

Original Research Article

Ethanol production potential from sweet sorghum fertilized with filter cake and vinasse from the sugarcane industry

ABSTRACT

Sweet sorghum (*Sorghum bicolor* L. Moench) has high potential to produce ethanol as a complementary crop to sugarcane, whose industry generates large amounts of waste that can be used as fertilizer. The effect of using vinasse and filter cake in the sweet sorghum production was evaluated in an experiment carried out at the "Luiz Jorge da Gama Wanderley" Experimental Station (Agronomic Institute of Pernambuco - IPA) in Vitória de Santo Antão, PE, Brazil, from July to October 2013. The experimental design was randomized blocks consisting of two independent factors (five levels of vinasse application (0; 19.42; 77.68; 155.36 and 310.72 m³ha⁻¹) and five levels of filter cake (0; 2.75; 11.0; 22.0 and 44.0 Mg ha⁻¹), with four replicates. Sorghum stem yield and ethanol potential, wet cake weight, total recoverable sugars, reducing sugars and fiber were determined. Vinasse promoted increased in sorghum stem, sugar and ethanol yield, while filter cake decreased productivity. The use of vinasse and filter cake enables production of sweet sorghum for ethanol production complementary to sugarcane.

Keywords: agriculture, industrial residues, energy crops, biofuel

1. INTRODUCTION

Reducing dependence on fossil fuels that emit greenhouse gases and meeting the growing demand of energy are challenges faced by humankind in the XXI century. In this scenario, renewable energy sources, particularly those based on biomass, appear as an alternative for the development of a sustainable model of energy sources [1].

Renewable energy sources (hydraulic, biomass, solar, wind, geothermal) currently represent nearly 14% of world energy supply [2], but in Brazil, they are equivalent to 42.4%. Of these, the largest contribution (15.4%) is generated by sugarcane biomass [3], which makes Brazil one of the few countries in the world with potential to replace significant amounts of energy from fossil sources by renewable energy [4].

Currently, Brazil is the largest sugar producer and exporter, the largest ethanol exporter and second largest ethanol producer. Estimates for the 2014/2015 season are that the area planted with sugarcane was just over 9 million hectares, with a total estimated production of 642 million tons of sugarcane, 36 million tons of sugar and 29 billion liters of alcohol [5]. The state of Pernambuco is the second largest sugarcane producer in the Northeast region of Brazil, with a planted area of 260,000 hectares [5]. Nevertheless, sugarcane cultivation in the state has some limitations, especially regarding the wide rainfall variation, including areas with marginal levels of rainfall for sugarcane production [6]. Therefore, new energy crops that produce ethanol with lower water consumption have been used, and among these, sweet sorghum stands out as a promising alternative [7].

Biochemical ethanol production can be made from many crops, particularly species with C4 photosynthetic cycle such as sugarcane, maize and sweet sorghum [8,9]. Sweet sorghum has a number of qualities that make it particularly suitable such as high biomass yield, high fermentable sugar content, fast growth, high photosynthetic rates, and tolerance to drought, flooding and salinity [10].

Generally, sugarcane yield ranges from 70 to 80 Mg ha⁻¹ and sweet sorghum from 54 to 69 Mg ha⁻¹, but sorghum needs 1/3 the amount of water required for sugarcane and presents average sugar and

ethanol yields of 7 Mg ha⁻¹ and 3000 L h⁻¹, respectively, which are similar to those obtained using sugarcane [11]. Furthermore, sorghum has a short-cycle crop (3-4 months) and cultivation system, harvest and post-harvest technologies similar to those used in sugarcane [12,13]. Based on these characteristics, sweet sorghum may be a viable crop to be used in the sugarcane off-season period, thus ensuring the continuous operation of the sugar industry in these periods.

The activities related to ethanol and sugar production generate large amounts of waste of difficult management and therefore require proper disposal in order to minimize environmental impacts [14]. Among the waste generated by the sugarcane processing, vinasse is the most important both due to the high polluting power as to the large amount generated, since for every liter of alcohol produced, 13 liters of vinasse, on average, are produced [15]. In addition to vinasse, 30 to 40 kg of filter cake per ton of sugarcane processed are also generated [16]. Both vinasse as filter cake have high concentrations of organic matter and nutrients, especially potassium, phosphorus, nitrogen, sulfur, calcium and magnesium, being widely applied as complementary sources of fertilizer on sugarcane crops, either direct or after the application of biological stabilization processes such as vinasse biodigestion [17] and filter cake composting [18], reducing the cost of agricultural inputs and contributing to the sustainability of the production system [14].

