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PHYSIOLOGICAL ADJUSTMENTS, YIELD INCREASE AND FIBER QUALITY OF 'BRS RUBI' NATURALLY COLORED COTTON UNDER SILICON DOSES[1]

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ABSTRACT – Globally, the demand for food and consumer products has accompanied population growth, forcing the agriculture and livestock sector to optimize the production systems. In the specific case of agriculture, using improved edible and energetic plant cultivars associated with abiotic stress-reducing substances is a strategy adopted to solve this problem. This investigation aimed to evaluate whether silicon (Si) promotes physiological adjustments, an increase in production, higher yield, and improved quality of naturally colored cotton fibers. Five doses of silicon (0 (control), 5, 10, 15, and 20 kg ha^{-1}) were tested in a completely randomized design. The variables assessed were physiological adjustments, production, yield and quality of fibers produced by BRS Rubi cultivar. Data were submitted to principal component analysis, multivariate and univariate analyses of variance, and multiple linear regression analysis. Silicon promotes physiological adjustments, enhanced production, yield, and quality of naturally colored cotton fibers of BRS Rubi cultivar grown in the Brazilian semiarid region. Fiber quality in plants that have been treated with Si is within the expected values for this cultivar and by the international standard D-4605 of the American Society for Testing and Materials. 10 kg ha^{-1} of Si is recommended to increase fiber quality of naturally colored cotton cv. BRS Rubi.

Keywords: *Gossypium hirsutum*. Semi-arid region. Abiotic stresses. Potassium silicate.

AJUSTES FISIOLÓGICOS, RENDIMENTO E QUALIDADE DA FIBRA DO ALGODÃO COLORIDO 'BRS RUBI' SOB DOSES DE SILÍCIO

RESUMO – Globalmente, demanda por alimentos e bens de consumo tem acompanhado o crescimento populacional, pressionando o setor agropecuário a otimizar os sistemas de produção. No caso específico da agricultura, a utilização de cultivares de plantas alimentícias e energéticas melhoradas e associadas ao uso de substâncias atenuadoras dos estresses abióticos, são estratégias adotadas para solucionar esse problema. Objetivou-se avaliar se o silício (Si) promove ajustes fisiológicos, aumento de produção, rendimento e qualidade de fibras de algodoeiro naturalmente coloridas. Foram testadas cinco doses de silício (0 (controle), 5, 10, 15, 20 kg ha^{-1} de Si), em delineamento inteiramente casualizado, em vasos. Foram avaliadas variáveis fisiológicas, produção, rendimento e qualidade de fibras da cultivar BRS Rubi. Os dados foram submetidos às análises de componentes principais, variância multivariada e univariada e regressão linear múltipla. O silício promove ajustes fisiológicos, aumento de produção, rendimento e qualidade de fibras de algodão. A qualidade das fibras de plantas tratadas com Si está dentro dos valores esperados para esta cultivar e em conformidade com a norma internacional D-4605 da American Society for Testing and Materials. Recomenda-se aplicações de 10 kg ha^{-1} de Si para aumentar a qualidade de fibras de algodão naturalmente coloridas cv. BRS Rubi.

Palavras-chave: *Gossypium hirsutum*. Região semiárida. Estresses abióticos. Silicato de potássio.

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INTRODUCTION

The demand for food is a current concern and deserves to be highlighted in the field of science (MOLAJOU et al., 2021). Research needs to be carried out to ensure food security because it is estimated that the growing population will reach 11 billion people by 2050 on Earth, which generates a greater demand for food, feed, fiber, and energy, highlighting the need to increase food production by 2 to 3 times (HIDAYAT; NURINDAH; SUNARTO, 2020). Cultivating species adapted to different agro-ecosystems, with potential for multiple uses, for example in the food, industry, and energy sectors and associated with substances that elicit abiotic stresses, for example potassium silicate, is an important strategy for world food production (ANDRADE et al., 2021).

Among the agricultural species grown worldwide for food, textile, and energy purposes, cotton (*Gossypium hirsutum* L.) stands out in the economic, social, and environmental sectors because it can be grown in different agricultural management systems and with different technological levels (DIAS et al., 2020). In the 2020/2021 harvest in Brazil, the area cultivated with cotton was 1.37 million ha, and the production was 2.36 million tons. In the Brazilian Northeast, 0.307 million ha were cultivated, and 0.574 million tons were produced, while in the state of Paraíba 1.5 thousand ha were cultivated, and 0.6 thousand tons were produced (CONAB, 2021). In these circumstances, the naturally colored fiber cotton (NCF) has received the attention of breeding programs, mainly in Northeast Brazil, due to the technological differential of these fibers (ALBUQUERQUE et al., 2020).

