.6	315.0	11.2	7.0	804.0	78.0	118.0
Entisol	6.9	0.7	2.3	0.8	0.0	0.03	0.1	65.4	5.1	4.9	918.0	14.0	68.0

[a] Soil classification according to the soil taxonomy system (Keys to Soil Taxonomy 2014); [b]silicon available in the soil extracted with $CaCl_2$ 0,01 mol L^{-1}; [c]soil organic carbon.

2.3 Chlorophyll Fluorescence

Four chlorophyll fluorescence measurements were performed in each treatment plot at the time of fruit harvest. The determinations took place in the middle third of the leaf opposite the first bunch counted from the apex of the branch. First, the leaves were kept in the dark through clipping for 30 min to reach the maximum oxidation state of the photosynthetic electron transport system. After this period, the leaves were exposed to pulses of high-intensity saturated light (2250 mmil m^{-2} s^{-1}) and the fluorescence was measured using a Fluorpen fluorometer, FP 100 model (Photon Systems Instruments). By determining the fast kinetic fluorescence, the initial fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv = Fm – Fo), and quantum yield of photosystem II (Fv/Fm) were obtained.

2.4 Harvest and Chemical Analyses

Leaf samples were taken at the first and second cropping seasons for Arra 15 (November 2020 and April 2021) and BRS Vitoria (November 2020 and March 2021). Ten leaves were collected in each plot to form a composite sample. The leaves were washed in running water, subjected to a triple wash with distilled water, dried in an oven (Solab SL 102/42) at 65 °C for 72 h, and subsequently crushed in a Wiley mill (Tecnal TE-648).

To Si analysis, the leaves were digested by hydrogen peroxide and sodium hydroxide solution in an autoclave. Silicon was measured by photocolorimetry (NI 2000UV, Nova Instruments, Brazil) at a wavelength of 410 nm using ammonium molybdate as a complexing agent [29]. The contents of P, K, Ca, Fe, Cu, Mn, and Zn were determined in extracts from the digestion of leaf samples with $HNO_3 + H_2O_2$ solution (3:1) in a microwave oven (Milestone – Ethos Easy) at 180 °C for 10 min according to modified 3050B methodology [30]. Phosphorus, Ca, Fe, Cu, Mn, and Zn were determined by inductively coupled plasma optical emission spectroscopy (ICP – OES Perkin Elmer Optima 7000 DV). Potassium was measured by flame photometry. The N content was obtained by digesting 0.2 g of the samples in sulfuric acid at 350 ºC, using the Kjeldahl method [31].

The analytical quality control used blank samples and SRM 1570a (Spinach Leaves) certified reference material from the National Institute of Standards and Technology (NIST). The recoveries of elements in the reference material ranged from 76 to 94%.

2.5 Yield and Postharvest Quality of Fruits

The yield was determined by weighing all bunches of four plants in each experimental plot. In addition, six bunches were randomly collected per plot to evaluate the postharvest quality; they were immediately taken to the laboratory for refrigeration and physical and chemical analyses. The physical variables bunch weight (BW), berry diameter (BD), berry length (LC), the number of berries per bunch (BB), berry crunchiness (BC), and berry firmness (BF) were determined. The chemical composition analyzed were soluble solids (SS), titratable acidity (TA), and SS/TA ratio.

Soluble solids (SS) were determined in juice samples using a digital refractometer PAL-1 (Atago, Brazil) with automatic temperature compensation. The results were expressed in percentage. Titratable acidity (TA) was evaluated by titration of 1 mL of juice diluted in 50 mL of distilled water with a solution of 0.1 N NaOH until pH 8.1. Results were expressed as percentage of tartaric acid in the juice. Berry firmness was determined as the maximum force required to press 20% of the fruit diameter with a P/75 (75 mm) pressure plate, whereas berry crunchiness was determined by the penetration of a P/2 (2 mm) probe for 6 mm into the fruit, using a TA.XT.Plus Texture Analyzer (Extralab®, Brazil). Flesh firmness and crunchiness results were expressed in kilogram (kg).