Given that sweet sorghum culture is an alternative to sugarcane cultivation for ethanol production, the objective of this work was to evaluate the use of waste (filter cake and vinasse) from the sugar industry to fertilize sweet sorghum for ethanol production.

2. MATERIAL AND METHODS

Description of the experimental area and agronomic traits

The experiment was carried out at the "Luiz Jorge da Gama Wanderley" Experimental Station (IPA) in Vitória de Santo Antão, Pernambuco, Northeastern Brazil, whose geographical coordinates are: 08°08'00"S and 35°22'00"W, altitude 146 m. According to [19], the climate is dry sub-humid megathermal (C₁S₂Aa), with maximum, minimum and mean temperatures of 33.1, 18.9 and 25.4°C, respectively; average annual rainfall of 1050 mm per year, average evapotranspiration of 1100 mm and average relative air humidity of 67%.

According to [20], the soil of the experimental area was classified as dystrophic Red Latosol (Oxisol). In order to characterize the soil physical and chemical characteristics, thirteen samples were collected at the depth 0-20 cm from each block with a soil auger and thereafter, the samples were air dried, crushed and sieved in mesh of 2 mm and homogenized, forming two composed samples.

The analysis of the soil physical and chemical attributes of the experimental area before waste application followed methods described by [21] and resulted in: 597 g kg⁻¹ sand, 113 g kg⁻¹ silt, 290 g kg⁻¹ clay, bulk density of 1.88 kg dm⁻³, pH in water 5.30, 10.45 g kg⁻¹ of organic carbon, 9.6 mg dm⁻³ of available phosphorus, 0.33 cmol_c dm⁻³ potassium, 0.07 cmol_c dm⁻³ sodium, 1.50 cmol_c dm⁻³ of calcium, 1.20 cmol_c dm⁻³ of magnesium, 0.10 cmol_c dm⁻³ of aluminum, 3.30 of hydrogen + aluminum, 3.10 cmol_c dm⁻³ of sum of bases, 6.40 cmol_c dm⁻³ CTC, 48.44% of v- base saturation and 1.56% of m- aluminum saturation.

Before planting, the soil was plowed and grooved in lines spaced 0.80 m with depth of 0.30 m. Drip irrigation was performed by means of a NETAFIM flexible tape of 16.2 mm and emitters spaced 0.30 m with flow of 1.6 L h⁻¹. The amount of water applied at each irrigation was estimated to meet crop evapotranspiration using climatological data from the Weather Forecast Station and Center for Climate Studies - CPTEC/INPE, located in Vitória de Santo Antão. During the complete crop cycle, a total of 532 mm of water was applied (Figure 1).

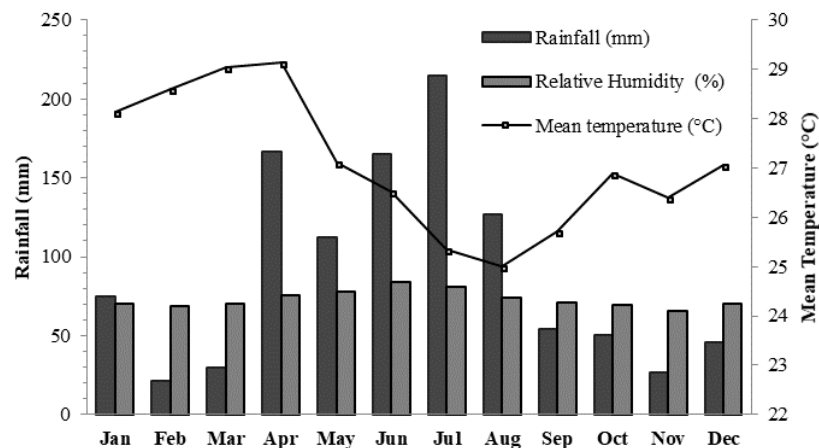


Fig 1. Rainfall, relative humidity and temperature during the crop cycle.

The SF-15 sweet sorghum variety has already shown potential for ethanol production in Northeastern Brazil [22]. Sowing was done on the twentieth day after vinasse and filter cake application on the soil. Three seeds were placed in each hill plot, and, after germination, pruning was carried out, keeping only one plant per hill. The planting spacing was 12 plants per linear meter (approximately 150,000 plants ha⁻¹). During the experiment, cultural practices consisted of hand weeding and pest control using natural pesticides (RotNeem) and manual harvesting because it is an organic plantation area.

