Biomass and sugar production of sweet sorghum (*Sorghum bicolor*) for different sowing dates in Veracruz, Mexico †

[Producción de biomasa y azúcares de sorgo dulce (*Sorghum bicolor*) en diferentes fechas de siembra en Veracruz, México]

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SUMMARY

Background. The most commonly used raw materials for ethanol production are maize (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L.). A specie that is gaining importance because of its comparative advantages over other energy crops is sweet sorghum (*Sorghum bicolor* (L.) Moench). The seasonality of production, which limits the continuous supply of sweet sorghum to the industry for ethanol production, is one of the limitations of this crop. **Objective.** To evaluate the biomass and sugar production of sweet sorghum genotypes for different sowing dates in Veracruz, Mexico conditions. **Methodology.** The development of ten genotypes was determined during the autumn-winter (October 2013), winter-spring (February 2014) and spring-summer (April 2014) cycles. Three genotypes were also tested on five planting dates: June 19th, July 1st, August 1st, September 1st, and October 2nd, at the Cotaxtla Experimental Station of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), located in the municipality of Medellín de Bravo, Veracruz, México. **Results.** Sweet sorghum developed in all cropping seasons, but the highest productivity was obtained in the spring-summer. Stem biomass, sugar concentration, juice volume, and sugar production were highest in June, July, and August, following planting. As the planting date was later, the values decreased. **Implications.** The optimal planting date for sweet sorghum cultivation in the state of Veracruz was identified. This information will be helpful for producers to obtain higher biomass yields and for the ethanol industry to plan sweet sorghum production as a complementary raw material to sugarcane. **Conclusions.** The optimum sweet sorghum planting period for producing biomass and sugars under Veracruz, Mexico, conditions is during June, July, and August.
Key words: harvest seasonality; plant morphology; sugar concentration.

RESUMEN

Antecedentes. Las materias primas más utilizadas para la producción de etanol son el maíz (*Zea mays* L.) y la caña de azúcar (*Saccharum officinarum* L.). Una especie que está ganando importancia debido a sus ventajas comparativas sobre otros cultivos energéticos es el sorgo dulce (*Sorghum bicolor* (L.) Moench). La estacionalidad de la producción, que limita el suministro continuo a la industria para la producción de etanol, es una de las limitaciones del sorgo dulce. **Objetivo.** Evaluar la biomasa y producción de azúcar de genotipos de sorgo dulce para diferentes fechas de siembra en las condiciones de Veracruz, México. **Metodología.** Se determinó el desarrollo de diez genotipos durante los ciclos otoño-invierno (octubre 2013), invierno-primavera (febrero 2014) y primavera-verano (abril 2014). También se evaluaron tres genotipos en cinco fechas de siembra: 19 de junio, 1 de julio, 1 de agosto, 1 de septiembre y 2 de octubre, en el Campo Experimental Cotaxtla del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), ubicado en el municipio de Medellín de Bravo, Veracruz, México. **Resultados.** El sorgo dulce se desarrolló

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en todas las épocas de cultivo, pero la mayor productividad se obtuvo en primavera-verano. La biomasa del tallo, la concentración de azúcar, el volumen de jugo y la producción de azúcar fueron mayores en las siembras de junio, julio y agosto. A medida que la fecha de siembra fue más tardía, los valores disminuyeron. **Implicaciones.** Se identificó la fecha óptima de siembra para el cultivo de sorgo dulce en el estado de Veracruz. Esta información será útil para que los productores obtengan mayores rendimientos de biomasa y para que la industria del etanol planee la producción de sorgo dulce, como materia prima complementaria a la caña de azúcar. **Conclusión.** El periodo óptimo de siembra de sorgo dulce para la producción de biomasa y azúcares bajo las condiciones de Veracruz, México, es durante los meses de junio, julio y agosto.
Palabras clave: estacionalidad de cosecha; morfología de la planta; concentración de azúcares.

INTRODUCTION

The most commonly used raw materials for ethanol production are maize (*Zea maize* L.) and sugarcane (*Saccharum officinarum* L.) (Balat and Balat, 2009). A species that is gaining importance due to its comparative advantages over other energy crops is sweet sorghum (Sorghum bicolor (L.) Moench) (Reddy *et al*., 2009). It exhibits rapid growth and early maturity, high efficiency in water use, limited fertiliser requirements, high carbon assimilation, and tolerance to abiotic stresses such as drought, excess moisture, salinity, and alkalinity (Prasad, Singh, and Joshi, 2007). Another characteristic of sweet sorghum is that its harvesting season can be complementary to that of sugarcane, and both crops can be planted and harvested in sequence to extend the milling period in most regions where sugarcane is produced (Burks *et al*., 2013; Rao *et al*., 2013). Due to the above characteristics and its higher content of fermentable sugars, sweet sorghum is considered the most suitable crop for ethanol production (Almodares and Hadi, 2009; Reddy *et al*., 2007).

Among the limitations of sweet sorghum are a short harvest period with maximum sugar concentration, seasonality in biomass production and sugar fermentation if not processed immediately after harvest (Prasad, Singh and Joshi, 2007). These characteristics limit the continuous supply of the raw material to the industry for ethanol production. The seasonality of sweet sorghum production is determined by biotic and abiotic factors, including water stress, low temperatures, and sensitivity to photoperiod (Reddy *et al.*, 2012). Photoperiod sensitivity primarily determines the length of the vegetative stage and serves as a mechanism of adaptation to various environments (Clerget *et al.*, 2007). Sorghum is a short-day plant, which flowers when illuminated for less than a certain number of hours per day. Varieties of tropical origin differentiate by their reproductive stage when the day length is equal to or less than 12 hours (Reddy *et al.*, 2012).

