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Sweet sorghum for ethanol production in the semi-arid: response to potassium silicate and maturation

Bruno França da Trindade Lessa[1], Alek Sandro Dutra[2], Antônio Francelino de Oliveira Filho[2], Tatiana Maria da Silva[2], Maria Neurilan Costa Silva[2], Marlos Alves Bezerra[3]

[1] Universidade Federal do Vale do São Francisco, Centro de Ciências Agrárias, Colegiado de Engenharia Agronômica, Petrolina, PE, Brasil. E-mail: bruno.ftlessa@univasf.edu.br (ORCID: 0000-0002-0472-1417)
[2] Universidade Federal do Ceará, Departamento de Fitotecnia, Fortaleza, CE, Brasil. E-mail: alekdutra@ufc.br (ORCID: 0000-0002-4298-383X); tatianad.silva@hotmail.com (ORCID: 0000-0003-2349-9978); marianeuri@hotmail.com (ORCID: 0000-0002-5299-3353); eng-francelino@hotmail.com (ORCID: 0000-0001-9337-8261)
[3] Embrapa Agroindústria Tropical, Fortaleza, PE, Brasil. E-mail: marlos.bezerra@embrapa.br (ORCID: 0000-0002-8622-0770)

ABSTRACT: The sweet sorghum is an important alternative source to ethanol production, and in a function of its rusticity and tolerance to adverse environment present high potential to Brazilian semi-arid region. With the purpose of seeking recommendations to improvements in agronomic performance, the objective of this study was to assess the biomass yield and juice quality of sweet sorghum cultivars as a function of foliar fertilization with potassium silicate and determine the optimal harvest time. The experiment was conducted in the semi-arid region (Pentecoste, CE, Brazil) in 2014 and 2015, using three genotypes (BRS 506, BRS 511 and EJX 7C30) fertilized with potassium silicate (0, 500, 1000 and 1500 mL ha^{-1}) and harvested at 90, 97, 104 and 111 days after sowing (DAS). The experiment was arranged in randomized blocks with four replications in a split-split-plot design (3 x 4 x 4). The total biomass and juice yield, total soluble solids (ºBrix), total soluble carbohydrates and estimated ethanol production were determined for each year. In 2014, the mean biomass yield for BRS 506, BRS 511 and EJX 7C30 were 58.6, 64.9 and 24.5 Mg ha^{-1}, respectively. As for 2015, the biomass yield of BRS 506 and BRS 511 decreased by 8.5 and 21 %. The juice of BRS 506 and BRS 511 showed a high quality standard, and the latter cultivar stood out with 157 g L^{-1} of total soluble carbohydrates at 111 DAS. The cultivars BRS 506 and BRS 511 showed high juice quality when harvested at 111 DAS.

Key words: BRS 506; BRS 511; carbohydrates; ethanol; *Sorghum bicolor*

Sorgo sacarino para produção de etanol no semiárido: resposta ao silicato de potássio e maturação

RESUMO: O sorgo sacarino é uma importante fonte alternativa para a produção de etanol, e em função de sua rusticidade e tolerância a ambientes adversos apresenta elevado potencial para a região semiárida brasileira. Afim de buscar recomendações para melhoria do desempenho agronômico, o objetivo deste estudo foi avaliar a produção de biomassa e a qualidade do caldo de cultivares de sorgo sacarino em função da adubação foliar com silicato de potássio e determinar o período ótimo de colheita. O experimento foi conduzido em Pentecoste, CE, nos anos de 2014 e 2015, utilizando três genótipos (BRS 506, BRS 511 e EJX 7C30) fertilizados com silicato de potássio (0, 500, 1000 e 1500 mL ha^{-1}) e colhidos aos 90, 97, 104 e 111 dias após a semeadura (DAS). O experimento foi em blocos casualisados repetidos quatro vezes de acordo com o esquema de parcelas subsubdivididas (3 x 4 x 4). Em cada ano foi determinada a produção de biomassa e caldo, os sólidos solúveis (ºBrix) e carboidratos solúveis do caldo e a produção estimada de etanol. Em 2014, a produção média de biomassa para as cultivares BRS 506, BRS 511 e EJX 7C30 foram de 58,6; 64,9 e 24,5 Mg ha^{-1}, respectivamente. No ciclo de 2015, a produção de biomassa das cultivares BRS 506 e BRS 511 diminuiu em 8,5 e 21 %. Estas cultivares apresentaram alta qualidade de caldo com destaque para a BRS 511 com conteúdo de carboidratos totais de 157 g L^{-1} aos 111 DAS. As cultivares BRS 506 e BRS 511 apresentam alta qualidade de caldo quando colhidas aos 111 DAS.

Palavras-chave: BRS 506; BRS 511; carboidratos; etanol; *Sorghum bicolor*

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is specie of the Poaceae family, native from Africa and classified into different types according to its potential use. Broomcorn, forage, grain, biomass and sweet are the main types of sorghum, the latest being characterized by accumulation of high levels of fermentable sugars in the stalk, being an alternative source for ethanol production (Ratnavathi et al., 2011; Ratnavathi & Patil, 2013).

With the current trend towards ecologically sustainable activities, the sweet sorghum stands as an important source of renewable energy. This specie stands out for: 1) physiological similarities to sugarcane (*Saccharum spp* L.), the main raw material used for ethanol production in Brazil; 2) being easy to establish and manage (use of seeds, short cycle, suitability for mechanical harvesting, use of the same industrial apparatus for extraction of sugarcane juice); and, 3) high level of resistance to water stress (Almodares & Hadi, 2009; Masson, et al., 2015). It is a promising crop for the semi-arid region, sorghum is water-use efficient, and under high temperature, light intensity, or both of these factors, maintains its photosynthetic efficiency due to the C4 metabolism (Taiz et al., 2017).

The use of silicate fertilization for Poaceae species and other botanical families, either via soil or foliar application, is growing in the few past years. The silicon (Si) is part of the macronutrient category being assertive in energy storage or structural integrity for most plants, thus silicon application improves growth and development of many crops (Taiz et al., 2017). Chagas et al. (2016) describe increase in grain yield and weight of dry matter of rice as a function silicon fertilization, while Lessa et al. (2017) proves increase in the seeds physiologic quality of sweet sorghum.