Experimental design

An experimental design was used with four randomized blocks, in an experimental design with two independent factors: Five levels of vinasse application (0; 19.42; 77.68; 155.36 and 310.72 m³ ha⁻¹) and five levels of filter cake application (0; 2.75; 11.0; 22.0 and 44.0 Mg ha⁻¹). Experimental plots consisted of rows of 8 m in length with a contour area of 1 m on each side, with spacing of 0.80 m between rows and 1.5 m between blocks. The initial vinasse dose was calculated considering its potassium concentration and sorghum fertilizer recommendation based on potassium content in the soil and crop requirements [23]. The initial filter cake dose considered its nitrogen content and the IPA recommendation [23]. Higher vinasse and filter cake doses were four, eight and sixteen times the values of the initial doses. The main difference between agroindustrial residues is that the filter cake is a solid compound, unlike vinasse, with a dark yellowish liquid appearance.

Data collection

Vinasse and filter cake were obtained from the sugar mill company Grupo JB located in Vitória de Santo Antão, PE, Brazil. The chemical composition of vinasse was determined according to methodology proposed by [24]. The chemical parameters of filter cake were determined according to methodology proposed by [25].

The harvest of the vegetal material of each experimental plot to evaluate the fresh biomass obeyed the orientation of the proposed treatments within the blocks (four). At the beginning of the experiment, a minimum of 50% flowering and maturation were considered between millet and dough. Ten plants of each treatment were collected for the determination of the technological variables and yield of stems (PRODT), ethanol (PRODE) and sugar yield (PRODTA), being conditioned and transported in plastic bags. The plants were cut at a height of 15 cm from the top of the plants.

All the plants of the plot area were weighed in a dynamometer scale, the values obtained were transformed into kg ha⁻¹ to obtain the green mass of the plant (stem, leaves and panicle, separately). In the DEN-PROTEN-UFPE laboratory, for milling in stainless steel model B120. Samples of the broths removed from each comminuted stem were stored at -5 °C. After pressing, the broth volume was measured and transformed into 1 ha⁻¹ and the total soluble solids content was measured with a

digital automatic refractometer in ° Brix. The total reducing sugars, total recoverable sugars (ATR), sucrose (POL) and alcohol estimation per hectare were determined according to the methodology described in [26].

The methodology adopted for the technological analysis followed recommendations of [26]. The content of soluble solids in the sugarcane juice (°Brix) was determined by digital refractometer with automatic temperature correction, and the final value was expressed at 20°C and the wet bagasse weight (cake) was used for the calculation of the sweet sorghum fiber content (F). The apparent juice sucrose content (Pol) was determined by means of Eq. 1, the sorghum fiber content was determined by means of Eq. 2, purity (PZA) by means of Eq. 3, the content of reducing sugars (AR) by means of Eq. 4, and total recoverable sugar (ATR) by means of Eq. 5.

$$\text{Pol (\%)} = \text{Lpb} * (0.2605 - 0.0009882 * \text{Brix}) \text{Eq.1}$$

Where: Lpb = saccharimetric reading equivalent to that of lead subacetate; Brix = soluble solids content

$$\text{Fiber (\%)} = (0.08 * \text{PBU}) + 0.876 \quad \text{Eq.2}$$

Where: Fiber= sweet sorghum fiber content; PBU= wet bagasse weight (g).

$$\text{Purity (\%)} = 100 * \frac{\text{Pol}}{\text{Brix}} \quad \text{Eq.3}$$

Where: Purity = juice purity; Pol= apparent juice sucrose content; Brix = content of soluble solids in the juice.

$$\text{AR (\%)} = 3.641 - 0.0343 * \text{purity} \quad \text{Eq.4}$$

Where: AR = content of reducing sugars; Purity = juice purity.

$$\text{ATR (kg Mg stem}^{-1}\text{)} = 9.5263 * \text{Pol} + 9.05 * \text{AR} \quad \text{Eq.5}$$

Where: ATR = total recoverable sugar; PC = sorghum pol; AR= sorghum juice reducing sugar.

The production of sugar per hectare was expressed by the product of ATR (kg Mg stem⁻¹) and sugarcane stem yield per hectare (Mg stem ha⁻¹).

To estimate of theoretical ethanol production potential per hectare, the equation proposed by [27] was used, which considers 80% of the theoretical values, from Eq. 6.

$$\text{PRODE (L ha}^{-1}\text{)} = \frac{\text{kg sugar}}{\text{ha}} * \frac{\text{gal ethanol}}{5.68 \text{ kg sugar}} * \frac{3.78 \text{ L}}{\text{gal}} * 0.8 \quad \text{Eq. 6}$$

Where: 5.68 kg gal⁻¹= theoretical factor for conversion of total sugars into ethanol, corresponding to 1.5 kg L⁻¹; 3.78 = equivalent to one gallon (1 gal = 3.78 L); and 0.80 = rate of conversion of sugars into ethanol.