NCF has been grown in Mexico since 3400-2300 B.C., Peru since 3100 B.C., Egypt since 2250 B.C., and China since 1200 A.D. (HIDAYAT; NURINDAH; SUNARTO, 2020). However, the quality of its fibers has been considered inferior to that of white fibers. This low quality of NCF is associated with reduced production due to the occurrence of abiotic stresses during its growth cycle, which requires technological alternatives in all phenological stages since most cultivars cultivated in Brazil are not well adapted to stressful environments (VASCONCELOS et al., 2020).

An ecologically correct and promising technological alternative to mitigate abiotic stresses is the use of silicon (Si) because this ion is linked to the growth and increase of crop production (ETESAMI; JEONG; RIZWAN, 2020; VERMA et al., 2020). The mechanisms by which Si attenuates the effect of stresses are related to the accumulation of ions in the root apoplast, the reduction of root hydraulic conductivity and transpirational flow, gene expression, increase of compatible solutes, antioxidative enzymes activity, and photosynthetic activity (THORNE; HARTLEY; MAATHUIS, 2020).

The application of Si on cotton plants improves their production and fiber quality since this ion is present from the anthesis until the development of the fibers (BOYLSTON, 1988; BOYLSTON et al., 1990), which demonstrates the importance of this nutrient in improving germination (FERRAZ et al., 2017), increasing photosynthesis, stomatal conductance, and water use efficiency (FERRAZ et al., 2014; BARROS et al., 2019), as well as reducing stresses (OLIVEIRA et al., 2012; ANWAAR et al., 2015). When studying the foliar application of Si on colored fiber cotton plants, Ferraz et al. (2021a, b) observed physiological adjustments and increases in yield and fiber quality of cultivars BRS Safira and BRS Topázio. The objective was to evaluate whether Si promotes physiological adjustments, increases the production, and the quality of the fibers of the naturally colored cotton.

MATERIAL AND METHODS

The research was carried out in Embrapa Cotton experimental area, located in the micro-region of Campina Grande, Paraíba state, Brazil, at the geographic coordinates: 07°13' south latitude and 53°31' west longitude, an altitude of 551 meters, with semi-arid equatorial climate, average temperature of 25 ºC and relative air humidity varying between 72 and 91%. Meteorological data such as air temperature, relative humidity, and rainfall were collected from an automated agrometeorological station located 100 m from the experimental area (Figure 1).

During the experimental period the following values were observed: rainfall - average 0.5 ± 1.6 mm and accumulated 69.6 mm; air temperatures - minimum 20.2 ± 1.0 °C, average 23.4 ± 0.9 °C, and maximum 29.4 ± 1.5 °C; relative air humidity - 77.5 ± 4.6%; daily sunshine - 8.1 ± 2.0 hours; and class A pan evaporation - average 4.8 ± 1.3 mm and accumulated 738.8 mm (Figure 1). This variability characterizes the Brazilian Northeast weather, which requires adequate management for greater cotton yield.

The experimental design was completely randomized with five doses of silicon (0 (control), 5, 10, 15, and 20 kg ha^{-1} of Si), considering the planting density of 100,000 plants ha^{-1}, and four replications in a total of 20 experimental plots for BRS Rubi cotton cultivar; this cultivar was developed by Embrapa Cotton breeding program (CARVALHO; ANDRADE; SILVA FILHO, 2011). Si doses were obtained by diluting potassium silicate (K_2SiO_3) in distilled water. Silicon source (Sifol®) was a liquid solution composed of 12% Si and 15% K and electric conductivity - EC of 1.93 dS m^{-1}, salt index of 26, density of 1.40 g L^{-1}, and pH of 10.96.