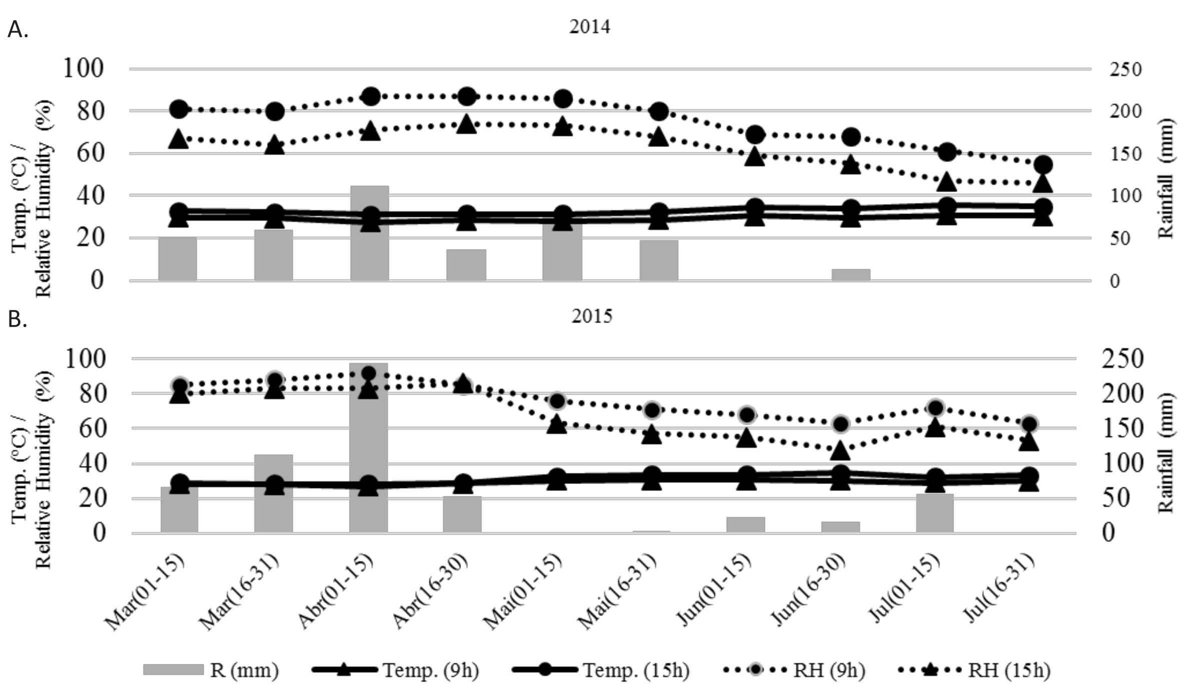
The silicon element promotes greater protection against pests and diseases and increased drought resistance and other stress (Camargo et al., 2013; Schurt et al., 2013; Peixoto & Boiça Junior, 2017), thus reducing the amount of energy spent by the plant metabolism and allowing it to be better used by metabolite accumulation processes in the stalk. The maximum accumulation of sugar in the stalk define, in these, the wanted moment to harvest. In typical regions of sweet sorghum crops, the harvest occurs between 100 and 130 days after sowing. In semiarid regions this moment could be anticipated depending on agronomics and climatic characteristics.

The objective of this study was to assess the yield and technological quality of three sweet sorghum genotypes as a function of foliar fertilization with potassium silicate and different harvest times.

Material and Methods

The experiment was conducted under rainfed conditions in Pentecoste-Ceará, Brazil (UTM coordinates 9577349 S and 462620 E; 48 m above sea level), in a haplic luvisol soil (IUSS-WRB, 2015) of sandy loam texture and area of 0.27 ha. According to the Köppen classification, the climate of the region is BSw'h', i.e. semi-arid with erratic rainfall. Meteorological data are shown in Figure 1.

The first cultivation cycle was in the rainy season of 2014, between March and July, with sowing on 22 March. The experiment was repeated in 2015, when sowing was made on 07 March.



Source: Meteorological Station located at the Vale do Curu Experimental Farm of the Federal University of Ceará. Temp.: temperature; RH: relative humidity; R: cumulative rainfall.

Figure 1. Average fortnightly air temperature, relative humidity and cumulative rainfall from March to July 2014 and 2015, Pentecoste, Ceará, Brazil.

After preparing the soil (disked twice in 2014 and subsoiled prior to disking in 2015), three sweet sorghum genotypes were manually sown along the planting furrow: two commercial cultivars, BRS 506 (obtained from the Commercial Department of Embrapa Products and Markets/ Sete Lagoas-MG, Brazil) and BRS 511 (provided by Ceres Sementes do Brasil Ltda.), and the experimental hybrid EJX 7C30 (also provided by Ceres Sementes do Brasil Ltda.).

Based on the soil analysis of both years (Table 1) and the recommendations of Coelho (2012), fertilization was performed at the time of sowing, with 30, 50 and 45 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, and 20 DAS (days after sowing) with 140 and 45 kg ha^{-1} of N and K_2O, respectively. The sources used were urea, single superphosphate and potassium chloride.

The main treatments were foliar fertilization using potassium silicate (12% SiO_2; 12% K_2O) at levels of 500, 1000 and 1500 mL ha^{-1}. Applications were performed using a knapsack sprayer (20 L), with a piston-type pump and a flat fan nozzle (with a flow of 19 L h^{-1}), which was attached to a spray shield to avoid influence among different plots. In addition, a spreader-sticker (adjuvant) was used at a concentration of 5 % of the spray volume (100 L ha^{-1}).

In the first cultivation cycle (2014), silicon fertilization was performed between the V7 and V9 stages (seven to nine fully expanded leaves), which occurred at 30 DAS. In the second cycle (2015), it was performed in earlier stages (V4 to V6) at 20 DAS and also in the same stage of the previous cycle (V7 to V9, which occurred at 25 DAS).

The experiment was arranged in randomized blocks with four replications in a split-split-plot design (3 x 4 x 4): three genotypes, four silicon levels (including the control) and four harvest times (90, 97, 104 and 111 DAS). With the proposed design, the experimental area had 2688 m^2 and 30720 plants. Blocks and plots had 672 and 14 m^2, respectively, with 160 plants per plot. Each plot consisted of four 5-m rows, containing 40 plants per row (8 plants m^{-1}) and rows spaced 0.70 m apart. The useful area was represented by the two centrelines.

At 90, 97, 104 and 111 DAS, samplings were performed by collecting 12 plants of each plot and weighing their total fresh matter (TFM) using a digital balance (15 kg). Four of them were randomly chosen for assessment of dry matter (DM). These plants were divided into leaves, stalks and panicles and packed in Kraft paper bags to be dried in a forced air oven at 65 °C. Thus, the total DM (TDM) was determined by summing the DM obtained for each part of the plants. Biomass data were extrapolated to Mg ha^{-1} based on number of plants ha^{-1}, according to the spacing and planting density used (114286 plants).

The remaining eight plants were processed for removal of leaves and panicles in order to obtain clean stalk samples for determination of juice yield (JY). An electric sugarcane mill (1 hp) was used to extract juice from the stalks. Immediately after the juice extraction, samples were collected in plastic bottles (100 mL) for subsequent measurement of the total soluble solids (TSS - ºBrix) using a portable refractometer (0 - 32 °Brix).

For determination of total soluble carbohydrates (TSC – g L^{-1}), the juice samples were taken to the laboratory and stored in an ultra-freezer (-80 ºC) during the period of analysis. The extract used was prepared by filtering the juice in cotton balls and diluting it 100 times with distilled water. Then, it was subjected to a modification of the phenol-sulfuric acid colorimetric method (Dubois et al., 1956). The absorbance of the solution was read in a spectrophotometer (490 nm) and compared to a standard curve of anhydrous glucose (98 %).