In addition to the agro-industrial variables common to the sugar industry, juices were analyzed for the quality of sugars. The levels of sucrose, glucose and fructose were quantified using high-performance liquid chromatography (HPLC) on Waters Alliance2695 chromatograph under flow conditions of 0.6 ml. min⁻¹ using mobile phase MilliQ water, infrared detector (IR), column temperature of 35°C and Rezex Penhomenex-type column with dimensions of 300 x 7.80 mm.

Statistical analysis

Data regarding stem production and agro-industrial technological variables were submitted to analysis of variance, using the F test, with significance levels of 1% and 5% and data were submitted to regression analysis using the SISVAR software [28].

3. RESULTS AND DISCUSSION

The physical and chemical characteristics of vinasse and filter cake are shown in Table 1. Data for filter cake is expressed on dry basis. As expected the vinasse presented in mg L^{-1} : 168 of N, 130 of P, 855 of K, 130 of Na, 118 of Ca, 62 of Mg, and 11 of organic matter (Table 1). The filter cake presented in g kg^{-1} : 11.6 of N; 12.4 of P; 10.2 of K; 3.0 of Na; 23.2 of Ca; 2.0 of Mg and 710 of organic matter (Table 1).

Table 1. Physical and chemical characteristics of vinasse and filter cake used in the assay for the production of sweet sorghum biomass cultivar SF-15.

Parameters	Vinasse	Filter cake
Electrical conductivity	2.76 dS m^{-1}	3.64 dS m^{-1}
pH	4.16	7.27
Total Nitrogen (mg L^{-1})	168.0 mg L^{-1}	11.6 g kg^{-1}
Phosphorus (mg L^{-1})	130.0 mg L^{-1}	12.4 g kg^{-1}
Potassium (mg L^{-1})	855.0 mg L^{-1}	10.2 g kg^{-1}
Sodium (mg L^{-1})	130.0 mg L^{-1}	3.0 g kg^{-1}
Calcium (mg L^{-1})	118.0 mg L^{-1}	23.2 g kg^{-1}
Magnesium (mg L^{-1})	62.0 mg L^{-1}	2.0 g kg^{-1}
Organic matter (mg L^{-1})	11.0 mg L^{-1}	710.0 g kg^{-1}

The fresh samples of filter cake had an average of 542 g kg^{-1} of moisture. The pH ranged from acid for vinasse (4.16) to neutral for filter cake (7.27). As expected, vinasse showed the highest K concentrations and filter cake the highest Ca and P concentrations. The composition of organic wastes from the sugar industry is quite variable because it depends on variety and degree of sugarcane ripeness, growing conditions, soil and climate and type of treatment process the juice is submitted to in the sugar industry [16]. Despite this variation, the results obtained were similar to those reported by [29] for filter cake and by [16] for vinasse.

Effect of the addition of agro-industrial residues on the agronomic characteristics of sweet sorghum

Data of stem production with addition of vinasse and filter cake were adjusted to the quadratic-type regression model (Table 2). At the highest vinasse dose, we observed a production of 53.5 Mg ha^{-1} of sweet sorghum stems, representing 20% more than the control treatment without addition of vinasse. The maximum values of sorghum stem production with addition of filter cake occurred in the treatments dose 11 with highest mean values 51.32 Mg ha^{-1} stems, respectively. Positive effects with the use of vinasse are associated with the response of sweet sorghum to nitrogen and potassium fertilization [7]. With the filter cake, which is basically a source of phosphorus, sweet sorghum is usually not very responsive [12].

Table 2. Sweet sorghum (SF-15) industrial technological variables responses to fertilization with different doses of vinasse and filter cake in Pernambuco, Brazil.

Residue Doses	Agroindustrial technological variables						
Vinasse	Stem productivity	Brix degree	Purity	WWC	Crude fiber	TRS (kg Mg)	RS