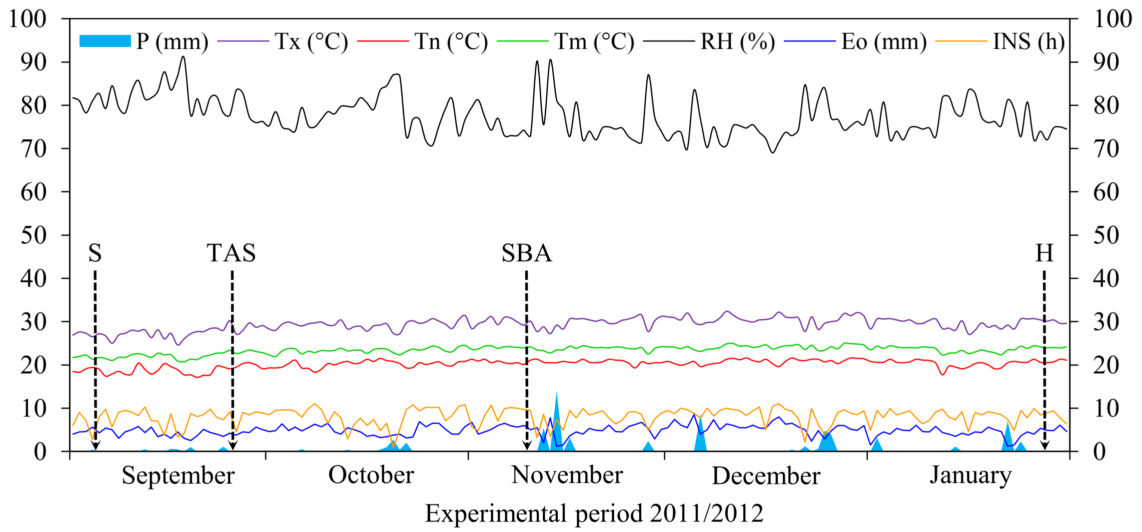


Figure 1. Meteorological variables recorded during the experimental period in Campina Grande, PB, Brazil. Precipitation (P); Mean air temperature (Tm); Minimum air temperature (Tn); Maximum air temperature (Tx); Mean air relative humidity (RH); Class 'A' pan evaporation (Eo); Daily insolation (INS); Sowing (S); Treatment application start (TAS); Sampling for biochemical analysis (SBA) and Harvest (H).

The experimental unit consisted of one cotton plant per pot (200 dm^3 in volume) filled with 10 dm^3 of crushed stone No. 2 and 180 dm^3 of soil classified as Neossolo Flúvico distrófico (SANTOS et al., 2018) or Fluvisol (FAO, 2015) or even dystrophic Fluvent Entisol by U.S. Soil Taxonomy (SOIL SURVEY STAFF, 2014), and with the following chemical and physical characteristics: pH in H_2O = 5.1; P = 0.3 mg dm^{-3}; K^+ = 0.5 $mmol_c$ dm^{-3}; Na^+ = 0.4 $mmol_c$ dm^{-3}; Ca^{+2} = 3.7 $mmol_c$ dm^{-3}; Mg^{+2} = 6.5 $mmol_c$ dm^{-3}; Al^{+3} = 5.0 $mmol_c$ dm^{-3}; H^++Al^{+3} = 28.9 $mmol_c$ dm^{-3}; T = 40.0 $mmol_c$ dm^{-3}; V = 28.0%; OM = 3.6 g kg^{-1}; N = 0.0 g kg^{-1}; sand = 81.44%; silt = 13.79%; clay = 4.77%; bulk density = 1.52 g cm^{-3}; particle density = 2.85 g cm^{-3}; porosity = 46.67%; natural moisture = 0.30%; available water = 1.43% and sandy loam texture.

Liming based on exchangeable Al was done with 1.2 t ha^{-1} of dolomitic limestone (90% of total neutralizing power). After liming, the soil was incubated for 60 days, turned and irrigated weekly with moisture kept close to 70% of field capacity. Afterward, N (2.7 g dm^{-3}), P (0.6 g dm^{-3}), and K (1.8 g dm^{-3}) fertilizers were applied. P source was applied 15 days before sowing, and N and K sources were split into two applications until flowering.

Seeds were treated with Thiram® fungicide at the proportion of 500 g of commercial product for 100 kg of seeds; afterward, 5 seeds were sown per experimental unit at 0.03 m depth. At 15 days after emergence (DAE), seedlings were thinned, and the most vigorous was selected in each experimental unit.

Initially, irrigation was used to keep soil moisture close to 70% of field capacity. The replacement of the water evapotranspired by plants (ETc) was done based on the class A pan evaporation (Eo) and the crop coefficient (Kc) throughout the phenological stages (BEZERRA et al., 2012):

$$ETc = Eo * Kc$$

Where, ETc is crop evapotranspiration (mm day^{-1}), Eo is reference evaporation estimated by class 'A' pan (mm day^{-1}), and Kc is crop coefficient.

After 15 DAE, Si was sprayed on the leaves weekly, in their abaxial and adaxial sides, until the solution drained. The surface of the pots was covered with plastic tarpaulin to prevent residual effect of silicon on the soil; also, a surfactant was used to increase the efficiency of Si application with a manual compression sprayer with a volume of 5 dm^3, a piston-type pump, and a 34 mm diameter nozzle.

During full bloom period (60 DAE), the first leaves, that is, fully expanded and counted from the base of the first branch with a floral bud, were identified, collected, and stored at -20 °C. Afterward, 113 mm^2 leaf discs were collected with a copper hole punch tool. These discs were used for extraction and quantification of chloroplast pigments contents, intracellular electrolyte leakage, and leaf relative water content.