The ethanol production (L ha^{-1}) was estimated using the equation proposed by Sakellariou-Makrantonak et al. (2007), where ethanol (L ha^{-1}) = total soluble carbohydrates (%) x 6.5 (conversion factor) x 0.85 (efficiency of the fermentation process) x fresh biomass of the stalk (Mg ha^{-1}).

The data were firstly tested for normality and homogeneity of variance. When these assumptions were met, analysis of variance (ANOVA) and Tukey test ($p \leq 0.05$) were performed to compare the means of the three genotypes. Polynomial regression was also used to analyse the different silicon levels and harvest times. In cases where the data did not meet at least one of the assumptions, they were subjected to the non-parametric Kruskal-Wallis test, with pairwise multiple comparisons when $p \leq 0.05$ (SFM, TFM, JY and

Table 1. Soil physicochemical properties (0-20 cm depth) of the experimental area at the Vale do Curu Farm, Pentecoste, Ceará (sampling in February 2014 and 2015).

Year	Ca^{2+}	Mg^{2+}	Na^+	K^+	H^++Al^{3+}	Al^{3+}	SB	CEC
	(cmolc kg^{-1})							
2014	6.0	2.5	0.34	0.68	0.99	0.10	9.5	10.5
2015	6.5	3.0	0.40	0.69	0.83	0.15	10.6	11.6
	BS	ALS	C	N	OM	P Assimil	C/N	ESP
	(%)		(g kg^{-1})					
2014	90	1	8.52	0.89	14.69	0.098	10	3
2015	91	1	5.70	0.58	9.83	0.150	10	3
	Density	pH	EC	Gravel	Sand	Silt	Clay	Natural clay
	g cm^{-3}	H_2O	dS m^{-1}	g kg^{-1}				
2014	1.34	7.0	0.84	13	572	280	135	85
2015	1.43	7.1	0.70	12	588	281	119	82

SB: sum of bases; CEC: cation exchange capacity; BS: base-saturation percentage; ALS: Al-saturation percentage; OM: organic matter; ESP: exchangeable sodium percentage. Source: Laboratory of Soil and Water; Department of Soil Science – Federal University of Ceará; Ceará Foundation of Meteorology and Water Resources – FUNCEME.

ethanol/cycle 1). The total soluble solids and ethanol/cycle 2 data were subjected to the Box-Cox transformation, which allowed their adjustment to perform the ANOVA.

Results and Discussion

In both cultivation cycles, biomass yield was the highest for BRS 506 and BRS 511, which did not differ from each other ($p \leq 0.05$). In 2014, the mean values for total fresh matter, main variable used for assessing the agronomic performance of sweet sorghum, was 58.6 Mg ha^{-1} for BRS 506 and 64.9 Mg ha^{-1} for BRS 511. For the second cycle (2015), the total fresh matter of BRS 506 and BRS 511 were 51 Mg ha^{-1} (Table 2). These values are above the average yield of 43 Mg ha^{-1} described by May et al. (2012) obtained from the evaluation of 13 cultivars of sweet sorghum in Nova Porteirinha-MG. This corresponds to the normal yield in the South-Central region of the country and usually from irrigated and highly technified fields, a very different situation from those under rainfed agriculture, which is the focus of this research, and for most farmers in the north-eastern semi-arid region in Brazil.

Assessing the adaptability and stability of 25 sweet sorghum cultivars in different regions of Brazil (Minas Gerais, Mato Grosso and Rio Grande do Sul), Souza et al. (2013) reported a biomass mean yield of 43.3 Mg ha^{-1}. In their study, the cultivar BRS 506 showed the highest yield when was grown in Nova Porteirinha, Minas Gerais, where it reached 59.6 Mg ha^{-1}. This value is close to that found in the first cultivation cycle of this study, 58.6 Mg ha^{-1}. In 2014, the cultivar BRS 511 showed a biomass yield of 64.9 Mg ha^{-1} (Table 2), which is higher than that obtained by all cultivars of the aforementioned work.

Even in rainfed system, with irregular rains (Figure 1), in the conditions this work the varieties presented high yield. This result shows the high adaptability these varieties of sorghum to semiarid climate (high temperature and radiation) as a function its C4 metabolism and specifics characteristics such as drought resistance proven to this species (Almodares & Hadi, 2009). It should be emphasized

Table 2. Total fresh matter (TFM) and juice yield (JY) of three sweet sorghum genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) and harvested at different days after sowing (DAS).

Genotypes	TFM[1*] (Mg ha^{-1})	TFM[2] (Mg ha^{-1})	JY[1] (m^3 ha^{-1})	JY[2] (m^3 ha^{-1})
BRS 506	58.60 a	51.05 a	21.77 a	19.31 a
BRS 511	64.94 a	51.18 a	19.93 a	18.31 a
EJX 7C30	24.51 b	30.40 b	03.97 b	06.72 b
DAS				
90	52.09 a	46.59 a	14.38 a	16.63 a
97	49.59 a	47.75 a	16.31 a	13.83 ab
104	50.82 a	42.18 a	15.87 a	12.62 b
111	44.42 b	40.42 a	14.33 a	15.89 a

*1 (cycle 1/2014); 2 (cycle 2/2015). [a,b] Different letters in a column indicate statistically significant differences (Kruskal-Wallis test, $p \leq 0.05$).

that rainwater dependence should be compensated for by the efficiency of the other production components, such as adequate planting techniques and correct soil and phytosanitary management.

The biomass yield of the hybrid EJX 7C30 was below expectations, reaching only 24.5 and 30.4 Mg ha^{-1} of total fresh matter in the first and second cycle, respectively (Table 2). At the time of this study, EJX 7C30 has not been released as a commercial hybrid; however, its agricultural performance was under evaluation in the South-East region of Brazil. It can be inferred that this low performance is due, in part, to the extreme conditions of the semi-arid region, which are distinct from the requirements of many hybrid genotypes.

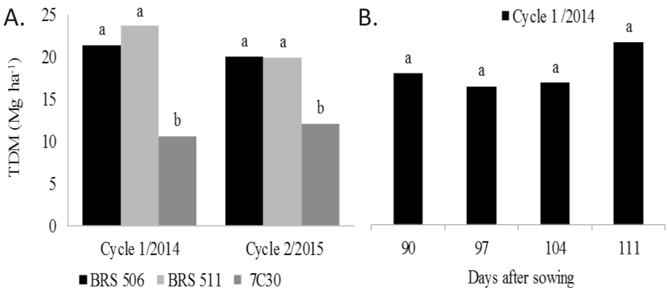
The absence of statistical difference ($p \leq 0.05$) between harvest times or the decrease in biomass along them are important facts to consider, given that the highest biomass yield was obtained since the shortest time period studied (Table 2). The semi-arid conditions seem to promote a shorter life cycle for sweet sorghum, which is an agronomic advantage when compared to the conditions of the South-Central region of the country, where the maximum biomass potential is reached between 100-110 days for hybrids and 110-120 days for varieties (May et al., 2012; Souza et al., 2016).