2.6 Statistical Analysis

Data were submitted to analysis of variance (one-way ANOVA) using the F test ($p \leq 0.05$), and, when significant effects were found, a Tukey test for comparing means was performed ($p < 0.05$). All statistical procedures were performed using the SISVAR software (v 5.6).

3 Results

3.1 Fruit Yield

Silicate fertilization significantly increased the yield of table grapes in both seasons for the cultivar BRS Vitoria and the first crop for Arra 15 (Fig. 3). The average yields of BRS Vitoria for the ASF rates of 175 and 350 kg ha^{-1} in the two seasons were 21 to 29 Mg ha^{-1}, i.e., 6 and 18% higher than the control ($p < 0.05$), respectively. For Arra 15, only the 350 kg ha^{-1} ASF rate significantly increased yield (22%) in the dry season (47 Mg ha^{-1}). Given the high market value of the crop, both Si rates can provide sufficient return to cover costs with fertilization. Therefore, the 350 kg ha^{-1} ASF rate is recommended due to the significant effect on yield for both cultivars.

3.2 Fruit Quality

The data on grape bunches and berries under ASF rates are in Table 2. Applying ASF promoted significant effects on the physical parameters BW, BB, and BC. For Arra 15, significant differences occurred only in the dry season. The use of 175 kg ha^{-1} ASF increased the BB by 20%. At the 350 kg ha^{-1}, there were increases of 34% for BB and 20% for BC. In the cultivar BRS Vitória, significant effects were observed in both seasons. In the dry season, the 175 and 350 kg ha^{-1} rates caused an average increase of 11% in BW compared to the control, while the 350 kg ha^{-1} rate increased BB by 29%.

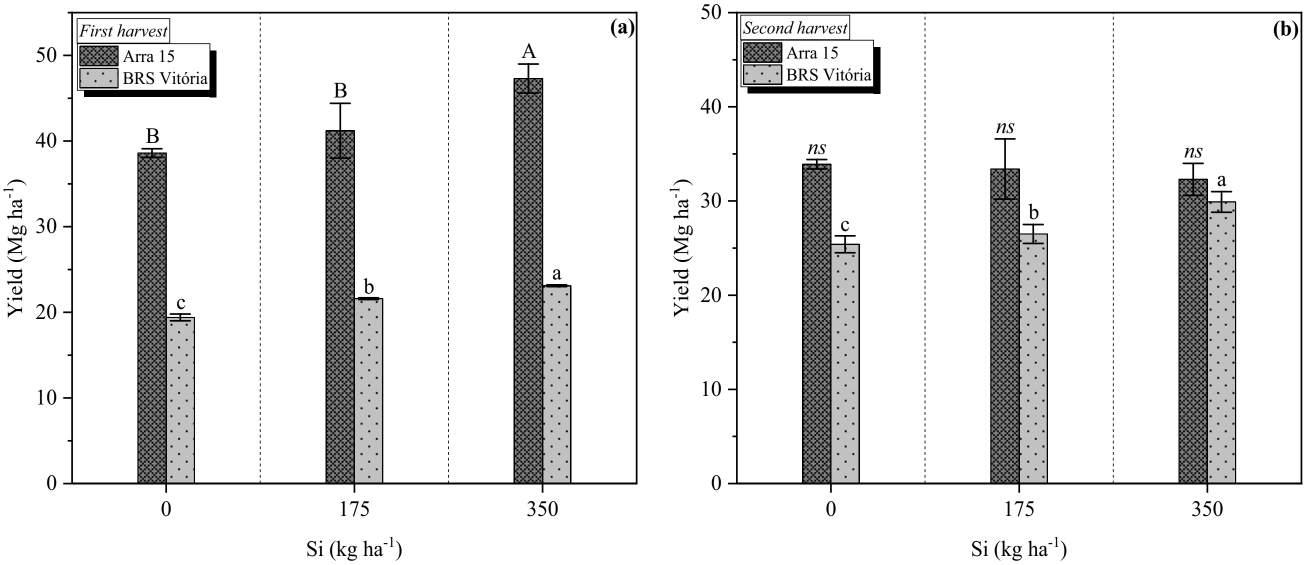


Fig. 3 Mean concentrations and standards deviation for the yield of table grape (*Vitis vinifera* L.) cultivated in soils amended with an amorphous silicon fertilizer (ASF) for two seasons. Values followed by different letters indicate that the ASF rates differ statistically by Tukey's test ($p < 0.05$); ns not significant tukey test ($p < 0.05$)