Agronomic practices developed for sweet sorghum to achieve a continuous supply include staggered sowing and the use of early-, intermediate-, and late-maturity genotypes (Burks, 2012; Burks *et al*., 2013; Rao *et al*., 2013). Several studies indicate that using early planting dates in April and May leads to higher biomass and sugar production in temperate regions such as Texas (Burks *et al*., 2013), Arizona (Teetor *et al.*, 2011), Florida (Erickson *et al.*, 2011) and Louisiana (Han *et al.*, 2012), allowing for an extended two-month grinding period. In contrast, for the semi-arid tropics in India, the optimal period for sweet sorghum sowing is from the first week of June to the first week of July, which enables an extension of the milling period from the first to the last week of October (Rao *et al.*, 2013).

The best areas in Mexico for sweet sorghum cultivation are located in the sub-humid tropics, characterised by rainfall between 700 and 1,600 mm per year, primarily along the coasts of the Gulf of Mexico. A potential optimum area of 2,250,000 ha is identified in the state of Veracruz alone (Ramírez-Jaramillo, Lozano-Contreras, and Ramírez-Silva, 2020). However, there is limited information regarding the optimal period and the most suitable genotypes to be used in conjunction with sugarcane for ethanol production.

The objective of this study was to evaluate the biomass and sugar production of sorghum genotypes planted at different dates to determine the optimal planting date for conditions in Veracruz, Mexico.

MATERIALS AND METHODS

Study area

This study was conducted in the Campo Experimental Cotaxtla of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), situated at 18° 56’ 13’’ North and 96° 11' 38 " West in Medellín de Bravo, Veracruz, México. The soil type was a clay loam texture. In the layer from 0 to 90 cm in depth, the pH was 5.5, and the organic matter content was 2.4%. The concentrations of N, P, K, Ca, Mg were 1-2, 59-66, 240-693, 2368-2751, 448-417 ppm, respectively.

During 2014, temperatures ranged from 12.5 °C to 32.8°C, with the lowest temperature recorded in

January and the highest in August. The rainy season lasted from June to September, with a total rainfall of 1,464 mm, accounting for 50% of the annual rainfall, which was recorded in the latter month. (Figure 1). Global radiation ranged from 303 to 493 W/m^2, values recorded in January and April, respectively. The highest radiation period occurred from March to August, with values exceeding 400 W/m^2. The photoperiod varied between 10.9 h in December and 13.1 h in June. The months of October to March had a photoperiod of less than 12 h, and from April to September, more than 12 hours (Figure 2).

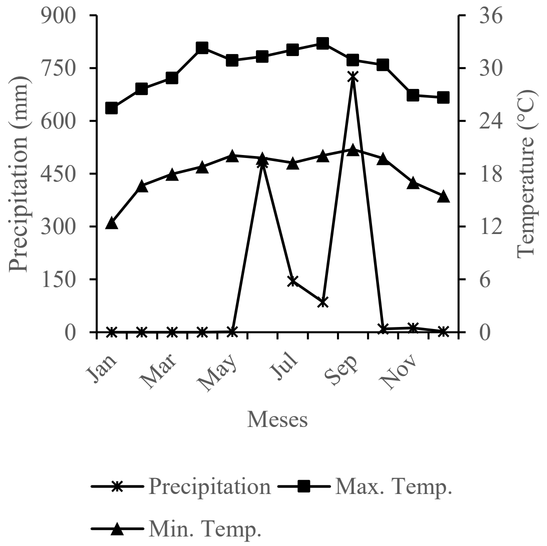

Figure 1. Temperature and precipitation distribution at the Cotaxtla Experimental Field during 2014.

In the state of Veracruz, 40 cold fronts occurred during the season from September 20, 2014, to May 15, 2015, with wind intensities ranging from 20 to 120 km h^{-1} (Mexico, 2015).

Experimental design and treatments

Experiment 1. In the first experiment, three planting dates were established: October 2013, February 2014 and April 2014, corresponding to the autumn-winter, winter-spring and spring-summer growing seasons, respectively. On the three dates, the same sweet sorghum genotypes were evaluated: RB-Cañero, Tanol 2, SBA25XUS1, SBA25XUS8, SBA25XUS9, SBA25XDALE, SBA22XUS1, SBA22XUS2, SBA22XUS7, and SBA22XUS8. The plot size was two rows of 5 m long and 0.8 m wide.

Experiment 2. The genotypes RB-Cañero, RB-Cañaveral and Tanol were evaluated on five sowing dates: June 19, July 1, August 1, September 1 and October 2, 2014. The main plot, measuring 240 m², corresponded to the sowing date and contained smaller plots of 80 m² each, where the genotypes were planted.

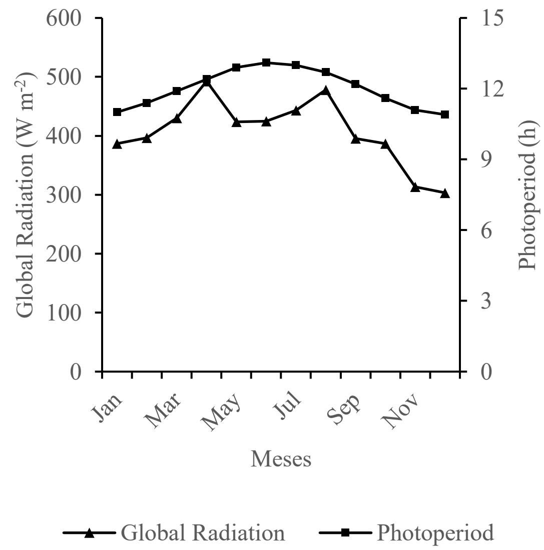

Figure 2. Distribution of global radiation and photoperiod at the Cotaxtla Experimental Field during 2014.