The methodology proposed by Arnon (1949) and adapted by Hiscox and Israelstam (1979) was used to extract chlorophylls *a* (Chla), *b* (Chlb), and total (Chlt). Total carotenoids (Tcar) were quantified using the equation described by Wellburn (1994).

Intracellular electrolyte leakage (IEL) was assessed by the methodology described by Brito et al. (2011). After incubation, the electrical conductivity of the medium (EC_i) was measured with a conductivity meter (W12D, BEL ENGINEERING, Italy). Then, these samples were subjected to 80 ºC for 90 minutes in an oven, and the conductivity was measured again (EC_f); then, the electrolytic leakage was quantified by:

$$IEL=\left(\frac{EC_i}{EC_f}\right)*100$$

where IEL is intracellular electrolyte leakage (%), EC_i is initial electrical conductivity of the medium (dS m^{-1}), and EC_f is final electrical conductivity of the medium (dS m^{-1}).

Relative water content in the leaf (RWC) was quantified by the methodology described by Brito et al. (2011):

$$RWC=\left(\frac{DFM - DDM}{DTM - DDM}\right)*100$$

where RWC is relative water content in the leaf (%), DFM is disc fresh matter mass (g), DDM is disc dry matter mass (g), and DTM is disc turgid matter mass (g).

Manual cotton harvesting was carried out at 145 DAE, when the number of bolls per plant (NBO, units per plant) was quantified. Harvested material was weighed on a scale (accuracy of 0.001 g) to quantify the boll mass per plant (BMP, g) and the average mass of one boll (AMB, g). The harvest index (HI) was obtained with the relationship between BMP and shoot dry matter weight according to Hussein, Janat and Yakoub (2011):

$$HI=\left(\frac{BMP}{SDM}\right)$$

where HI is harvest index, dimensionless, BMP is boll mass per plant (g), and SDM is shoot dry matter mass (g).

Cotton samples quality was measured with an HVI (High Volume Instrument) by determining the upper half mean length (UHM, mm), fiber length uniformity index (FUI, %), short fiber index (SFI, %), specific strength or toughness of fiber (STR, gf tex^{-1}), elongation at break (ELG, %), micronaire fiber index (MIC, µg in^{-1}), fiber maturity index (FMI), and count strength product or reliability index (CSP, %) (ALMEIDA et al., 2011). The classification was evaluated by the standard values of each cultivar (CARVALHO; ANDRADE; SILVA FILHO, 2011), by the cotton fiber quality manual (LIMA, 2018), and HVI test results (FONSECA; SANTANA, 2002) according to the American Society for Testing and Materials international standard D-4605.

Data were submitted to the normality test, standardized to obtain zero mean ($\overline{X}$ = 0.0) and unit variance (s^2 = 1.0) and submitted to exploratory Principal Component Analysis (PCA). To discuss the principal components (PCs), eigenvalues greater than the unit ($\lambda > 1.0$) were considered, according to Kaiser (1960), which could explain more than 10% of the total variance (GOVAERTS et al., 2007).

Variables with correlation coefficient (r) greater than 0.65 were maintained in PC (HAIR JUNIOR et al., 2009). Variables not associated with PCs (r <0.65) were removed from the standardized database, and a new analysis was performed. Variables on each PC were submitted to multivariate analysis of variance (MANOVA) by Roy's test (P <0.05). The data of original variables not associated with PCs were submitted to univariate analysis of variance (ANOVA) by F test (P <0.05). Statistical analyses were processed with the software program Statistica v. 7.0 (STATSOFT, 2004).

The data of variables of each PC were submitted to multiple linear regression analysis (MLRA), considering each variable of fiber quality as a dependent variable and the other variables contained in the same PC, plus the doses of Si, as independent variables, to fit forecasting models for fiber quality variables. The multiple linear regression model with k independent variables was used:

$$FQV=\alpha+\sum_{i=1}^{K}\beta_i X_{ij}+\varepsilon_j$$

where FQV is each fiber quality variable, α is linear coefficient, βi is regression coefficient of the independent variables, Xij is independent variable Xi in observation j, εj is error associated with FQV in observation j, and K is number of independent variables (CARGNELUTTI FILHO; STORCK; LÚCIO, 2004).

RESULTS AND DISCUSSION

PCA and MANOVA results are shown in Table 1. The multiple dimensions, represented by 18 original variables evaluated, were condensed into two dimensions, represented by the principal components (PC_1 and PC_2) with eigenvalues greater than the unit ($\lambda > 1.0$). There was a significant effect ($p < 0.01$) of Si doses in two PCs.