Table 2 Mean concentrations (± standard deviation) of physical variables of table grape bunches under rates of an amorphous silica fertilizer (ASF, kg ha− 1) applied to the soil in two cropping seasons

Cultivar	ASF	BW^a (g)	BD^b (mm)	BL^c (mm)	BB^d (un.)	BF^e (kg)	BC^f (kg)
	Dry season						
Arra 15	0	173.6 ± 11.9 ns	16.6 ± 0.3 ns	21.2 ± 1.2 ns	55.0 ± 2.1 b	16.8 ± 1.1 ns	0.5 ± 0.01 b
	175	207.5 ± 22.3 ns	16.5 ± 0.3 ns	21.5 ± 0.9 ns	66.0 ± 1.0 a	18.8 ± 0.5 ns	0.6 ± 0.03 ab
	350	215.5 ± 28.8 ns	16.1 ± 0.3 ns	21.3 ± 0.8 ns	74.0 ± 4.3 a	21.2 ± 2.3 ns	0.6 ± 0.03 a
BRS Vitória	0	335.1 ± 5.3 b	18.6 ± 0.3 ns	28.9 ± 0.9 ns	54.0 ± 0.9 b	13.0 ± 1.0 ns	0.4 ± 0.01 ns
	175	369.8 ± 2.4 a	18.9 ± 0.3 ns	30.1 ± 1.1 ns	58.0 ± 1.0 b	13.6 ± 1.4 ns	0.4 ± 0.01 ns
	350	376.9 ± 2.3 a	18.7 ± 0.5 ns	29.6 ± 0.9 ns	70.0 ± 2.3 a	13.3 ± 0.2 ns	0.4 ± 0.02 ns
	Humid season						
Arra 15	0	392.9 ± 40.3 ns	19.1 ± 1.0 ns	28.9 ± 2.1 ns	64.1 ± 13.1 ns	5.7 ± 0.9 ns	0.4 ± 0.01 ns
	175	395.9 ± 17.5 ns	19.8 ± 0.5 ns	29.8 ± 1.3 ns	64.2 ± 1.8 ns	6.1 ± 0.4 ns	0.4 ± 0.03 ns
	350	356.9 ± 21.3 ns	19.6 ± 0.4 ns	29.8 ± 1.2 ns	64.6 ± 11.0 ns	5.8 ± 0.8 ns	0.4 ± 0.03 ns
BRS Vitória	0	159.3 ± 16.6 b	17.6 ± 0.5 ns	23.6 ± 0.8 ns	39.6 ± 5.5 b	4.1 ± 0.1 ns	0.3 ± 0.05 ns
	175	565.9 ± 83.3 a	18.1 ± 0.2 ns	23.2 ± 0.9 ns	70.0 ± 16.4 a	4.0 ± 0.1 ns	0.3 ± 0.01 ns
	350	585.6 ± 80.2 a	17.1 ± 0.4 ns	24.7 ± 0.2 ns	74.0 ± 11.2 a	4.5 ± 0.3 ns	0.3 ± 0.05 ns

^{a} Bunch weight; ^{b}berry diameter; ^{c}berry length; ^{d}berries per bunch; ^{e}berry firmness; ^{f}berry crunchiness; Values followed by different lowercase letters in each parameter indicate that the doses differ statistically by Tukey's test ($p < 0.05$); ns not significant tukey test ($p < 0.05$)

Berry weight tripled in the humid season, with an increase of approximately 80% in BB at the rates 175 and 350 kg ha^{-1}.

Silicon applied to soil also improved the chemical quality of the berries for both cultivars in the dry season. The 350 kg ha^{-1} ASF rate increased the SS contents of Arra 15 and BRS Vitória by 13 and 20%, respectively (Table 3). The TA concentrations for the two cultivars were on average 13% higher in the rates 175 and 350 kg ha^{-1} compared to the control. However, ASF had no significant effect on the SS/TA ratio ($p < 0.05$).