	(m ³ ha ⁻¹)	(Mg ha ⁻¹)	(g 100g ⁻¹)	(%)	(g)	(%)	stem ⁻¹)	(%)
	0	41.15	13.2	62.67	182.1	17.13	63	1.23
	19.42	42.62	13.26	65.02	184	17.22	64.5	1.26
	77.68	53.5	13.74	70.36	196.48	18.24	75.79	1.49
	155.36	43.29	13.34	69.49	187.65	17.8	72	1.41
	310.72	42.63	13.33	67.49	186.78	17.4	67.97	1.33
	GM	44.60	13.40	67.01	187.00	17.60	68.82	1.34
Significance		**	ns	**	ns	ns	**	**
CV(%)		6.69	2.38	3.36	9.61	9.40	4.32	5.77
CD (R ²)		0.282	---	0.854	---	---	0.741	0.731
				$\hat{Y}$				$\hat{Y} =$
	$\hat{Y} = 42.6074 + 0.0722X - 0.0002X^2$			$= 63.4121 + 0.0837X - 0.0002X^2$			$\hat{Y} = 63.450 + 0.1340X - 0.0004X^2$	$1.23940 + 0.00270X - 0.00001X^2$
Equations			---		---	---		
Filter cake								
	(Mg ha ⁻¹)							
	0	38.26	12.92	57.06	170.83	15.49	66.17	1.19
	2.75	42.49	13.17	61.44	173.9	16.81	69.7	1.21
	11	51.32	14.16	71.39	185.5	17.2	75.5	1.69
	22	51.3	13.42	70.77	175.33	17.06	71.65	1.53
	44	44.12	13.2	70.08	174.55	16.92	71.37	1.24
	GM	45.50	13.37	66.15	176.02	16.70	70.87	1.37
Significance		**	ns	**	ns	ns	*	**
CV(%)		7.91	4.90	7.23	10.25	9.79	5.67	12.01
CD (R ²)		0.927	---	0.888	---	---	0.551	0.767
				$\hat{Y} =$			$\hat{Y} = 67.83 + 0.510X - 0.01X^2$	$\hat{Y} = 1.1872 + 0.0402X - 0.0009X^2$
	$\hat{Y} = 39.29 + 1.148X - 0.023X^2$			$58.41 + 1.093X - 0.019X^2$				
Equations			---		---	---		

ns: not significant; * and ** significant 0,05 and 0,01 probability, respectively, by F test; GM - general mean; CV - coefficient of variation; CD- coefficient of determination; WWC - weight wet cake; TRS - total recoverable sugar; RS - reducing sugars.

On average, cultivars showed stem productivities ranging from 40 to 60 Mg ha⁻¹, depending on the variety used [30]. This stem production yielded, on average, 3000 L of ethanol per hectare [11]. Therefore, the range of stem productivity observed in the present study fell within the expected limits, regardless of the type of waste used.

[31] assessed the production of stems from four sorghum cultivars in four harvest times (15, 30, 45 and 60 days after flowering) and found average values equal to 50 Mg ha⁻¹, similar to the results obtained in this study. [32] quantified the production of stems from five sorghum cultivars (Dale, Della, Keller, M81E and Sugar Drip) grown with nitrogen fertilization under cover and without irrigation and found average yields of 40 Mg ha⁻¹ in three years of cultivation (2009, 2010 and 2011).

Sugarcane responses to fertilization with wastes are similar to those observed for sorghum SF-15 cultivar. [33] evaluated the effect of sewage sludge as a source of N and vinasse as a source of K on yield and technological variables of sugarcane for two consecutive years (plant cane and ratoon cane) and found mean stem productivity in plant cane and ratoon cane equal to 126 and 99 Mg ha⁻¹, respectively, which productions are equal to that shown by the control treatment (mineral fertilizers) of 125.7 Mg ha⁻¹ for stem production of plant cane and 105.6 Mg ha⁻¹ for stem production of ratoon cane.

Effect of the addition of vinasse and filter cake on the agro-industrial variables of sweet sorghum

The main technological variables for the sorghum crop are Brix, purity, wet cake weight, fiber content, total recoverable sugars and reducing sugars [30]. In the present study, the values of total soluble solids (Brix) were not affected significantly by the addition of vinasse and filter cake (Table 2). The means values Brix in the juice in the milky to pasty grain harvest stage were 13.40 and 13.37 for treatments with vinasse and filter cake, respectively. The analysis of Brix and its variations is an important tool for the determination of production potentials [34] and harvest moments for sweet sorghum biomass [35].

Purity was affected by the addition of the two types of waste (Table 2). Purity showed an increasing linear response for vinasse and decreasing linear response for filter cake fertilization. Purity expresses the relationship between the sucrose content of a solution and its Brix. Purity values are quite variable for sweet sorghum cultivars depending on growing conditions such as soil type, fertilization, irrigation, planting season and harvest [7]. Purity values of 70%, 83.4% and 70.7% have been reported for Rio [36], Rome [37] and BRS 511 cultivars [30], respectively.