The first two PCs explained 82% of the total experimental variance (s^2), where PC_1 explained 41.46% of s^2 and it was comprised by a linear combination of pigments (Chla, Chlt, and Tcar), number of bolls (NBO), and fiber quality variables (UHM, FUI, SFI, STR, and CSP); and PC_2 contributed to 35.59% of the remaining variance and was formed by the relative water content in the leaves (RWC), average mass of boll (AMB), boll mass per plant (BMP), and fiber quality variables (ELG and MIC). There was loss of information on 18% of s^2. The chlorophyll ‘b’ content (Chlb), intracellular electrolyte leakage (IEL), harvest index (HI), and fiber maturity index (FMI) were not associated with PCs.

Table 1. Correlation among original variables and principal components, eigenvalues, explained and accumulated variance, and probability significance of hypothesis test.

EV – Evaluated Variables	Principal Components	
	PC_1	PC_2
Chla – Chlorophyll ‘*a*’	-0.78^*	-0.63
Chlb – Chlorophyll ‘*b*’	r-PCA	r-PCA
Chlt – Total chlorophyll	-0.82^*	-0.54
Tcar – Total carotenoids	-0.82^*	-0.42
IEL – Intracelular electrolyte leakage	r-PCA	r-PCA
RWC – Relative water content	0.46	0.65^*
NBO – Number of bolls	0.73^*	0.59
AMB – Average mass of boll	-0.57	-0.75^*
BMP – Boll mass per plant	0.24	-0.75^*
HI – Harvest index	r-PCA	r-PCA
UHM – Upper-half mean length	0.86^*	-0.36
FUI – Fiber length uniformity index	0.80^*	-0.46
SFI – Short fiber index	-0.77^*	0.61
STR – Specific strength or toughness of fiber	0.66^*	-0.34
ELG – Elongation at break	-0.63	0.76^*
MIC – Micronaire fiber index	0.03	0.70^*
FMI – Fiber maturity index	r-PCA	r-PCA
CSP – Count strength product or reliability index	0.77^*	-0.56
λ – Eigenvalues	6.50	4.98
S^2 (%) – Explained variance	46.41	35.59
S^2 (%) – Accumulated variance	46.41	82.00
Roy’s test (*p* valor)	< 0.01	< 0.01

r-PCA – Variable removed from principal component analysis. * – Variable considered relevant in each principal component ($r \geq 0.65$).

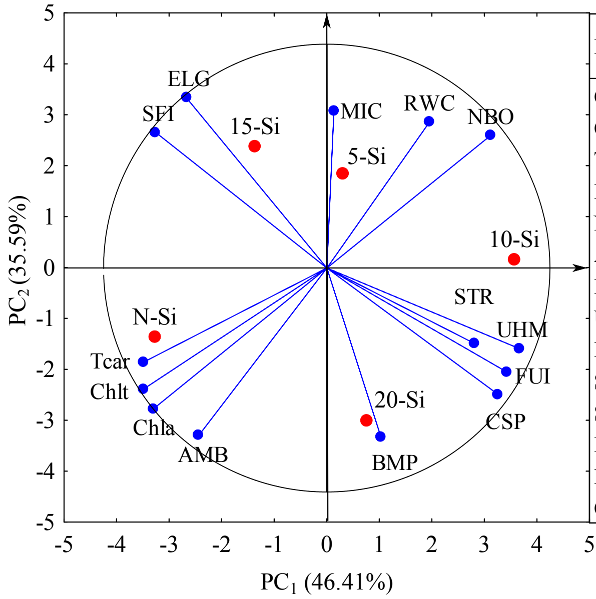
The reduction of 18 original variables into two constructed variables (PCs) is important to understand the Si effect from all the joint variables, because the PCA is efficient in reducing many variables into smaller subspace with minimal information loss (ALKARKHI; ALQARAGHULI, 2020; SACCENTI; CAMACHO, 2020; KHERIF; LATYPOVA, 2020). Thus, PCA application was efficient in this research, since, with both PCs, it was possible to explain high proportions of s^2 (82%) with low information losses (18%).

In cotton, Asha et al. (2013) verified the formation of 7 PCs ($\lambda > 1.0$) to explain 87.98% of s^2, when they evaluated 40 genotypes and 15 variables. Nazir et al. (2013) found 3 PCs with 64.1 % of s^2, when they evaluated 70 genotypes and 7 variables. Shakeel et al. (2015) found that 4 PCs explained 65.2% of s^2 in 50 genotypes and 12 variables. Rathinavel (2018) found 8 PCs with 83.1% of s^2 when 101 varieties and 21 variables were evaluated. Rathinavel (2019) found that 5 PCs explained 76.8% of s^2, when they evaluated 340 germplasm accessions and 14 variables.