Table 3 Mean concentrations (± standard deviation) of soluble solids (SS), tartaric acid (TA), and the ratio SS/TA of table grapes cultivars amended with an amorphous silica based fertilizer (ASF) applied to the soil

Cultivar	ASF (kg ha^{-1})	SS (%)	TA (%)	SS/TA
		Dry season		
Arra 15	0	11.6 ± 0.1 b	1.9 ± 0.1 b	6.1 ± 0.1 ns
	175	12.5 ± 0.3 ab	2.1 ± 0.1 a	6.0 ± 0.2 ns
	350	13.1 ± 0.4 a	2.1 ± 0.1 a	6.2 ± 0.1 ns
BRS Vitória	0	17.5 ± 0.5 b	0.6 ± 0.1 b	27.9 ± 0.3 ns
	175	19.2 ± 1.0 ab	0.6 ± 0.1 b	29.1 ± 1.3 ns
	350	21.1 ± 1.1 a	0.7 ± 0.1 a	29.4 ± 1.7 ns
		Humid season		
Arra 15	0	14.8 ± 1.0 ns	1.0 ± 0.1 ns	14.2 ± 1.2 ns
	175	14.9 ± 1.2 ns	1.0 ± 0.1 ns	14.3 ± 1.6 ns
	350	14.9 ± 1.2 ns	1.0 ± 0.1 ns	15.5 ± 3.2 ns
BRS Vitória	0	22.2 ± 0.5 ns	0.6 ± 0.1 ns	35.2 ± 4.8 ns
	175	20.9 ± 1.3 ns	0.7 ± 0.1 ns	29.9 ± 4.5 ns
	350	21.3 ± 2.5 ns	0.7 ± 0.1 ns	28.0 ± 2.9 ns

SS: soluble solids (°Brix); TA: titratable acidity (g. tartaric acid.100 g $^{-1}$). Values followed by different lowercase letters in each parameter indicate that the doses differ statistically by Tukey's test ($p < 0.05$); ns not significant tukey test ($p < 0.05$)

3.3 Effects of ASF on the Chemical Composition of Leaves

The season affected the leaf Si concentration as leaves sampled in the dry season showed Si concentrations higher than in the humid season (Table 4). It is likely that the high rain intensity in the humid season right after Si application to the soil (Fig. 2) promoted Se leaching to below roots uptake zone. The Si contents in leaves showed a significant difference only for the BRS Vitória in the dry season, increasing approximately three times at 175 and 350 kg ha^{-1} ASF. In general, the most significant nutritional effects were observed in this season (Table 4). For the macronutrients N and P, the rates of 175 and 350 kg ha^{-1} showed increases between 12 and 19%, respectively, in the two cultivars. BRS Vitória also showed an increase of 13% in Ca leaf concentration when supplied with 350 kg ha^{-1} ASF. Additionally, this cultivar showed increases in Fe (13%), Cu (27%), and Zn (45%) concentrations at both rates of ASF applied to the soil. The increased micronutrient accumulation in Arra 15

Table 4 Mean concentrations (±standard deviation) of Si and nutrients in the shoots of table grape (*Vitis vinifera* L.) cultivated in soils amended with an amorphous silicate fertilizer (ASF) for two cropping seasons