For juice yield, the cultivars BRS 506 and BRS 511 showed mean values of 21.77 and 19.93 m^3 ha^{-1}, respectively (Table 2). In both years, BRS 511 showed values slightly lower than those of BRS 506, although not statistically different ($p > 0.05$), and the lowest mean volume found was 18.31 m^3 ha^{-1} (Table 2). These values are similar to those in regions other than the semi-arid. In one experiment in India, the juice yield of four of the six genotypes evaluated ranged from 20 to 23 m^3 ha^{-1} (Ratnavathi et al., 2010). Juice yield is one of the main agronomic characteristics of the sweet sorghum because is positively correlated to ethanol production. By analysing harvest times, it can be observed that there was no difference for this variable when plants were harvested to 90 or 111 DAS (Table 2).

The TDM showed mean values with 21.3 and 23.6 Mg ha^{-1} for BRS 506 and BRS 511, respectively (Figure 2). If compared with the technical information about BRS 511, wherein DM yield varies from 15 to 20 Mg ha^{-1} under the conditions of Sete Lagoas, Minas Gerais (Embrapa, 2012b), the results of this study are above what was reported for this cultivar.

In 2014, the TDM obtained as a function of different harvest times (Figure 2B) shows that DM accumulation in the plant was stabilized at 90 DAS, which is represented by no statistical difference over time.

In the second cycle, significant interactions were observed for the TDM and there was influence of the potassium silicate factor. The effects of K_2SiO_3 on the sweet sorghum grown in 2015 were probably a result of the higher number of applications. Silicon fertilization was performed twice in that year, unlike 2014, when plants were fertilized only once. Another likely factor that may have contributed to the effect of silicon only in the second cycle was the

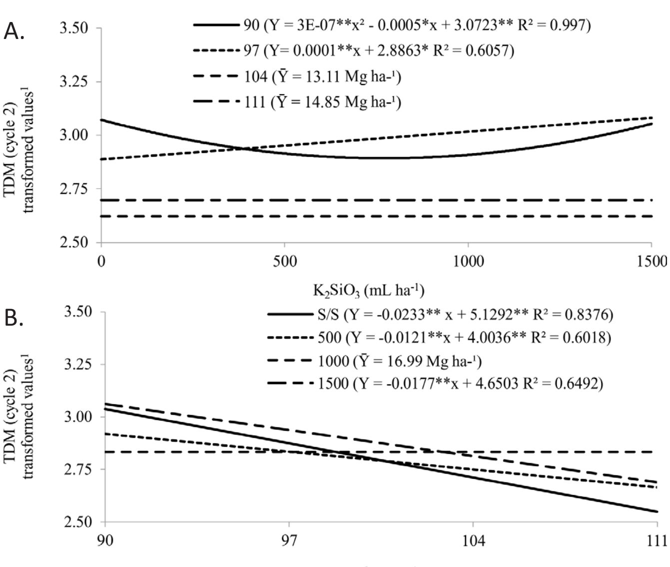


[a,b]Different letters in columns indicate statistically significant differences (Kruskal-Wallis test, $p \leq 0.05$).

Figure 2. Total dry matter (TDM) of sweet sorghum grown in the semi-arid region (Pentecoste, Ceará, Brazil) between March and July 2014 and 2015 as a function of different genotypes (graph A) and harvest times (graph B).

presence of the fungus *Gloecercospora sorgui*, which was diagnosed in the field. The high rainfall in 2015 provided favourable conditions for the disease. Given that silicon acts as a barrier to attack by phytopathogenic fungi, often even as a resistance inducer (Dann & Muir, 2002; Ratnadass et al., 2012; Rodrigues et al., 2015), the benefit of this element was more pronounced under fungal attack. Therefore, the effect of silicon in 2015 may have occurred due to its protective action against diseases.

Figure 3 shows the statistical breakdown of the total dry matter according to the different silicon levels and harvest times. At 90 DAS, the data fitted to a quadratic model ($p \leq 0.05$) with high coefficient of determination (99%), showing an increase of 3.6 Mg in dry matter when the silicon level increased from 833.3 mL (calculated value) to 1500 mL ha^{-1}



[1]Data previously transformed by the Box-Cox transformation ($\lambda = 0$); F-test: [ns]not significant; *$p \leq 0.05$ %; **$p \leq 0.01$. $\bar{Y}$: Mean of the original data when there was no significant mathematical adjustment.

Figure 3. Interaction of potassium silicon levels and harvest times for the total dry matter (TDM) of sweet sorghum grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2015. (graph A) Statistical breakdown of the silicon factor within each harvest time; (graph B) Statistical breakdown of the harvest times factor within each silicon level.

(maximum level used). Based on the mathematical model, it can be concluded that dry matter accumulation would increase if higher levels of this fertilizer were used (> 1500 mL).

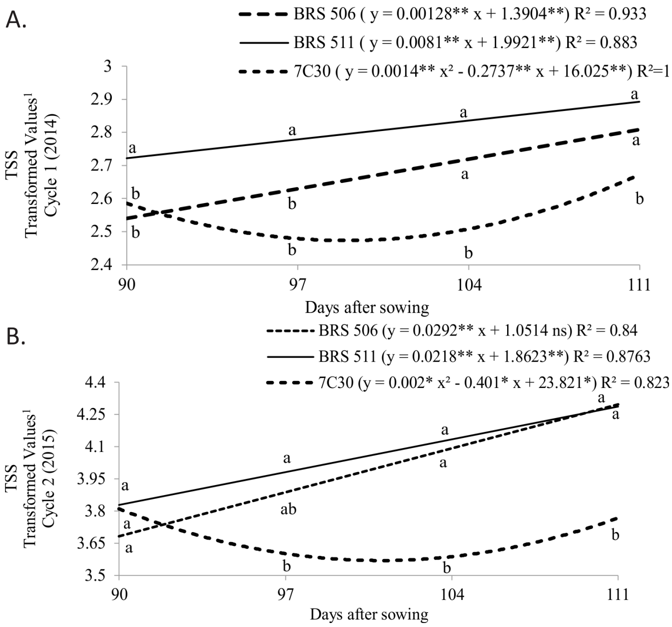
When plants were harvested at 97 DAS, the data fitted to a linear model ($p \leq 0.05$) and showed an increase in dry matter as the silicon level increased (Figure 3A). Thus, it was also verified that silicon significantly benefits plant development, despite the low coefficient of determination (61%). The highest level used (1500 mL ha^{-1}) allowed an increase of 2.9 Mg in dry matter, which represents an increase of 16% over the control treatment. Sousa et al. (2010) studied the use of different potassium silicate levels for foliar fertilization of maize and found an increase in stalk dry matter, photosynthetic efficiency and grain yield.