Similar to Brix responses, crude fiber content was not significantly affected by the fertilization with vinasse or filter cake (Table 2). The mean sorghum crude fiber content was 17.6% and 16.7% after fertilization with vinasse and filter cake, respectively. The fiber content is directly related to the chemical composition of the sweet sorghum biomass and is a variable that determines the quality of the material for the grinding process. High crude fiber values (over 12%) reduce the sugar extraction efficiency [30]. Similar crude fiber values were observed for sugarcane clones and varieties selected for sugarcane energy with high fiber value, 16.4% [38]. [39] found negative correlation between fiber content and theoretical ethanol production of sweet sorghum cultivars.

The wet cake weight showed no significant difference among doses for the two types of waste applied, reaching average values of 187 and 176 g when using vinasse and filter cake, respectively (Table 2). The wet cake weight values obtained in this study are higher when compared to values found by [40], who studied the system of calculation for the purpose of payment for sugarcane by the content of total recoverable sugars (TRS) in the states of Rio de Janeiro, Espírito Santo and São Paulo, and found an average wet cake weight of 150 g. This difference is explained by the higher fiber content observed for sweet sorghum cultivar SF-15 when compared to sugarcane (14%).

The production of total recoverable sugars, which expresses the production of sugars by megagram of stem, showed different responses to the two types of waste (Table 2). The application of vinasse increased the TRS production described by the quadratic model, ranging from 63 kg Mg stem⁻¹ for the control treatment to 72 kg Mg stem⁻¹ for the highest vinasse dose. The addition of filter cake showed the opposite effect, reducing the TRS values with increasing doses, ranging from 75.5 kg Mg stem⁻¹ for the control treatment to 69.7 kg Mg stem⁻¹ for the highest filter cake dose.

Evaluations for the series of TRS sorghum cultivars developed by the Brazilian Corporation of Agricultural Research (EMBRAPA) indicated the possibility of obtaining TRS values ranging from 72 to 107 kg per Mg of green mass using the same technology used in sugar plants [30]. This study obtained highest mean values of 75.79 vinasse and 75.5 kg Mg⁻¹ stem filter cake, in the treatments with doses 77.68 and 11 respectively, being lower than result obtained by the above author. The sorghum variety (SF-15) adopted in this work comes from a crossing of a variety of sweet sorghum with forage sorghum, which may have influenced the TRS content present in stems.

When compared to sugarcane, TRS values observed for the SF-15 cultivar are lower, indicating lower production of sugars from sweet sorghum biomass. [41] obtained TRS values ranging from 158 to 161 kg Mg⁻¹ depending on the waste used (sewage sludge or vinasse) and the application mode. The results found by these authors are similar to those found by [33], who studied ten cultivars in two municipalities in the mid-northern region of São Paulo, and found values between 137 and 166 kg Mg⁻¹.

The addition of vinasse and filter cake influenced the contents of reducing sugars (RS) in the juice obtained from SF-15 cultivar. The addition of vinasse and filter cake increased quadratically RS in the juice until doses treatments 77.68 and 11 respectively, decreasing the mean values after these doses (Table 2). Similar RS values were observed by [31], when evaluating sweet sorghum cultivars in the stage of maturity, with an average RS content of 1.3%.

In the sugarcane industry, recommended RS% values can be up to 1.5 and should not exceed 1% over the course of the season [41]. Factors influencing the RS content in the sugarcane juice are related to soil moisture, excessive fertilization, mainly N, presence of organic matter in the soil and application of organic waste. For sugarcane in advanced maturation stage, it is expected that the sucrose content is high and the fraction of sugars in the sugarcane juice is low; however, the reverse situation can occur, depending on the factors mentioned above [33].

Effect of the addition of vinasse and filter cake on the quality of sorghum juice sugars

The percentages of sucrose, glucose and fructose in treatments with vinasse and filter cake are shown in Figure 2, respectively. The sucrose, glucose and fructose increased percentage according to a quadratic model when vinasse and filter cake were added, with maximum percentage for vinasse at dose of 77.68 m³ h⁻¹ and for filter cake at dose of 22 Mg ha⁻¹. Knowing the profile of sugars present in the sweet sorghum juice allows choosing the best use of this resource, juices with high sucrose content > 90% can be used to produce sugar and ethanol, while juices with reduced sucrose contents (below 85%) may be used exclusively for the production of ethanol [30] or other bioproducts [42].