Sweet sorghum establishment and agronomic management

All genotypes were sown with a row spacing of 0.8 m and a plant spacing of 0.1 m, resulting in a plant population density of 120,000 plants ha^{-1}. Fertilization was 138-46-0 NPK; half of the nitrogen was supplied at planting, the rest was added 30 days later, and the full dose of phosphorus was applied at planting. The herbicide atrazine provided weed control at a dose of 3 L ha^{-1} applied the day after sowing. Insect control was performed with the active ingredients cypermethrin and permethrin at doses of 400 mL ha^{-1} and 10 kg ha^{-1}, respectively.

Among the biotic factors that could affect the productivity of the genotypes were the competition of weeds, especially Johnson Grass (*Sorghum halepense* (L.) Pers.), and the attack of the fall armyworm (*Spodoptera frugiperda* (J.E. Smith)); however, it is considered that these factors were satisfactorily controlled with the management practices described above.

When the grain was at the stage of physiological maturity, identified by the presence of a black layer or dark spot at the base of the grain, known as the hilum, the sweet sorghum plants were harvested in an area corresponding to 1 m^2 in the first experiment and to 4 m^2 in the second experiment. The Tanol, planted on June 19 and July 1, and the RB-Cañaveral from the first date were harvested on October 1. By October 15, the RB Cañero, planted on the first and second dates, and the RB-Cañaveral were harvested. On November 18, December 8, and January 13, the three genotypes were harvested from the sowings carried out on August 1, September 1, and October 2, respectively.

Data collection

The sorghum plants were then cut to ground level, and the leaves and panicles were removed. To estimate total fresh biomass and fresh stem biomass, leaves, stems, and panicles were weighed and converted to tons per hectare. Juice was then extracted from the stalks, and the glucose and fructose content was determined. After inversion treatment of the sucrose present in the sorghum juice, the sugar content (glucose and fructose) was quantified using a high-resolution liquid chromatograph (HPLC), brand Alliance Waters. HPLC operating conditions were 0.05 N H_2SO_4 as the mobile phase, a flow rate of 0.6 mL/min, a column temperature of 55 °C, and a Waters model 2414 refractive index detector. The injection volume was 10 µL, and the analysis time was 30 min per sample. Standards used were anhydrous glucose (Golden Bell foodgrade) at concentrations of 100, 50, 16.6, 10, 5, 2.5, 1.66, 1.25, 1, 0.50, and 0.33g/mL and fructose (Baker's reagent grade) at concentrations of 100, 50, 16.6, 10, 5, 2.5, 1.66, 1.25, 1, 0.50, and 0.33g/mL. Five plants were randomly selected from the total number of harvested plants. Height, diameter, weight and total soluble solids were measured from the top of even internodes. Brix values were averaged to obtain a single value for each sample. Height was measured from the base of the stem to the top of the panicle using a tape measure, and diameter was measured with a calliper at 75 cm. Weighing was carried out using a digital balance with an accuracy of 0.1 g.

Data analysis

For statistical analysis, the SAS program, version 9.2 (SAS Institute Inc., 2008), was used, using general linear model (GLM) procedures and Tukey's honestly significant difference (HSD) test. For the first experiment, a randomised block experimental design with four replications was used, and the results were analysed as a series of experiments. An experimental design of randomised blocks in split plots with four replications was employed for the second experiment.

RESULTS

Effects of planting date on productivity

The highest mean values for plant height, diameter, stem weight, stem biomass, juice volume, and sugar production were recorded for the April 2014 planting date. The values obtained on this date were significantly different ($P < 0.05$) from those observed in October 2013 and February 2014. Total soluble solids and sugar concentration in the juice were higher in February 2014, with a statistically significant difference (Table 1).

The genotypes exhibited different behaviours across the three sowing dates evaluated. No significant differences were found between treatments in any of the variables assessed in October 2013. All genotypes exhibited higher sugar concentrations and lower juice content in February 2014; however, no significant differences were found between treatments. Genotypes SBA25XUS8, SBA22XUS8 and SBA22XUS7, in the April 2014, stood out for their higher productivity in stem biomass, with values of 85, 75 and 71 t ha^{-1}, respectively; juice volume (24,100, 18,150 and 24,250 L ha^{-1}, respectively) and total sugars (2,440, 1,208 and

Table 1. Average of sweet sorghum parameters in the autumn-winter, winter-spring and spring-summer growing seasons in Veracruz, Mexico.

Parameters	October 2013[1]	February 2014	April 2014	LSD (Tukey)[2]
Plant height (cm)	191.9 b[3]	188.3 b	283.0 a	7.42
Plant diameter (mm)	11.1 b	10.5 b	19.8 a	0.64
Stem weight (g/planta)	157.8 b	173.1 b	713.3 a	45.62
Total soluble solids (°Brix)	9.0 c	18.4 a	11.3 b	1.02
Stem Biomass (t ha^{-1})	13.7 c	17.5 b	56.9 a	3.69
Juice Volume (L ha^{-1})	5645 b	3403 c	15779 a	1800
Total sugar concentration (g L^{-1})	67.88 b	136.65 a	65.27 b	15.98
Total sugar production (kg ha^{-1})	401.8 b	461.0 b	1120.6 a	212.03

[1]Planting date; [2]LSD = Least Significant Difference; [3]Different letter (a, b, c) in the rows, denotes significant differences (P<0.05).