The greater number of PCs found by these researchers was due to the huge number of accessions, genotypes, and varieties studied. In our research, the reduced number of Si doses justifies the fact that two PCs explain a large part of s^2. This behavior was also observed by Ferraz et al. (2021a) when they studied Si doses in BRS Safira colored cotton cultivar and by Ferraz et al. (2021b) who studied Si doses in cultivar BRS Topázio, in which the researchers reduced the original variable set by two PCs.

In PC_1, it was found that plants not treated with Si had higher levels of Chla (174.86 μmol m^{-2}), Chlt (210.34 μmol m^{-2}), and Tcar (124.42 μmol m^{-2}) and there were reductions to 98.08 μmol m^{-2}, 121.77 μmol m^{-2}, and 90.20 μmol m^{-2}, respectively, when plants received 10 kg ha^{-1} of Si, which represented reductions of 43%, 9%, 42.1%, and 27.5%. On the other hand, 10 kg ha^{-1} of Si increased NBO by 22.55% (31.25 bolls), UHM by 24.59% (28.17 mm), FUI by 1.1% (84.66%), STR by 16.7% (28.51 gf tex^{-1}), and CSP by 29.81% (2664.72%), compared to 25.5 bolls, 22.61 mm, 83.74%, 24.43 gf tex^{-1}, and 2,052.82%, respectively, recorded in plots not treated with Si. The SFI was 10.29% in untreated plants and increased to 11.55%, with 15 kg ha^{-1} of Si, followed by a reduction to 8.25% with 20 kg ha^{-1} of Si (Figure 2).

In PC_2, 5 kg ha^{-1} of Si allowed a higher RWC (75.25%) and MIC (5.12 µg in^{-1}) compared to untreated plants, which had 57.39% and 4.11 µg pol^{-1}, respectively. BMP was 135.25 g with the application of 20 kg ha^{-1} of Si, and it was 2.66% higher than the value of 131.75 g recorded in the control (0 kg ha^{-1} of Si). Plants not treated with Si had higher AMB (5.18 g), which decreased by 18.34% when they received 10 kg ha^{-1} of Si. 15 kg ha^{-1} of Si promoted increase in ELG (7.32%) of 11.76% compared to the value of 6.55% observed in the control, while 20 kg ha^{-1} of Si reduced ELG to 5.72%, which represented a 12.67% reduction (Figure 2).



EV	Silicon dose (kg ha^{-1})				
	0	5	10	15	20
Chla	↑ 174.86	↘ 116.75	↓ 98.08	↘ 127.35	↗ 154.77
Chlt	↑ 210.34	↘ 151.96	↓ 121.77	↘ 149.52	↗ 175.09
Tcar	↑ 124.42	↓ 87.98	↓ 90.20	→ 108.69	→ 106.63
RWC	↘ 57.39	↑ 75.23	↗ 70.34	↘ 59.63	↓ 52.29
NBO	↓ 25.50	↗ 29.00	↑ 31.25	↑ 30.25	↘ 27.75
AMB	↑ 5.18	→ 4.62	↓ 4.23	↓ 4.34	↑ 5.06
BMP	→ 131.75	↗ 132.75	→ 131.25	↓ 127.75	↑ 135.25
UHM	↓ 22.61	↓ 22.64	↑ 28.17	↓ 21.96	→ 25.17
FUI	↘ 83.74	↗ 84.27	↑ 84.66	↓ 83.34	↑ 84.57
SFI	↗ 10.29	→ 9.84	↓ 8.03	↑ 11.55	↓ 8.25
STR	↓ 24.43	↘ 26.39	↗ 28.51	→ 27.56	↑ 30.65
ELG	→ 6.55	↗ 6.77	↓ 5.79	↑ 7.32	↓ 5.72
MIC	↓ 4.11	↑ 5.12	↓ 4.20	↘ 4.49	↓ 4.15
CSP	↓ 2052.82	↓ 2005.74	↑ 2664.72	↓ 2076.82	↑ 2629.15

Figure 2. Two-dimensional coordinates projection (biplot) of silicon doses and correlation coefficients of the variables with the first two principal components (PC_1 and PC_2) and average variables.

In the absence of Si, the highest levels of Chla and Chlt could be explained by the lower RWC and lower NBO, which may have induced less translocation of photo-assimilated compounds to the fruits and increased light capture surface and concentrations of photosynthetic pigments, suggesting that the growth in Tcar happened due to the photoprotection of membrane systems against the electronic energy transfer from chlorophylls, singlet oxygen development, and the consequent lipid peroxidation and excess of energy dissipation in the form of Chla fluorescence (RONSEIN et al., 2006; UENOJO; MARÓSTICA JUNIOR; PASTORE, 2007).