Cultivar	ASF kg ha^{-}	Si leaf g kg^{-1}	N	P	K	Ca	Fe mg kg^{-1}	Mn	Cu	Zn
		Dry season								
	0	10.7 ± 0.7 ns	30.4 ± 0.7 b	6.6 ± 0.6 b	7.0 ± 0.8 ns	17.3 ± 1.1 ns	93.6 ± 6.6 ns	68.1 ± 6.8 c	6.9 ± 0.3 ns	13.2 ± 1.2 ns
Arra 15	175	13.1 ± 1.5 ns	31.9 ± 0.5 ab	7.7 ± 0.2 a	6.7 ± 0.1 ns	19.8 ± 0.4 ns	105.3 ± 1.2 ns	82.3 ± 0.9 b	7.4 ± 0.2 ns	14.6 ± 0.4 ns
	350	12.6 ± 0.6 ns	34.3 ± 1.7 a	8.0 ± 0.1 a	6.4 ± 0.3 ns	18.7 ± 1.5 ns	109.9 ± 8.5 ns	93.9 ± 4.3 a	7.8 ± 0.8 ns	15.4 ± 1.4 ns
	0	8.3 ± 2.1 b	25.7 ± 1.5 b	2.2 ± 0.2 b	4.5 ± 0.3 ns	18.9 ± 0.4 b	59.8 ± 0.3 b	66.2 ± 5.6 ns	5.7 ± 0.1 b	16.7 ± 1.8 b
BRS Vitória	175	23.5 ± 3.1 a	28.9 ± 1.2 a	2.6 ± 0.1 ab	5.1 ± 0.3 ns	20.2 ± 1.0 ab	62.1 ± 2.1 b	77.9 ± 7.8 ns	6.9 ± 0.4 a	23.1 ± 2.3 a
	350	30.3 ± 3.1 a	29.6 ± 0.8 a	2.6 ± 0.1 a	5.1 ± 0.5 ns	21.4 ± 0.9 a	67.6 ± 2.8 a	83.6 ± 5.7 ns	7.6 ± 0.3 a	25.3 ± 1.0 a
		Humid season								
Arra 15	0	4.0 ± 0.5 ns	31.9 ± 2.8 ns	7.0 ± 1.0 ns	7.3 ± 1.0 a	18.1 ± 1.7 ns	102.9 ± 14.7 ns	80.0 ± 18.1 ns	7.8 ± 0.7 ns	15.4 ± 1.4 ns
	175	3.9 ± 0.4 ns	32.0 ± 0.5 ns	7.2 ± 1.0 ns	6.3 ± 0.8 ab	19.8 ± 0.4 ns	101.9 ± 6.0 ns	78.5 ± 16.4 ns	6.9 ± 0.7 ns	14.1 ± 0.9 ns
	350	5.2 ± 2.6 ns	33.4 ± 2.4 ns	6.8 ± 1.0 ns	6.1 ± 0.2 b	18.7 ± 1.5 ns	95.9 ± 5.4 ns	68.4 ± 13.1 ns	6.3 ± 0.9 ns	12.3 ± 1.9 ns
BRS Vitória	0	3.6 ± 0.8 ns	18.6 ± 0.7 ns	1.0 ± 0.1 ns	1.9 ± 0.1 ns	11.0 ± 1.1 ns	41.4 ± 1.7 b	64.7 ± 12.2 ns	35.2 ± 4.1 ns	18.9 ± 0.6 a
	175	3.5 ± 0.6 ns	21.2 ± 2.4 ns	1.0 ± 0.2 ns	2.1 ± 0.3 ns	11.0 ± 0.3 ns	36.5 ± 2.5 b	61.1 ± 5.6 ns	30.6 ± 7.0 ns	15.4 ± 0.5 b
	350	4.7 ± 0.6 ns	20.9 ± 0.6 ns	0.9 ± 0.1 ns	1.7 ± 0.1 ns	9.3 ± 1.2 ns	38.0 ± 2.4 a	49.8 ± 8.4 ns	35.4 ± 5.7 ns	18.1 ± 1.7 a

Values followed by different lowercase letters in each parameter indicate that the doses differ statistically by Tukey's test ($p < 0.05$); ns not significant Tukey test ($p < 0.05$)

occurred only for Mn: 20 and 38% in the dry season at rates of 175 and 350 kg ha^{-1}, respectively.