1,891 t ha^{-1}, respectively), compared to treatments SBA22XUS2, Tanol 2 and SBA25XUS1, which obtained the lowest production, with stem biomass values between 33-42 t ha^{-1}, juice content between 9,350 and 11,500 L ha^{-1} and sugar production, between 300 and 845 kg ha^{-1}.

All genotypes increased their stem biomass (Figure 3), juice content (Figure 4), sugar concentration (Figure 5), and sugar production (Figure 6) values in different proportions at the April 2014 planting date compared to October 2013. Genotype SBA25XUS8 increased biomass from 13 to 85 t ha^{-1}, juice volume from 5,200 to 24,100 L ha^{-1}, and sugar production from 571 to 2,440 kg ha^{-1}; while SBA22XUS2 increased biomass from 12 to 33 t ha^{-1}, juice volume from 4,700 to 9,350 L ha^{-1}, and total sugars from 288 to 300 kg ha^{-1}.

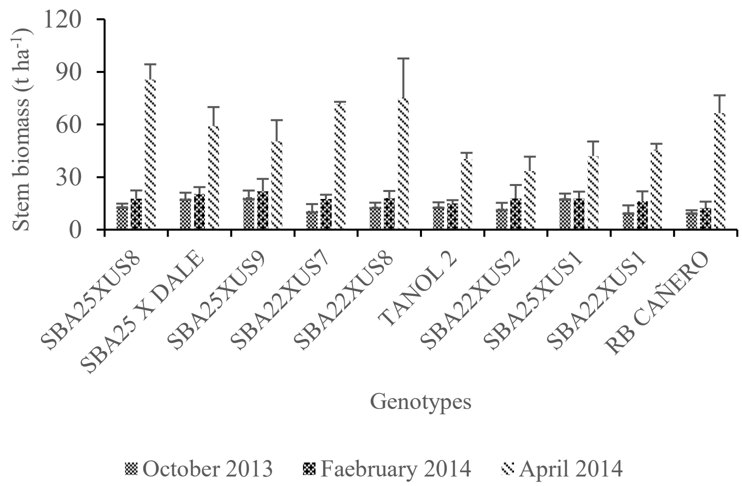

Figure 3. Fresh biomass of stems produced by genotypes of sweet sorghum on tree different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

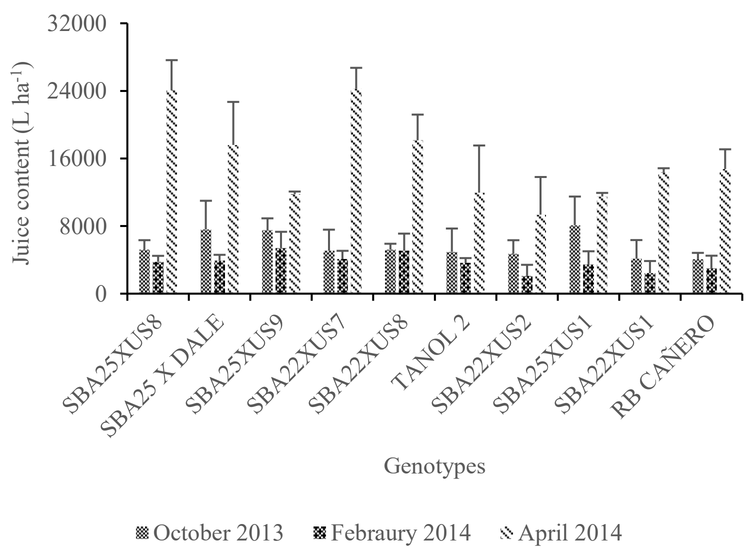

Figure 4. Volume of juice produced by genotypes of sweet sorghum on tree different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

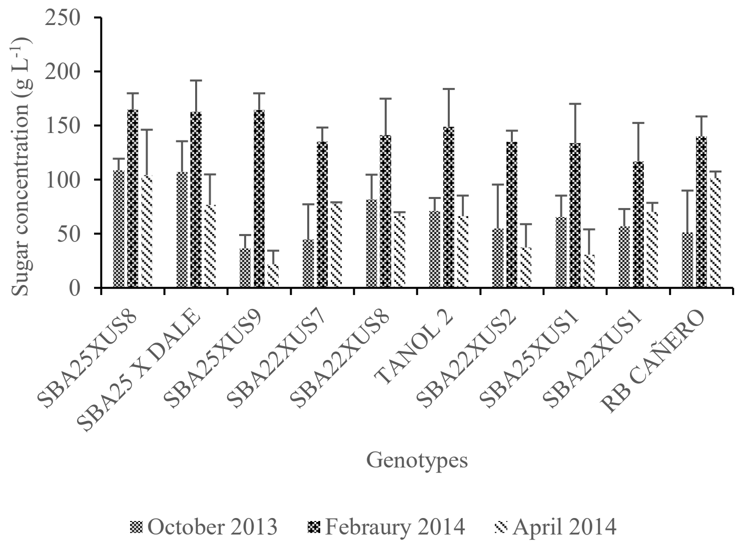

Figure 5. Sugar concentrations (glucose and fructose) of genotypes of sweet sorghum on tree different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

Effects of sowing times on growth and sugar content

The highest values for plant height, stem diameter and stem fresh weight were obtained on the June, July and August planting dates, and were statistically different from those obtained in September and October for these variables. In October, decreases of 26 %, 44 % and 79 % were recorded for plant height, diameter and stem weight, respectively, compared to the values recorded in June (Table 2). Time from planting to flowering was similar for the June and July planting dates, decreasing from 72 to 60 days in October, which represented a 17% decrease compared to the value recorded in June.