Increases in NBO with 10 kg ha^{-1} of Si and BMP verified in plants treated with 20 kg ha^{-1} of Si may be related to the morphophysiological adjustments; e.g. better spatial arrangement of leaves for improved light interception, accumulation and polymerization of silicates in epidermal cells, reduction in transpiration rate, and increase in photosynthetic rate, which could have triggered the translocation of photo-assimilated compounds to cotton boll dry matter production and accumulation (FERRAZ et al., 2014; BARROS et al., 2019).

In addition, improvement of fiber production and quality variables (NBO, UHM, FUI, SFI, ELG, and CSP), with treatments 10 and 15 kg ha L^{-1} of Si, is related to the presence and contribution of this element in fiber production and development (BOYLSTON, 1988). Actually, Si plays a role in cotton fiber elongation and in secondary cell wall formation, and such contribution is evidenced by Si close association with classes of organic compounds, e.g. polyhydroxy pectins (SCHWARTZ, 1973), callose (WATERKEYN, 1981), tannins and starch (SANGSTER; PARRY, 1981; SCURFIELD; ANDERSON; SEGNET, 1974), which have essential functions in the early stages of cotton fiber development (WATERKEYN, 1981; BERLIN, 1986; DELANGE, 1986; MEINERT; DELMER, 1977; STEWART, 1986; BOYLSTON et al., 1990).

It is important to note that cotton is not considered a Si accumulator due to low root absorption (KATZ, 2014), which supports the need for Si foliar supply to improve morphophysiological processes in which this element is involved (BARROS et al., 2019). Thus, reduction in some variables (AMB, BMP, UHM, FUI, and CSP with 15 kg ha^{-1} of Si and RWC, SFI, ELG, and MIC with 20 kg ha^{-1} of Si) suggest that cotton needs lower quantities of this element and its excess may damage important processes in cotton (FERRAZ et al., 2017).

The NCF quality values (UHM, STR, MIC, and FUI), in plants treated with 10 kg ha^{-1} of Si, were higher than those recommended by Carvalho, Andrade and Silva Filho (2011) for cv. BRS Rubi; according to classifications of Fonseca and Santana (2002), Almeida et al. (2011), and Lima (2018), these fibers were rated as of: short, strong, medium micronaire index, high uniformity index, regular short fiber index, high elongation at break, and medium reliability index. These results justify the use of silicon in the Brazilian cotton chain, especially in the growing of naturally colored fiber cotton, whose fiber quality improves with the application of Si (FERRAZ et al., 2021a). In the univariate analysis of variance (ANOVA), it was observed that Si doses had a significant effect on Chlb content and IEL. BRS Rubi cultivar leaves, not treated with Si, had higher levels of Chlb (36.04 µmol m^{-2}) and IEL (30.17%). There was a reduction as the doses of Si were added up to 20 kg ha^{-1}, obtaining 18.7 µmol m^{-2} of Chlb and 12.09% of IEL and reductions of 48.11 and 59.92%, respectively (Figure 3 A and B). Si doses had no effect on HI and FMI, which reached mean values of 0.44 and 86.44. For Lima (2018), these fibers are classified as mature.