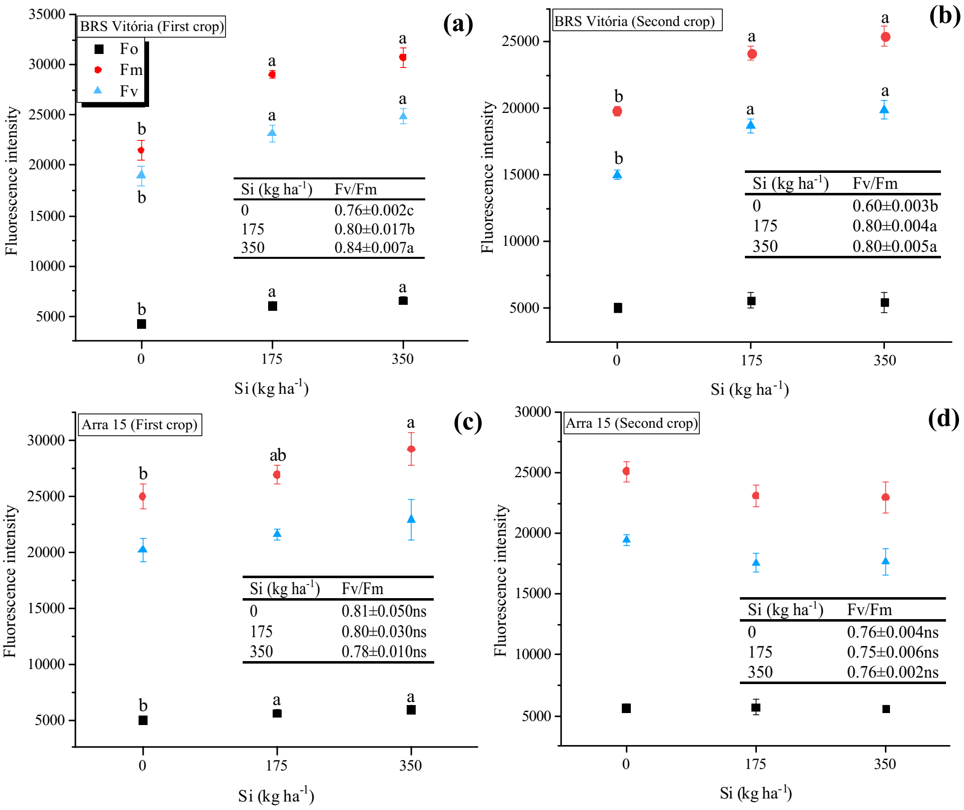
3.4 Chlorophyll-a Fluorescence

Fluorescence (Fm), variable fluorescence (Fv), and photosystem II quantum yield (Fv/Fm) of the two cultivars evaluated during the two seasons (Fig. 4). The 175 and 350 kg ha^{-1} rates promoted significant increases for Fo (48%), Fm (39%), and Fv (26%) of the cultivar BRS Vitória in the dry season. Additionally, the Fv/Fm of this cultivar increased 5 and 10% in the rates of 175 and 350 kg ha^{-1}, respectively. In the humid season, significant effects were found at 175 and 350 kg ha^{-1} with increased fluorescence intensities for Fm (25%), Fv (28%), and Fv/Fm (33%). For cultivar Arra 15, significant increases occurred only in the dry season for Fo (16%), at 175 and 350 kg ha^{-1}, and Fm (17%), at 350 kg ha^{-1}. Fv and Fv/Fm in the dry season and all parameters evaluated in the humid season did not show significant differences regarding ASF application to the soil ($p < 0.05$).

4 Discussion

Abiotic stresses, especially drought and heat, are the main plant stresses in semiarid ecosystems [32, 33]. Therefore, soil and plant amendments alleviating such stresses can potentially increase the yield and quality of fruits produced in these conditions. The application of ASF significantly increased the yield of table grapes due to increases in bunch weight and the number of berries per bunch. The yield increase between 6 and 22% is highly significant for high-value crops such as the grape varieties tested here. Moreover, such yield increases can pay off the investment in silicon fertilizers. Correlations between table grape yield and bunch and berry weights were found in other studies and associated with the effect of Si as a mediator in the transport of water along with the plant to the fruits, thus increasing the berry filling potential [23, 34]. These results indicate that Si fertilization increased the water retention inside the fruit and inhibited fruit decay [23]. Therefore, Si can help berries maintain their size under declining soil moisture conditions, which is desirable in premium fruit production. Furthermore, the commercial quality of the berries, measured by variables such as soluble solids content, titratable acidity, and crunchiness, was also significantly improved with the Si application. Similarly, Si uptake through the roots improved the yield and quality of other fruit crops, such as strawberries [35] and melons [9].