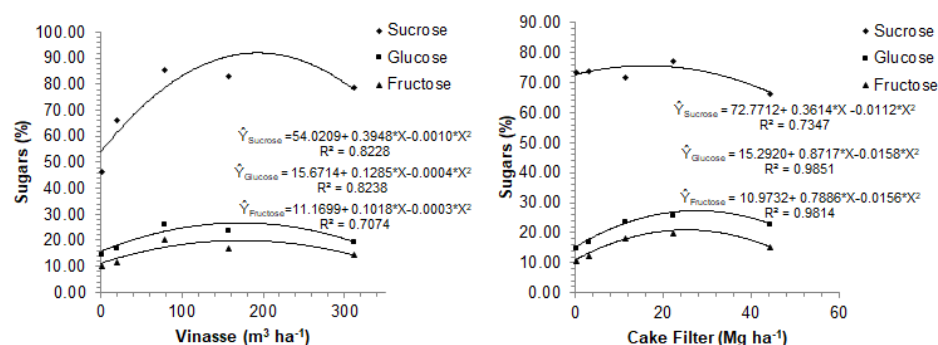


Fig 2. Profile broth sugars due to the application of vinasse and filter cake in cultivar SF-15. Significant at *P < 0.05.

Due to the wide genetic variability for sweet sorghum crop [43,44], the results indicated in literature are quite variable in terms of the profiles of sugars, sucrose, glucose and fructose. A comparison with a sweet sorghum cultivar widely used in Brazil, BRS 506, which has 63% sucrose, 26% glucose and

11% fructose [30], indicates the good quality of juice obtained from SF-15 variety. KCU40 cultivar, grown mainly in Asia, presented percentages of 71.7% sucrose, 12.1% glucose and 9.7% fructose [45]. Importantly, the percentages of sugars were determined in the grain stage from pasty to milky, and usually sucrose contents increase with the advance in the plant development stage and reach their maximum accumulation in the grain maturation phase but on the other hand, the nutrient content of juices decrease [13] and juices generally show lower quality [7].

Effect of the addition of agro-industrial waste on the production of sugar and theoretical ethanol per hectare of sweet sorghum SF-15 cultivar

Sugar production per hectare increased quadratically with the addition of vinasse ($P < 0.05$) and filter cake ($P < 0.05$) (Figure 3 and 4). Maximum sugar productivities were observed at the highest vinasse ($77.68 \text{ m}^3 \text{ ha}^{-1}$) and filter cake doses (11 Mg ha^{-1}), reaching values up to 3831 kg ha^{-1} and 3872 kg ha^{-1} , respectively. The determination of the total sugar production per area allows determining the maximum theoretical ethanol production for the sweet sorghum cultivar evaluated. Sugar production is directly related to plant cultivar, cultivation system, irrigation and fertilization and soil and climatic conditions of production environments [46].

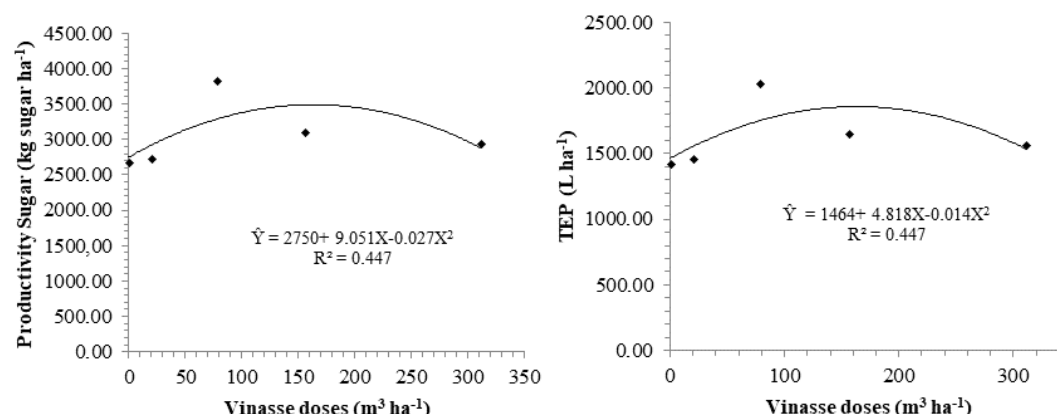


Fig 3. Productivity of sugar and theoretical ethanol (TEP) per hectare for cultivate SF-15 due to the application of vinasse. Significant at *P < 0.05.