From 104 DAS, there was no mathematical adjustment as a function of the silicon levels (Figure 3A), which indicates that there is no longer effect of this element. Thus, it can be verified that despite the short time between the first and the last harvest (seven days), this period seems to contain the critical moment for the final plant development. Treated plants were positively influenced by the effect of silicon up to 97 DAS. Over the following days, control plants continued their maturation process, usually reaching the same yield of treated plants. Hence, foliar application of K_2SiO_3 allowed greater dry matter accumulation when plants were harvested earlier, which suggests that this management led to a shorter cycle.

By comparing the effect of silicon levels in each harvest time (Figure 3B), it can be observed that plants treated with 1000 mL ha^{-1} showed no loss of dry matter between 90 and 111 DAS. Thus, there was no mathematical adjustment for this particular silicon level ($p > 0.05$). Given the maintenance of dry matter even in the longest harvest time, it can be inferred that this form and level of silicon delayed the senescence process, or at least broke its uniformity, which was a positive factor.

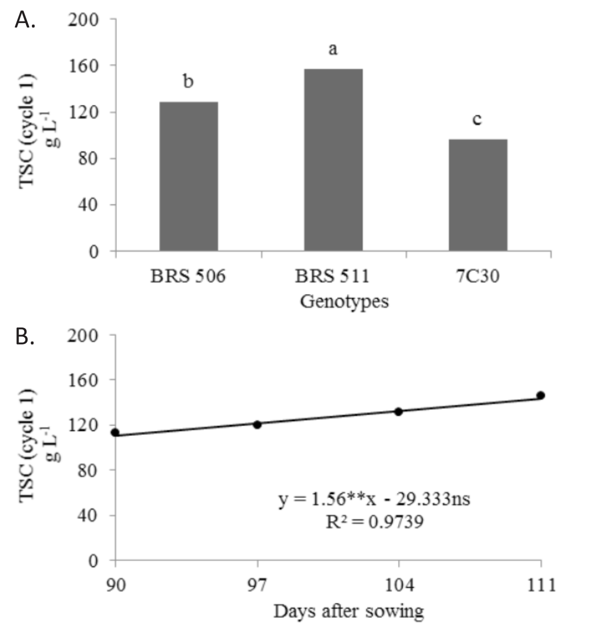
The total soluble solids of the three genotypes ranged from 12.7 to 18.1 ºBrix (Figure 4). In both cultivation cycles, the cultivars BRS 506 and BRS 511 were superior to the hybrid EJX 7C30 since the 97 DAS until the end of the maturation period, with statistic difference from 104 DAS. As it can be seen from Figure 4, the cultivars accumulated soluble solids linearly in both years ($p \leq 0.01$) and reached 16.4 to 18.1 ºBrix at 111 DAS. May et al. (2012) reported values between 15 and 20 ºBrix similar to those found in sugarcane, which gives support to the use of these two cultivars. Similarly, in an experiment carried out in Iran, the total soluble solids of 36 sweet sorghum cultivars ranged from 14.32 to 22.85 ºBrix (Almodares & Hadi, 2009).

During the evaluation period, the hybrid showed a different mathematical model for soluble solids accumulation. In both years, the data fitted to a quadratic model over the final days of maturation. In the first and second cycle (Figures 4, A and B), the ºBrix decreased up to 98 and 100 DAS, when there was a resumption of soluble solids accumulation. This



F-test: [ns]not significant; *p ≤ 0.05; ** p ≤ 0.01. [1]Data transformed by the Box-Cox transformation (λ = 0.27778). In each harvest time, means with different letter are statistically different (Tukey test, p ≤ 0.05).

Figure 4. Total soluble solids (TSS) in the juice of three sweet sorghum genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2014 (graph A) and 2015 (graph B) as a function of different harvest times.



[a; b]In Figure 5A different letters in columns indicate statistically significant differences (Tukey test, p ≤ 0.05). In the regression (graph B), F-test: [ns] not significant; ** p ≤ 0.01.

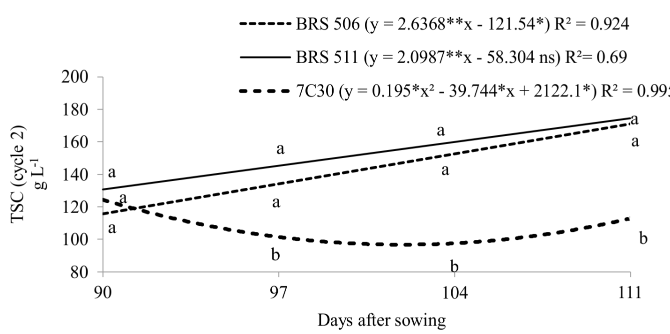
Figure 5. Total soluble carbohydrates (TSC) in the sweet sorghum juice produced in the semi-arid region (Pentecoste, Ceará, Brazil) in 2014 as a function of the different genotypes (A) and harvest times (B).

was probably the grain maturation period for this genotype, which led to redirection of photoassimilates from stalks to panicles in accordance with the natural source/sink logic (Taiz et al., 2017). Up to 111 DAS (final assessment date), the ºBrix values for the hybrid EJX 7C30 did not reach significant levels when compared to the cultivars BRS 506 and BRS 511.

Regarding total soluble carbohydrates in the juice, the cultivar BRS 511 stood out in 2014 with a mean value of 157.12 g L^{-1} (Figure 5 A). A linear carbohydrate accumulation over time can be observed in Figure 5 B. There was an increment of 32.76 g of sugars per litre of juice up to 111 DAS, which corresponds to an increase of 30%. This behaviour indicates the plant maturation natural process, in search of the maximum accumulation of sugars.

In the first cycle, there was no effect of the interaction between different factors on total soluble carbohydrates. There was an interaction ($p \leq 0.01$) between genotypes and harvest times in 2015 (Figure 6). In 2014, the cultivar BRS 511 was superior to the other genotypes (Figure 5A), but in the following year the two cultivars did not differ from each other ($p > 0.05$), and the hybrid EJX 7C30 was similar to them only at 90 DAS (Figure 6).

As for the harvest times, BRS 506 and BRS 511 fitted to a linear regression model ($p < 0.01$), with a carbohydrate accumulation of 47.8 and 34%, respectively, between 90 and 111 DAS. As a result, these cultivars showed 171.14 and 174.64 g L^{-1} of total soluble carbohydrates at 111 DAS (Figure 6). These values are higher than those recorded in 2014, possibly due to the higher rainfall in 2015 (Figure 1 B). The technological indices of BRS 506 and BRS 511 (suitable



F-test: [ns]not significant; *p ≤ 0.05 %; ** p ≤ 0.01. In each harvest time, means with different letter are significantly different (Tukey test, p ≤ 0.05).

Figure 6. Total soluble carbohydrates (TSC) in the sweet sorghum juice of three genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2015 as a function of different harvest times.

growing conditions) estimate total sugar values in 172.5 and 194 g L^{-1}, respectively (EMBRAPA, 2012a, b). Thus, under semi-arid conditions, BRS 506 reached juice quality results equivalent to those obtained in benchmark cultivation, and BRS 511, despite the lower index compared to the reference value, also obtained highly satisfactory results, especially in the second cultivation cycle.