Planting date influences the morphology and phenology of sweet sorghum, but the intensity of the effects depends on the sown genotype. In this experiment, plant height of all genotypes decreased with planting dates of September and October. Values of 227, 236 and 219 cm were obtained for RB-Cañaveral, RB-Cañero and Tanol when planted in October, representing a decrease of 29, 32 and 14%, respectively, compared to those obtained when planted in June (Figure 7). Days to flowering were similar for RB-Cañaveral planted in June and July, but gradually decreased starting in August to reach 60 days in October, representing a decrease of 19% compared to the value recorded in June. The number of days to flowering decreased from June to October in RB-Cañero, registering a decrease of 29% compared to the value recorded in June. Tanol maintained a constant number of days to flowering (Figure 8).

Stem biomass, sugar concentration, juice volume and sugar production were highest at June planting (Table 3). As the planting date was later, the values decreased. The stem biomass decreased from 59.3 to 17 t ha^{-1} when planting date varied from June to October. These values represent 70% of biomass production in June. The concentration of sugars (glucose and fructose) decreased from 144 to 60.5 g L^{-1}, a difference that was statistically significant when the planting date was in October. Juice volume ranged from 19.6 kL ha^{-1} to 5.95 kL ha^{-1} for the different dates under study. The highest juice volume was recorded in June. It decreased by 50% and 70% for the September and October plantings, respectively. The sugar production varied between 2,865 and 400 kg ha^{-1} for the different planting dates. The highest sugar production per hectare was obtained with the planting date in June, with a tendency to decrease by 35%, 30%, 59% and 86% in the months of July, August, September and October, respectively.

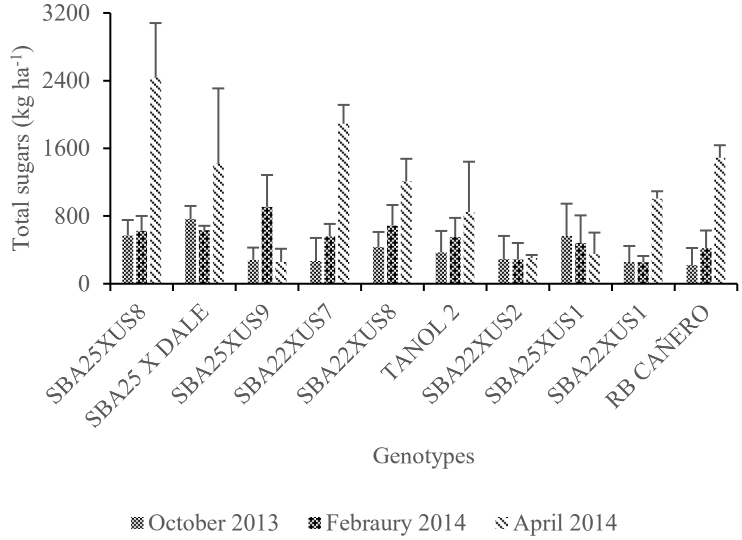

Figure 6. Sugar production genotypes of sweet sorghum on tree different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

Table 2. Average plant parameters of three sweet sorghum genotypes sowing in five planting dates in Veracruz, Mexico.

Seedtime	Plant height (cm)	Stem diameter (mm)	Fresh stem weight (g)	DSF[1] (d)
June	306.9 a[2]	20.2 a	771.8 a	72
July	319.5 a	18.9 a	652.7 a	73
August	326.8 a	18.5 a	615.8 a	67
September	282.7 b	14.9 b	328.7 b	62
October	227.7 b	11.4 b	161.2 b	60
LSD (Tukey)[3]	30.9	2.0	109.2	
Reduction (%)[4]	26	44	79	17

[1]DSF= Days from sowing to flowering; [2]Different letter (a,b,c) in the columns, denotes significant differences ($P<0.05$); [3]LSD = Least Significant Difference;[4]Reduction= Reduction registered in October, compared to June variable value.

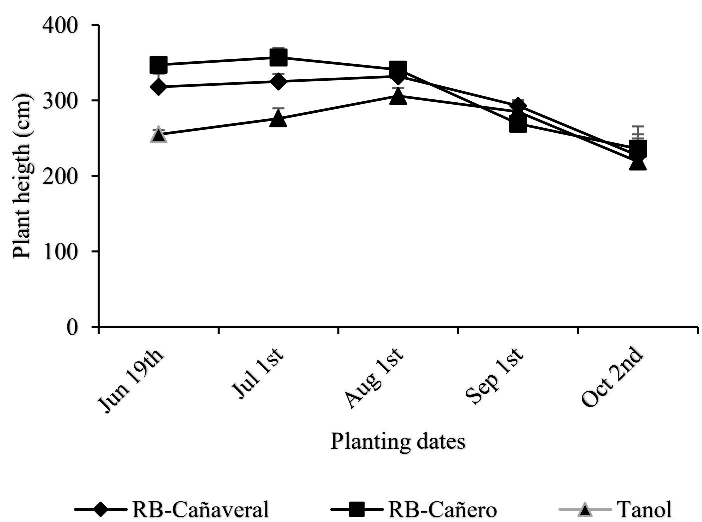

Figure 7. Plant height of three genotypes of sweet sorghum on different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