Similar results have been reported and attributed to the increased concentration of sugars and starch in grapes driven by Si [20, 23], likely due to the combined beneficial effect of better photosynthetic performance and transport of solutes in the phloem in the source-drain direction, resulting in



(a)

Si (kg ha-1)	Fv/Fm
0	0.76±0.002c
175	0.80±0.017b
350	0.84±0.007a

(b)

Si (kg ha-1)	Fv/Fm
0	0.60±0.003b
175	0.80±0.004a
350	0.80±0.005a

(c)

Si (kg ha-1)	Fv/Fm
0	0.81±0.050ns
175	0.80±0.030ns
350	0.78±0.010ns

(d)

Si (kg ha-1)	Fv/Fm
0	0.76±0.004ns
175	0.75±0.006ns
350	0.76±0.002ns

Fig. 4 Initial fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv), and photochemical efficiency index, (Fv/Fm) of table grape (*Vitis vinifera* L.) cultivars under application of an amorphous silica fertilizer (ASF) to the soil. Values followed by different lowercase letters in each parameter indicate that the ASF doses differ statistically by Tukey's test ($p < 0.05$); ns not significant tukey test ($p < 0.05$)

higher accumulation of carbohydrates in the berries. Additionally, Si accumulates under the berry cuticles, forming a cuticle-silicon double layer, strengthening the cell wall structures, reducing fruit weight loss, and increasing shelf life [36]. Zhang et al. [23] reported that Red Globe grapes' weight loss was 19% higher, on average, in control compared to the Si fertilizer application. These characteristics are of great importance as they mainly meet the requirements of the export market.

Silicon concentrations in the leaves of Arra 15 and BRS Vitória were higher than reported for the cultivars Monukka and Red Globe grew on calcareous grey desert soil amended with 600 kg ha^{-1} SiO_2 applied as steel slag fertilizer [23]. Such difference can be due either to the lower solubility of steel slag than ASF or the higher temperatures in our study that increase Si uptake driven by transpiration. It is well known that Si can reduce the excessive leaf transpiration through cuticular layers thickened by silica deposits under normal growth conditions [37]. However, Si plays a role in maintaining higher transpiration rates and root water uptake under stress conditions [38, 39], such as those in semiarid climates, which increases the uptake of Si and nutrients.

The positive effects of ASF on plant mineral nutrition may be related to direct and indirect effects of Si in the soil and the plant. The ASF tested aids in the retention of cationic ions as it is a porous material (35–65%) and has a relatively high specific surface (CTC > 50 $cmol_c$ kg^{-1}) [18]. The application of ASF may have contributed to the increase of negative charges in the soil, favoring the retention and consequently improving the uptake of cationic macro and micronutrients, especially for the sandy, low CTC soils studied here. Furthermore, the competition between monosilicic acid and phosphates for the adsorption onto Fe oxides provides the release and increases the P availability in the soil [40]. Additionally, P has a synergistic and essential interaction in N metabolism, increasing the efficiency of the N distribution to the plant [41, 42]. Increased nutrient accumulation in Si-treated plants is also associated with the increase in citrate concentration triggered by the application of Si in the soil and favoring the integrity of membranes, resulting in a better redistribution of elements and metabolic functioning of plants [43, 44]. Besides, Oliva et al. [15] related the entry of micronutrients into sandy soils as impurities during ASF application with the respective increases in micronutrient contents in plants.

Photosynthesis is one of the critical physiological processes affected by the drought and heat stress in semiarid environments [45]. The chlorophyll a fluorescence is an efficient parameter to study physiological characteristics and activities of the photosystem II. It has been used to monitor changes in the photosynthetic system caused by environmental stresses fast, non-invasive, and non-destructive [46–49]. In addition to assessing photosystem II (PSII) functionality, it reflects the electron transport rate within the thylakoid membrane and the subsequent functioning of the ferredoxin-NADP oxidoreductase and Calvin cycle [50, 51].