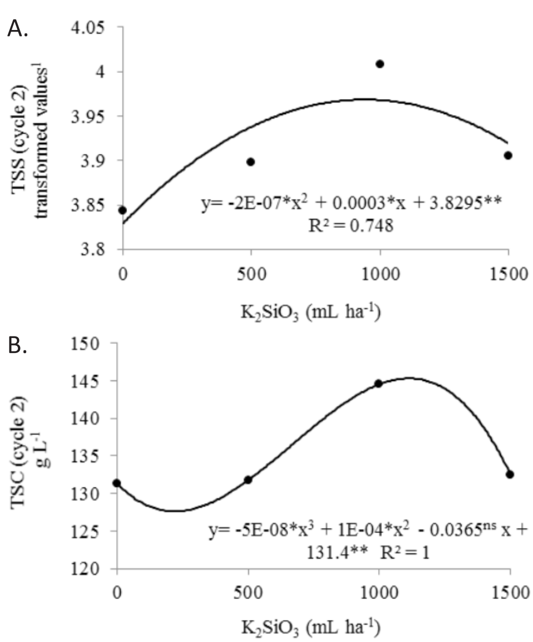
For the hybrid EJX 7C30, the maturation pattern over time (Figure 6) is similar to that observed for the ºBrix values. The data fitted to a quadratic model ($p \leq 0.01$) with a decrease up to 102 DAS, after that, resuming the carbohydrate accumulation, without reaching values similar to BRS 506 and BRS 511.

In the second cycle, for the potassium silicate levels, the total soluble solids and total soluble carbohydrates data fitted to quadratic and cubic models, respectively ($p \leq 0.01$). Through the equations, it is possible to find 750 and 1115 mL ha^{-1} as the best silicon levels for total soluble solids (Figure 7 A) and total soluble carbohydrates (Figure 7 B), respectively.

The difference concerning the best silicon level for each variable might be related to the distance between the actual data and those generated by the regression models, which promoted an R^2 of approximately 75% for total soluble solids (Figure 7 A) and 100% for total soluble carbohydrates (Figure 7 B). The high value for the latter ensures complete reliability, which also ensures greater reliability to the calculated level of 1115 mL ha^{-1}.

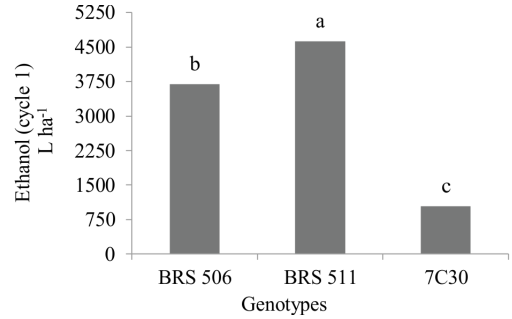
The level of 1115 mL ha^{-1} (calculated peak) promoted an increment of 11% in total soluble carbohydrates in the juice of the sweet sorghum genotypes (Figure 7 B). Once absorbed, silicon accumulates in leaves, particularly in grasses, forming a protective barrier to the attack of pests, diseases and also regulating the plant water loss (transpiration). Thus, plants treated with silicon seem to intensify their primary metabolism, represented here by greater sugar accumulation, at the expense of secondary metabolism, which is associated with plant protection (Guntzer et al., 2012; Haynes, 2014).

For ethanol production in 2014, BRS 511 was superior also in semi-arid regions, showing a production of 4631.05 L ha-1, which was 939.99 L ha^{-1} over the production of BRS 506. Despite the stressful conditions of the semi-arid region, both cultivars showed good performance, unlike the hybrid EJX 7C30, that reached only 1040.1 L ha^{-1} (Figure 8) and it was much lower than expected.



F-test: ns not significant; *$p \leq 0.05$; **$p \leq 0.01$. [1]Data transformed (graph A) by the Box-Cox transformation ($\lambda = 0.278$).

Figure 7. Total soluble solids (A) and total soluble carbohydrates (B) in the sweet sorghum juice produced in the semi-arid region (Pentecoste, Ceará, Brazil) in 2015 as a function of foliar fertilization using potassium silicate (K_2SiO_3).



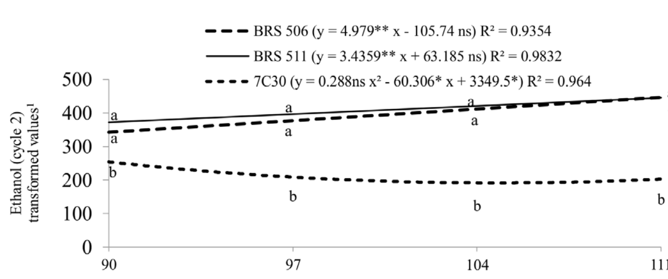
Different letters above the bars compare the genotypes and indicate statistical difference (Kruskal-Wallis test, $p \leq 0.05$).

Figure 8. Estimated ethanol production of three sweet sorghum genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2014.

The ethanol production obtained in our study reflects the juice quality discussed so far. In Sete Lagoas, Minas Gerais, Brazil, May et al. (2012) found an ethanol production of 2062.35 and 4352.51 L ha-1 for BRS 506 and BRS 511, respectively. In their study, the latter cultivar was the most promising variety for this purpose. Almodares & Hadi (2009) estimated that the ethanol production from sweet sorghum is around 3000 L ha-1, which reinforces the superiority of BRS 511, one of the latest varieties released by Embrapa (EMBRAPA, 2012b).

In 2015, the interactions involving the harvest times factor were also significant. Figure 9 shows the statistical breakdown of the genotype x harvest times interaction. In comparison to the previous cycle, it can be observed an increase in ethanol production for the cultivar BRS 506. Regardless of harvest times, this cultivar was similar to BRS 511. Ethanol production increased linearly over time ($p \leq 0.01$), and at 111 DAS it reached approximately 4415.93 and 4378.1 L ha^{-1} (values estimated by regression) for BRS 506 and BRS 511, respectively.

Similarly, to the total soluble solids and total soluble carbohydrates data, the ethanol production over time for the hybrid EJX 7C30 fitted to a quadratic model (Figure 9). It can be seen from the curve that the production potential of this genotype starts to increase at 104.7 ~ 105 DAS, although it remains lower than that observed for BRS 506 and BRS 511.



F-test: ns not significant; * $p \leq 0.05$; ** $p \leq 0.01$. [1]Data transformed by the Box-Cox transformation ($\lambda = 0.682$). In each harvest time, means with different letters are statistically different (Tukey test, $p \leq 0.05$).

Figure 9. Estimated ethanol production of three sweet sorghum genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2015 as a function of different harvest times.