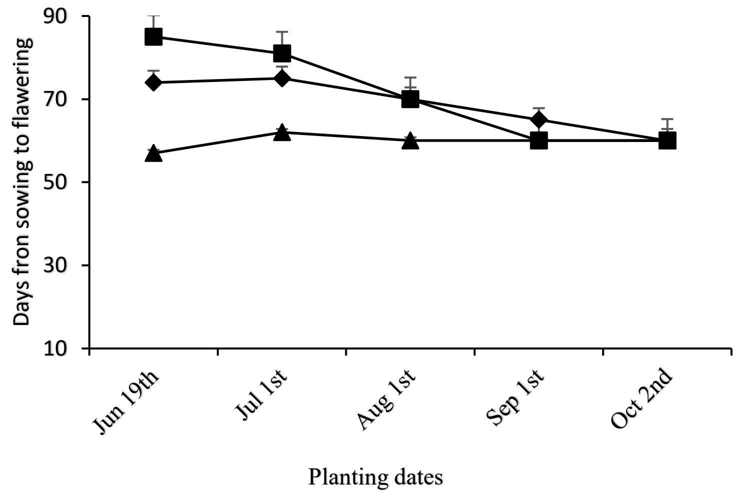

Figure 8. Number of days to flowering of three genotypes of sweet sorghum on different planting dates in Veracruz, Mexico. The lines in the symbols correspond to the standard error.

All cultivars decreased stem biomass (Figure 9) and juice volume (Figure 10) with a delayed planting date. RB-Cañaveral reduced its stem biomass from 62.7 to 15.8 t ha^{-1} and its juice volume from 22.1 to 5.7 kL ha^{-1}, representing a reduction of 74% and 75%, respectively, compared to the June planting time. For RB Cañero, the stem biomass decreased from 73 to 20 t ha^{-1}, and its volume decreased from 21.2 to 6.9 kL ha-1, while for Tanol, the stem biomass decreased from 45.5 to 14.8 t ha-1, and its juice volume decreased from 15.9 to 5.2 kL ha^{-1}.

RB-Cañaveral had the highest concentrations of glucose and fructose in juice at most planting dates. They remained high until September, but were reduced by 50% in October. RB-Cañero showed a similar juice concentration to RB-Cañaveral in June and July, decreasing from August and reaching 68% in October compared to the June value. The Tanol variety showed the lowest concentration of sugar in its juice. It significantly reduced from September and reached a 52% decrease in October (Figure 11).

RB-Cañaveral recorded higher sugar production in 3 of the five planting dates, reaching its maximum in June and decreasing with the later planting dates, until it recorded an 84% decrease in October. RB-Cañero achieved the highest sugar production among the three genotypes in July and August, exhibiting a similar decreasing trend until it registered an 89% decrease in October. Tanol obtained the lowest sugar production, compared to the other genotypes, and showed the same decreasing trend as the sowing date was delayed (Figure 12).

Table 3. Stem biomass, sugar concentration (glucose and fructose), juice volume, and sugar production averages for three genotypes of sweet sorghum across five planting dates in Veracruz, Mexico.

Seedtime	Stem Biomass ($t\ ha^{-1}$)	Sugar concentration ($g\ L^{-1}$)	Juice volume ($kL\ ha^{-1}$)	Sugar production ($kg\ ha^{-1}$)
June	59.3 a[1]	144.0 a	19.6 a	2864.8 a
July	43.5 b	128.3 a	14.5 b	1877.1 b
August	48.5 b	115.9 a	17.9 a	2001.8 b
September	28.5 c	118.1 a	9.95 c	1169.7 c
October	17.0 d	60.2 b	5.95 d	399.5 d
LSD (Tukey)[2]	6.3	58.4	3.0	584.7
Reduction (%)[3]	70	58	70	86

[1] Different letter (a,b,c) in the columns denotes significant differences (P<0.05); [2]LSD = Least Significant Difference. [3]Reduction= Reduction registered in October, compared to June variable value.

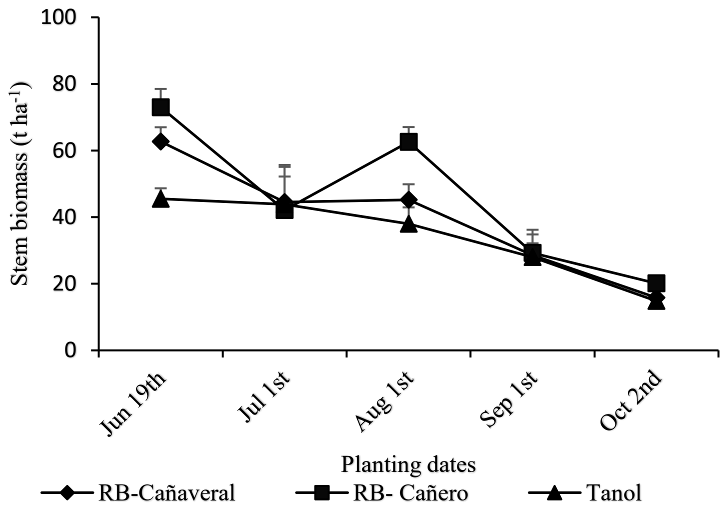

Figure 9. Fresh biomass of stems produced by three genotypes of sweet sorghum for different planting dates. The lines in the symbols correspond to the standard error.