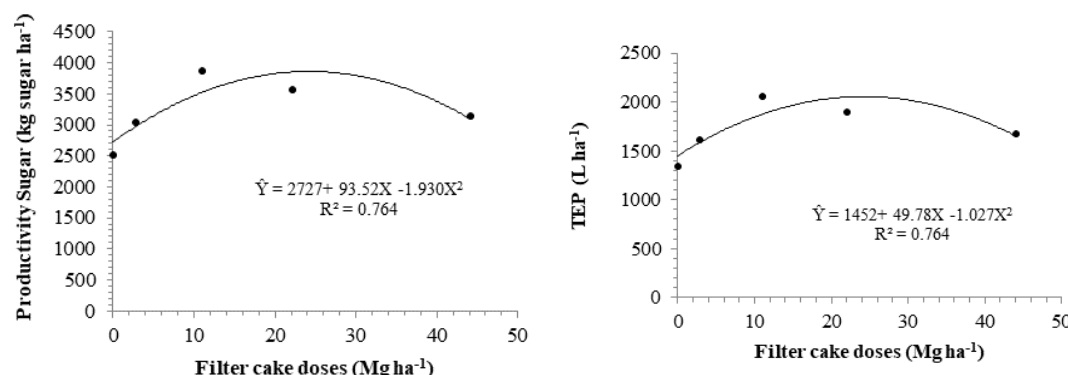


Fig 4. Productivity of sugar and theoretical ethanol (TEP) per hectare for cultivate SF-15 due to the application of filter cake doses. Significant at *P < 0.05.

The maximum sugar production per hectare for SF-15 cultivar showed intermediate values compared to those described in literature. Cultivars such as Rio, M81E and Della showed sugar productions of

1852 kg ha⁻¹, 1990 kg ha⁻¹ and 2030 kg ha⁻¹, respectively [35]. This difference may be related to improved fertilization obtained with the addition of vinasse and filter cake. In systems requiring higher amounts of water, varieties such as Keller, SSV 84, BJ 248, Wray, grown in India, presented productions of 4660 kg ha⁻¹, 7350 kg ha⁻¹, 4140 kg ha⁻¹ and 4810 kg ha⁻¹, respectively [47].

The theoretical ethanol production potential as a function of the application of vinasse and filter cake are shown in Figure 3 and 4. The addition of vinasse had a significant effect in accordance with a quadratic model ($P < 0.05$), with intermediate production potential ranging from 1429 L ha⁻¹ for control treatment to 2040 L ha⁻¹ for the highest vinasse application dose (77.68 m³ h⁻¹). Similarly, the addition of filter cake had a significant negative effect ($P < 0.05$) on theoretical ethanol production per hectare, with average production potential ranging from 1347.53 L ha⁻¹ for control treatment to 2061.78 L ha⁻¹ for the highest filter cake application dose (11 Mg ha⁻¹) (Table 2).

Similarly to the production of sugar per hectare, theoretical ethanol production is variable according to the cultivars that are commonly grown in different regions of the world. However, theoretical ethanol production per hectare is one of the most important variables for the establishment of a cultivar to produce ethanol in a given region [48]. Similar values were observed by [49], 1425 L ha⁻¹ to 2622 L ha⁻¹ when estimating the production of ethanol by four sorghum cultivars, KKKU40, Theis, and BJ248 SPV1411 with different equations, with the best results for the equation of [27]. Other studies have quantified the production of ethanol per hectare for different sweet sorghum cultivars. [50] observed for Dalle, M81E, Rio, Theis and Toper cultivars, productions of 3380, 2780, 3000, 2950 and 2620 L ha⁻¹, respectively. [51] reported theoretical ethanol production from 2639 to 2878 L ha⁻¹ for M81E cultivar and [52] observed potential of 2465 L ethanol ha⁻¹ for Top 76-6 variety.

The Brazilian production of ethanol per hectare is currently 6,800 liters considering the national average productivity of 85 Mg ha⁻¹ of sugarcane and yield of 85 L Mg cane⁻¹. Comparing the best ethanol productivity presented in this work of 2040 L ha⁻¹, obtained when vinasse was used as a source of fertilizer for sweet sorghum cultivation to produce ethanol, a difference of 70% was observed. However, the fast crop cycle of sorghum the similar mechanization system between sweet sorghum and sugarcane, the relatively high content of directly fermentable sugars contained in the stem and the requirements in terms of climatic factors may justify the adoption of sweet sorghum cultivation [30] as a complementary biomass source for ethanol and electricity production in sugarcane regions, especially during sugarcane off-season [53].

4. CONCLUSIONS

Vinasse and filter cake proved to be effective in increasing industrial technological variables: Stem productivity, purity, TRS and RS. The highest percentages of sugars were found at doses 77.68 m³ ha⁻¹ and 22 Mg ha⁻¹ for vinasse and filter cake, respectively. Higher doses than 77.68 m³ ha⁻¹ for vinasse and 11 Mg ha⁻¹ for filter cake did not offer advantages in terms of cost-benefit for the production of ethanol. The results obtained support the technical feasibility of using the wastes from sugarcane ethanol industry, vinasse and filter cake, for sweet sorghum production with high potential for ethanol production in Northeastern Brazil.

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