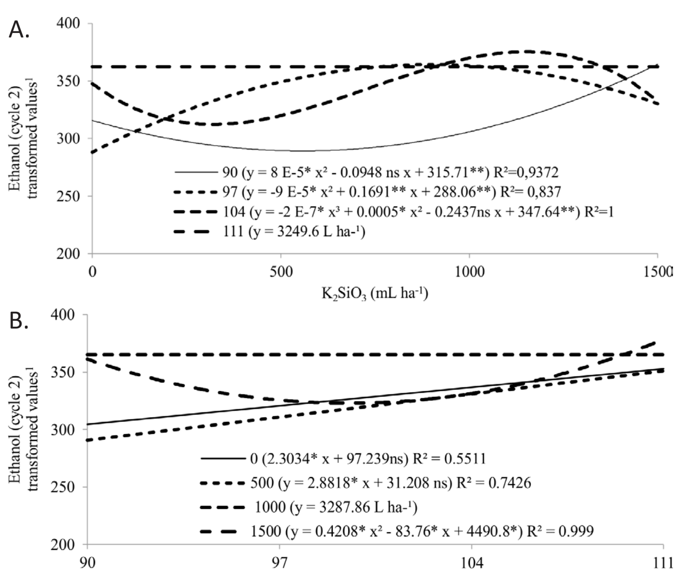
Figure 10 shows the statistical breakdown of the silicon levels x harvest times interaction for the estimated ethanol production. Regarding the potassium silicate levels applied, there were different mathematical adjustments for each harvest time (Figure 10 A), which justifies the aforementioned interaction ($p \leq 0.05$) due to the effect of silicate on the maturation process of sorghum plants.

When plants were harvested at 90 DAS, the effect of silicon showed a positive trend only from the minimum level of 592.5 mL ha^{-1} (calculated value, $p \leq 0.05$). The levels that best contributed to ethanol production were found in cases where plants were harvested latter. The peaks for the quadratic and cubic adjustments at 97 and 104 DAS, respectively, were 939.44 and 1370.2 mL ha^{-1}. No effect of silicon was observed in plants harvested at 111 DAS, given that there was no mathematical adjustment (Figure 10 A).

By analysing these results along with the best silicon level found for total soluble carbohydrates (1115.1 mL ha^{-1}), the range between 1100 and 1400 mL ha^{-1} of potassium silicate can be considered appropriate for use in the management of sweet sorghum in semi-arid regions, improving carbohydrate accumulation and, hence, ethanol production.

The manufacturer of the commercial product used in this study suggests a silicon level of 1000 mL ha-1 for different crops of the family Poaceae, such as maize, wheat and sorghum. Therefore, in addition to specifying the management for sweet sorghum in the semi-arid region, the results presented here clearly show that the information on the label is underestimated for these conditions, at least for sweet sorghum.

Besides the direct effect on ethanol production, silicon fertilization seems to alter the final process of maturation over time, i.e., the ethanol production potential was differentiated for plants treated with the highest levels (Figure 10B). The ethanol production of plants fertilized with 0 or 500 mL ha^{-1} of silicon increased linearly ($p \leq 0.05$) due to the increasing carbohydrate accumulation. There was no mathematical adjustment when using a level of 1000 mL ha^{-1}. Therefore, it can be inferred that the maximum ethanol production potential had already stabilized at 90 DAS. However, when using 1500 mL ha^{-1}, ethanol production started to increase only from 99.5 ~ 100 DAS, i.e., this silicon level delayed the maturation (Figure 10B).



F-test: [ns]not significant; * $p \leq 0.05$; ** $p \leq 0.01$. [1]Data transformed by the Box-Cox transformation ($\lambda = 0.682$).

Figure 10. Estimated ethanol production of three sweet sorghum genotypes grown in the semi-arid region (Pentecoste, Ceará, Brazil) in 2015 as a function of different silicon levels (graph A) and harvest times (graph B).

Thus, the silicon level of 1000 mL ha^{-1} was beneficial, whereas such benefit was not observed with 1500 mL ha^{-1}. This result reinforces the range previously considered as the most appropriate for additional fertilization with potassium silicate for sweet sorghum in semi-arid regions, which is between 1100 and 1400 mL ha^{-1}.

Regarding harvest times, overall, BRS 506 and BRS 511 showed satisfactory indices of juice yield and quality. During the evaluation period (90 to 111 DAS), these indices increased until the final assessment date, when the best results were obtained (Figures 2, 3 B, 4, 7 and 8 B). By evaluating the physiological maturity of sweet sorghum stalk in Sete Lagoas, Minas Gerais, Brazil, Souza et al. (2016) concluded that the highest sugar content is obtained between 114 and 135 DAS, a longer cycle when compared to our study. This is an important advantage for the agricultural management of sweet sorghum in semi-arid regions of Brazil, confirming the hypothesis regarding utilization of silicon to hasten the physiological maturity.

Conclusion

The cultivars BRS 506 and BRS 511 show high technological indices for ethanol production in semi-arid regions, with higher biomass yield and juice quality at 111 days after sowing. And, the fertilization with potassium silicate at levels between 1100 and 1400 mL ha^{-1} in the management of sweet sorghum, for the aforementioned varieties, promotes increased juice quality and ethanol production.

Literature Cited

Almodares, A.; Hadi, M. R. Production of bioethanol from sweet sorghum: a review. African Journal of Agricultural Research, v. 4, n. 9, p. 772-780, 2009. http://www.grassohol.org/documents/Production%20of%20Bioethanol%20from%20Sweet%20Sorghum.pdf. 21 Out. 2017.

Camargo, M. S. de; Rocha, G.; Korndorfer, G. H. Silicate fertilization of tropical soils: silicone availability and recovery index of sugarcane. Revista Brasileira de Ciência do Solo, v. 37, n. 5, p. 1267-1275, 2013. https://doi.org/10.1590/S0100-06832013000500016.

Chagas, R. de C. S.; Muraoca, T.; Korndorfer, G. H.; Camargo, M. S. de. Silicon fertilization improve yield and quality of rice and pearl millet in cerrado soils. Bioscience Journal, v. 32, n. 4, p. 899-907, 2016. https://doi.org/10.14393/BJ-v32n4a2016-32792.

Coelho, A. M. Adubação. In: May, A.; Durães, F. O. M.; Pereira-Filho, I. A.; Schaffert, R. E.; Parrella, R. A. da C. (Eds.). Sistema Embrapa de produção agroindustrial de sorgo sacarino para bioetanol: Sistema BRS 1G – Tecnologia qualidade Embrapa. Sete Lagoas: Embrapa Milho e Sorgo, 2012. p. 42-50. (Embrapa Milho e Sorgo. Documentos, 139). https://www.embrapa.br/busca-de-publicacoes/-/publicacao/938275/sistema-embrapa-de-producao-agroindustrial-de-sorgo-sacarino-para-bioetanol-sistema-brs1g-tecnologia-qualidade-embrapa. 17 Set. 2017.

Dann, E. K.; Muir, S. Peas grown in media with elevated plant available silicon levels have higher activities of chinase and ß-1,3-glucanase, are less susceptible to a fungal leaf spot pathogen and accumulate more foliar silicon. Australasian Plant Pathology, v. 31, n. 1, p. 9-13, 2002. https://doi.org/10.1071/AP01047.