Chlorophyll-a fluorescence has been used to monitor the tolerance of plants to various stresses and nutritional requirements. Therefore, changes in fluorescence parameters observed through increases in Fo, Fv, and photosystem II quantum yield were associated with water deficiency indicators in vines due to variation in soil moisture [52]. In this regard, the influence of water stress on the photosynthetic performance was due to the rapid reactive oxygen species (ROS) accumulation, which causes photoinhibition in PSII reaction centers [53]. Under stress conditions, typically, Fo is increased, and the Fv/Fm ratio is reduced [47, 52]. An increase in Fo suggests photosystem II degradation or interference in transferring excitation energy from the antenna to reaction centers [54]. We found high Fo values for the two cultivars in the period of more significant water stress (dry season) and rates of 175 and 350 kg ha^{-1}. The Fo values of the humid season were lower than those of the dry season, confirming the occurrence of higher hydric stress. In addition, the high temperatures recorded in this season have also been reported to trigger the production of ROS [45]. Such findings reinforce the role of Si in ameliorating water and heat stresses in the semiarid.

The negative effect on Fo caused by applying ASF can be attributed to the formation of large starch grains that destroyed thylakoids, reducing the number of photochemical reactions [20]. However, the Fv/Fm values for BRS Vitória in the two seasons without ASF application were close to or below the level considered as severe water stress (< 0.70) [55]. This result indicates the positive and most significant action of Si on the evaluated parameters of this cultivar. The ASF tested here has been shown to improve the water use efficiency for onions grown in a semiarid climate [33], which can be responsible for the better response to Si of grapes cultivated in the dry season. Besides, as water and heat stress commonly coincides, Si may have played a role in diminishing the damage caused by the high temperatures in the dry season. The maximum photochemical efficiency ratio (Fv/Fm) in Si-treated plants may be related to the protection of the photosynthetic apparatus driven by Si, such as forming chloroplast ultrastructure [20]. Therefore, the Fv/Fm may represent a good indicator of the influence of FSA application on table grapes. The increase in quantum yield was likely to have a more significant impact on production variables of the cultivar BRS Vitória compared to Arra 15.

Silicon is responsible for increasing root hydraulic conductance and cell wall stability, conferring high tolerance to a certain degree of water deficit [56, 57]. It is also reported that this element can reduce water loss through transpiration and increase water uptake by roots [34]. It is worthy to notice that the average precipitation during the dry season

(10 mm) was six times lower than in the humid season [24]. Therefore, the higher rainfall in the region in the humid season likely limited the Si action since the soils naturally have low Si available contents and a sandy texture, characteristics that make Si prone to leaching. Such hypothesis is confirmed by the higher Si concentration in the leaves sampled in the dry season.

5 Conclusions

Abiotic stresses such as drought and heat are severe drawbacks to the yield and quality of grapes growing in semiarid settings. We found that applying an amorphous silica based-fertilizer to soil improved the nutritional status and ameliorated abiotic stresses in two table grapes cultivars and significantly affected the yield and the quality of berries. The magnitude of such effects depended on the cropping season. The better Si response in the plants grown during the dry season was probably due to the higher leaf Si concentration. On the other hand, it is likely that heavy rains in the humid season resulted in Si leaching and decreased plant uptake with concomitant reduced effects on plant stress. The alleviation of damage to the photosynthetic apparatus seems to be one of the primary mechanisms for the Si positive effects found here. Despite the highly heterogeneous photosynthetic performance, especially under the more stressful conditions of the dry season, chlorophyll fluorescence *a* constitutes a promising tool for investigating the effects of Si on the performance of table grapes in the study region. Overall, our findings support that silicon can make part of the management of table grapes in semiarid climates, where abiotic stresses are intense and limit the yield and quality of table grapes.

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Authors Contribution Clístenes Williams Araújo do Nascimento was responsible for the study conception and design. Material preparation, data collection and analysis were performed by Clístenes Williams Araújo do Nascimento, Fernando Bruno Vieira da Silva, Luiz Henrique Vieira Lima, Josévaldo Ribeiro Silva, Franklone Lima da Silva, Luana Ferreira dos Santos, Monaliza Alves dos Santos and Sérgio Tonetto de Freitas. The first draft of the manuscript was written by Clístenes Williams Araújo do Nascimento and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability All the data and materials are included in the article or available under reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication All authors have provided consent for publication.

Competing Interests All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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