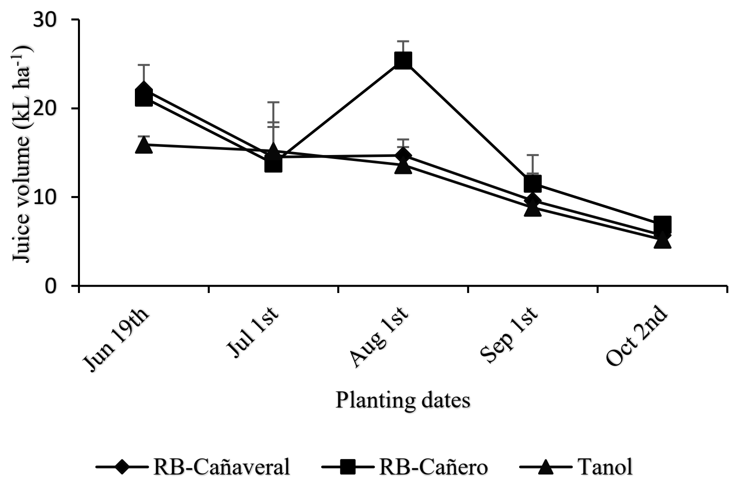

Figure 10. Volume of juice produced by three genotypes of sweet sorghum for different planting dates. The lines in the symbols correspond to the standard error.

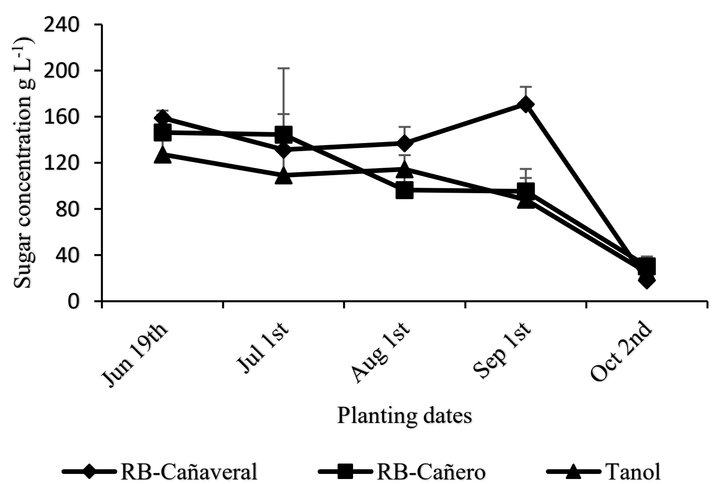

Figure 11. Sugar concentrations (glucose and fructose) of three genotypes of sweet sorghum at different planting dates. The lines in the symbols correspond to the standard error.

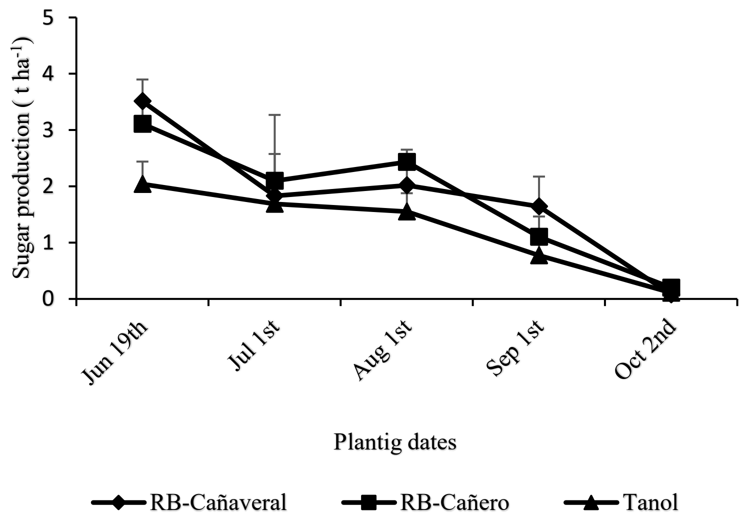

Figure 12. Sugar production of three genotypes of sweet sorghum at different planting dates. The lines in the symbols correspond to the standard error.

DISCUSSION

Effects of cropping season on productivity

The productivity of sweet sorghum genotypes is influenced by the biotic and abiotic conditions prevailing during the different stages of plant development, particularly the photoperiod during flower induction and the efficiency of radiation use.

The same sweet sorghum genotypes —RB-Cañero, Tanol 2, SBA25XUS1, SBA25XUS8, SBA25XUS9, SBA25XDALE, SBA22XUS1, SBA22XUS2, SBA22XUS7, and SBA22XUS8 —were evaluated on all three dates. In October 2013, planting date, no significant differences were recorded between them in any of the evaluated parameters, perhaps because they developed under photoperiod conditions between 11 and 11.6 h and radiation values between 303 and 387 W/m^2 (Figure 2). These conditions, characterised by a short photoperiod and low radiation, as described by Naoura et al. (2023), induced faster floral differentiation and reduced the duration of the vegetative phase, resulting in plants with shorter height and diameter, limited stem biomass production, reduced juice volume, and lower sugar production.

No significant differences were observed between treatments in February 2014, due to the conditions under which they were developed. The 11-h photoperiod during the vegetative phase induced faster flowering, limiting vegetative development (Alagarswamy, Reddy, & Swaminathan, 1998), with parameters similar to those obtained in October 2013, but with greater photosynthetic efficiency due to the greater amount of radiation received during March and April (Houx & Fritschi, 2015).

The higher radiation received in March and April, with values between 430 and 493 W/m^2, resulted in higher sugar concentration values, but with lower juice volume, possibly due to the limited moisture availability during the growth period (Figure 1), which hindered sugar production. The decrease in juice volume is consistent with that observed by Capecchi *et al*. (2017), who reported lower juice volumes under conditions of low moisture availability.

The outstanding genotypes in April 2014 were: SBA25XUS8, SBA22XUS7 and SBA22XUS8. They were developed under unfavourable conditions for rapid flowering induction (Shinde *et al*., 2013), with a photoperiod between 12.4 and 13 h. This resulted in taller and larger plants, with higher stem biomass production and increased juice volume, which was ultimately reflected in higher sugar production. However, the sugar concentration was lower than that of the February 2014 planting date.