Dubois, M.; Gilles, K. A.; Hamilton, J. K.; Rebers, P. A.; Smith, F. Colorimetric method for determination of sugars and related substances. Analitical Chemistry, v. 28, n. 3, p. 350- 356, 1956. https://doi.org/10.1021/ac60111a017.

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. BRS 506: o sorgo sacarino mais testado e plantado no Brasil. Sete-Lagoas: Embrapa Milho e Sorgo, 2012a. 2p. http://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/937340/1/brs506.pdf. 21 Out. 2017

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. BRS 511: o sorgo sacarino com alto potencial de colmos. Sete-Lagoas: Embrapa Milho e Sorgo, 2012b. 2p. http://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/937343/1/brs511.pdf. 21 Out. 2017.

Guntzer, F.; Keller, C.; Meunier, J-D. Benefts of plant silicon for crops: a review. Agronomy for Sustainable Development, v. 32, n. 1, p. 201-213, 2012. https://doi.org/10.1007/s13593-011-0039-8.

Haynes, R. J. A contemporary overview of silicon availability in agricultural soils. Journal of Plant Nutrition and Soil Science, v. 177, n. 6, p. 831-844, 2014. https://doi.org/10.1002/jpln.201400202.

IUSS Working Group WRB. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. Rome: FAO, 2015. 192p. (World Soil Resources Reports, 106). http://www.fao.org/3/i3794en/I3794en.pdf. 27 Oct. 2017.

Lessa, B. F. da T.; Dutra, A. S.; Silva, T. M. da; Santos, C. C.; Sousa, W. N. Physiological maturation in seeds of sweet sorghum for foliar fertilizition with silicate. Revista Caatinga, v. 30, n. 3, p. 718-729, 2017. https://doi.org/10.1590/1983-21252017v30n320rc.

Masson, I. dos S.; Costa, G. H. G.; Roviero, J. P.; Freita, L. A. de; Mutton, M. A.; Mutton, M. J. R. Produção de bioetanol a partir da fermentação de caldo de sorgo sacarino e cana-de-açúcar. Ciência Rural, v. 45, n. 9, p. 1695-1700. https://doi.org/10.1590/0103-8478cr20130549.

May, A.; Durães, F. O. M.; Pereira-Filho, I. A.; Schaffert, R. E.; Parrella, R. A. da C. (Eds.). Sistema Embrapa de produção agroindustrial de sorgo sacarino para bioetanol: Sistema BRS 1G – Tecnologia qualidade Embrapa. Sete Lagoas: Embrapa Milho e Sorgo, MG, Brazil. 2012. 118p. (Embrapa Milho e Sorgo. Documentos, 139) https://www.embrapa.br/busca-de-publicacoes/-/publicacao/938275/sistema-embrapa-de-producao-agroindustrial-de-sorgo-sacarino-para-bioetanol-sistema-brs1g-tecnologia-qualidade-embrapa. 21 Out. 2017.

Peixoto, M. L.; Boiça Junior, A. L. Associação entre genótipos de feijoeiro, silício e nim no controle da mosca-branca, *Bemisia tabaci* (Gennadius, 1889) biótipo B (Hemiptera Aleyrodidae). Revista Ceres, v. 64, n. 4, p. 376-383, 2017. https://doi.org/10.1590/0034-737x201764040006.

Ratnadass, A.; Fernandes, P.; Avelino, J.; Habib, R. Plant species diversity for sustainable management of crops pest and diseases in agroecosystems: a review. Agronomy Sustainable Development, v. 32, n. 1, p. 273-303, 2012. https://doi.org/10.1007/s13593-011-0022-4.

Ratnavathi, C. V.; Chakravarthy, K.; Komala, V. V.; Chavan, U. D.; Patil, J. V. Sweet sorghum as feedstock for biofuel production: a review. Sugar Tech, v. 13, n. 4, p. 399-407, 2011. https://doi.org/10.1007/s12355-011-0112-2.

Ratnavathi, C. V.; Patil, J. V. Sorghum utilization as food. Journal of Nutrition & Food Sciences, v. 4, n. 1, 1000247, 2013. https://doi.org/10.4172/2155-9600.1000247.

Ratnavathi, C. V.; Suresh, K.; Vijay-Kumar, B. S.; Pallavi, M.; Komala, V. V.; Seetharama, N. Study on genotypic variation for ethanol production from sweet sorghum juice. Biomass & Bioenergy, v. 34, n. 7, p. 947-952, 2010. https://doi.org/10.1016/j.biombioe.2010.02.002.

Rodrigues, F. A.; Resende, R. S.; Dallagnol, L. J.; Datnoff, L. E. Silicon potentiates host defense mechanisms against infection by plant phatogens. In: Rodrigues, F. A.; Datnoff, L. E. (Eds.). Silicon and plant diseases. Cham: Springer, 2015. p.109-138. https://doi.org/10.1007/978-3-319-22930-0_5.

Sakellariou-Makrantonak, M.; Papalexis, D.; Nakos, N.; Kalavrouziotis, I. K. Effect of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in Central Greece. Agricultural Water Management, v. 90, n. 3, p. 181-189, 2007. https://doi.org/10.1016/j.agwat.2007.03.004.

Schurt, D. A.; Rofrigues, F. A.; V. Carré-Missio, V.; Soares, N. F. F. Silício alterando compostos derivados da pirólise de bainhas foliares de plantas de arroz infectadas por *Rhizoctonia solani*. Bragantia, v. 72, n. 1, p. 52-60, 2013. https://doi.org/10.1590/S0006-87052013005000020.

Sousa, J. V.; Rodrigues, C. R; Luz, J. M. Q.; Carvalho, P. C.; Rodrigues, T. M.; Brito, C. H. Silicato de potássio via foliar no milho: fotossíntese, crescimento e produtividade. Bioscience Journal, v. 26, n. 4, p. 502-513, 2010. http://www.seer.ufu.br/index.php/biosciencejournal/article/view/7148. 21 Out. 2017.

Souza, R. S.; Parrella, R. A. C.; Souza, V. F.; Parrella, N. N. L. D. Maturation curves of sweet sorghum genotypes. Ciência e Agrotecnologia, v. 40, n. 1, p. 46-56, 2016. https://doi.org/10.1590/S1413-70542016000100004.

Souza, V. F.; Parrella, R. A. C.; Tardin, F. D.; Costa, M. R.; Carvalho-Júnior, G. A.; Schaffert, R. E. Adaptability and stability of sweet sorghum cultivars. Crop Breeding and Applied Biotechnology, v. 13, n. 2, p. 144-151, 2013. https://doi.org/10.1590/S1984-70332013000200007.

Taiz, L.; Zeiger, E.; Moller, I. M.; Murphy, A. Fisiologia e desenvolvimento vegetal. 6.ed. Porto Alegre: Artmed, 2017. 858 p.