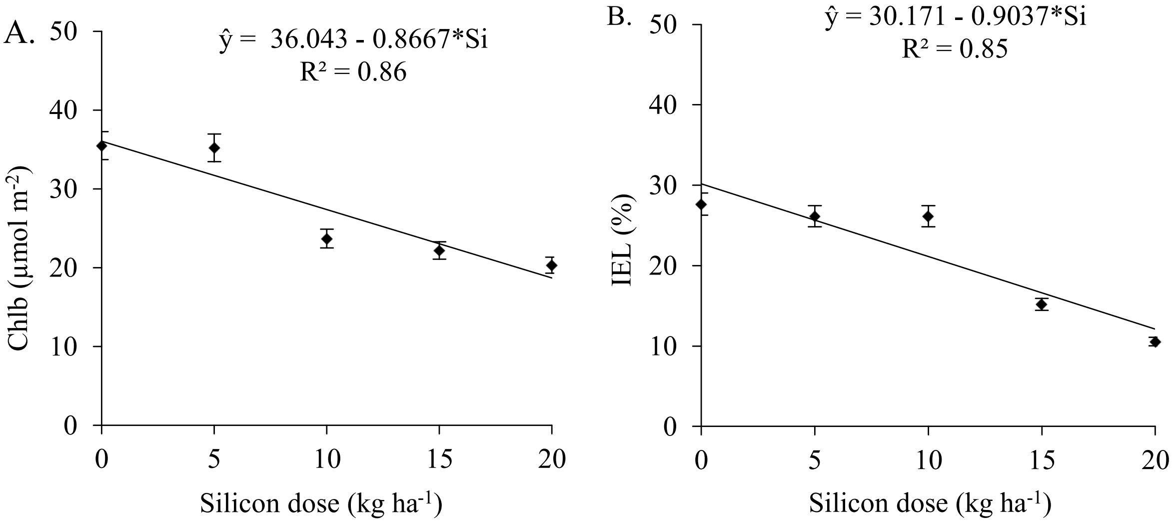


Figure 3. Chlorophyll 'b' content (A) and intracellular electrolyte leakage (B) in BRS Rubi cultivar leaves as a function of silicon doses. ** and * – indicate the significant slope of the straight line ($p \leq 0.01$) and ($p \leq 0.05$) by the F test, respectively.

The highest accessory pigment (Chlb) accumulation in control plants (0 kg ha^{-1} of Si) suggests the activation of natural mechanisms for ecophysiological adjustments and protection against changes in meteorological variables, mainly solar radiation because Chlb C-3 carbon aldehyde group has electron affinity for better stability (STREIT et al., 2005). The reduction in Chlb because of the increase in Si doses could probably be the result of the inhibition of chlorophyll enzyme 'a' oxygenase (CAO) activity in this pigment biosynthesis pathway (REINBOTHE et al., 2006). This indicates the physiological tolerance adjustment of the plant to the recurrent abiotic stresses in the semiarid region.

The IEL reduction, in response to the increment in Si, proves the role of this chemical element in protecting cotton plants against reactive oxygen species, which is demonstrated by the stability of membrane systems. Silicon reduces cell membrane rupture; consequently, lower amount of electrolytes was lost to the external environment (KARUPPANAPANDIAN et al., 2011; ANWAAR et al., 2015).

Physiological variables (chloroplast pigments, relative water content in the leaves, and intracellular electrolyte leakage), assessed throughout the flowering, as well as cotton production and yield components (number of bolls, average boll mass, boll mass per plant, and harvest index) obtained at 145 DAS, are not good regressors for predicting the quality of naturally colored cotton fibers, because multiple linear regression models, with significant fit, were not obtained (Table 2).

Table 2. Summary of multiple regression analyses for fiber quality variables as a function of Si doses and other variables for each PC.

Multiple regression	Fiber quality variables							
	UHM	FUI	SFI	STR	ELG	MIC	FMI	CSP
Significance probability (P)	0.84[ns]	0.84[ns]	0.96[ns]	0.25[ns]	0.41[ns]	0.82[ns]	r-PCA	0.39[ns]
R multiple	0.35	0.35	0.25	0.59	0.40	0.23	r-PCA	0.53
R square	0.13	0.13	0.06	0.35	0.16	0.05	r-PCA	0.29
R adjusted square	-0.19	-0.19	-0.27	0.12	4.43e-3	-0.12	r-PCA	0.03
Standard error	2.88	1.19	2.41	3.16	1.24	0.91	r-PCA	358.89

[ns] – not significant; r-PCA – variable removed from Principal Component Analysis.

In this study, the attempt to fit fiber quality forecasting models is supported by the necessity to obtain in advance important information for decision -making and planning of crop management in the field (BALAJI PRABHU; DAKSHAYINI, 2020), because, according to Alkarkhi and Alqaraghuli (2020), multiple linear regression models are efficient to explain large amounts of correlated variables. On the other hand, Hope (2020) highlights the possibility that these models may fail when many predictor variables are studied.

Using PCA and MLRA to estimate the quality of colored cotton fibers as a function of Si doses and other variables of each CP, Ferraz et al. (2021a, b) concluded that it is not possible to accurately predict fiber characteristics and suggested that other variables should be included in these models in future work. Consequently, the absence of fit of the models in this study validates the information provided by these authors and highlights the demand for technological advances in the field of modeling to predict fiber quality from variables collected in pre-flowering.

Sawan (2013), for cotton plants, fitted multiple linear regression models to predict production components as a function of climatic variables. This researcher pointed out that it is possible to minimize the injurious effects of abiotic stresses by using appropriate management practices (adequate irrigation regime and specific plant growth regulators). Therefore, there is a clear need for further research involving more variables for models that predict the quality of naturally colored cotton fibers.

CONCLUSION

Silicon promotes physiological adjustments, enhanced production, yield, and quality of naturally colored cotton fibers from BRS Rubi cultivar grown in the Brazilian semi-arid region. Fiber quality in plants that have been treated with Si is within the expected values for this cultivar and by the international standard D-4605 of the American Society for Testing and Materials. 10 kg ha^{-1} of Si is recommended to increase fiber quality of naturally colored cotton cv. BRS Rubi.

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