In the state of Veracruz, Mexico, the highest productivity of sweet sorghum was obtained during the April 2014 planting date, when the photoperiod and global radiation were greater than 12 hours and 400 W/m^2, respectively. This result is in agreement with that indicated by Xuan *et al*. (2015), that the highest productivity of sweet sorghum is obtained in the spring-summer growing season for the conditions of Vietnam.

Effects of sowing times on growth and sugar content

Similarly, a photoperiod of less than 12 hours, as recorded from October at the experimental site, favoured floral differentiation (Reddy, Kumar, and Ramesh, 2007). It decreased plant height, stem diameter and plant weight, which was reflected in a 50% reduction in biomass and juice, and had an impact on sugar production. In this regard, Paul (1990) indicated that photoperiod-sensitive sorghum varieties sown in Central America after the beginning of September did not have sufficient vegetative development before the stimulus for flowering was received during the short days between October and January.

Another limiting factor for sweet sorghum production during the spring-summer cycle in the state of Veracruz is the availability of moisture at the beginning of the cycle. Therefore, the planting date must be adjusted between June and September for rainfed conditions (Figure 1).

The planting dates of June, July and August were developed with a suboptimal photoperiod for flowering, greater than 12 hours, a condition that favours a longer vegetative phase (Clerget *et al*., 2004; Clerget *et al*., 2007; Sanon *et a*l., 2014). This is reflected in a difference of up to 25 and 14 days in flowering time between the cultivars RB-Cañero and RB-Cañaveral, respectively, when planted in June and October. For its ease of use, the response variable "days to flowering" was used in this study. However, for future trials, it is suggested to estimate heat units to understand better the behaviour of the genotypes in relation to photoperiod.

In this study, higher indicators of plant height (307-327 cm), stem diameter (19-20 mm), plant weight (616-772 g), stem biomass production (49-59 t ha^{-1}), juice volume (18-20 kL ha^{-1}) and sugar concentration (116 - 144 g L^{-1}) were obtained in the planting dates from June to August. These results coincide with those obtained by Tovignan *et al*. (2016a), Tovignan *et al.* (2016b), Naoura *et al*. (2023) and Rao *et al*. (2013), who found that early sowing in photoperiod-sensitive sweet sorghum varieties allows for lengthening the vegetative phase and increasing the productive parameters of plant height, diameter, biomass and sugars production for higher ethanol production.

Lower biomass and juice levels in July were attributed to root lodging, which occurred when the plants initiated flowering, caused by the strong north winds prevalent during that time of year. Root lodging occurs when root growth is insufficient to anchor the plant against the forces of powerful storm winds and heavy rainfall. In the sub - humid tropics of Mexico, lodging poses a significant risk as north winds blow from September to May at speeds ranging from 20 to 120 km h^{-1}, and 80% of annual precipitation is recorded in June to October (Figure 1). Therefore, emphasis should be placed on breeding programs for sweet sorghum that prioritize tolerance to lodging (Burks, 2012).

The sensitivity of genotypes to photoperiod was not evaluated in this study. However, due to the close relationship between the length of the cycle from planting to physiological maturity and their sensitivity to photoperiod (Clerget *et al*., 2007), it is inferred that RB-Cañero is most sensitive to photoperiod, followed by RB-Cañaveral and Tanol, based on their degree of precocity (Cisneros *et al*., 2018). RB-Cañero exhibited greater sensitivity, reflected in a more pronounced decrease in their productive parameters. Therefore, it is essential to assess the sensitivity of genotypes to photoperiod (Shinde et al., 2013) and select those that are best adapted to the local environmental conditions in the region where commercial plantings of sweet sorghum for ethanol production are planned.

The amount of radiation received and the radiation use efficiency are other factors that help explain the results obtained in this study. Maximum solar radiation (493-478 W/m²) (Figure 2) was received at the experimental site from April to August, coinciding with the crop's development during the planting dates, when the best productive parameters were obtained. In this respect, Chavez *et al*. (2022) found that the highest dry matter production of sweet sorghum was obtained in the early and intermediate sowings (April and May), as well as the highest values of leaf area index and radiation use efficiency, compared to the late sowing (June), when the lowest values were recorded.

Moisture conditions of the Veracruz state would allow two harvests per year if drought-tolerant, photoperiod and low temperature-insensitive cultivars are used, especially for the autumn-winter crop (November to March), where conditions of limited moisture and short photoperiod prevail, similar to India (Shinde *et al*., 2013; Reddy *et al*., 2012). There is a need to explore these alternatives to realise this production potential.

The optimum sowing dates for sweet sorghum vary in different environments: April and May for the temperate zone (Burks *et al*., 2013; Teetor *et al*., 2011; Erickson *et al*., 2011; Han *et al*., 2012), June, for the semi-arid tropics (Rao *et al.*, 2013), June, July and August in the Veracruz state, as seen in the results of this study.

Commercial plantings of sweet sorghum under the conditions of the state of Veracruz, established during June, July and August with the cultivars RB-Cañaveral and RB-Cañero, would allow supplying raw material to sugar mills to produce ethanol from October 15 to November 30, and in this way extend the harvest period of the mills at least a month and a half before the start of the sugarcane harvest, scheduled from December 1 to April 30. Similar results were obtained by Rao et al. (2013) for dry tropical conditions and Burks (2012) for temperate conditions in extending the harvest period with sweet sorghum.

CONCLUSIONS

Based on the results obtained, it is concluded that the planting date has a significant impact on the biomass and sugar production of sweet sorghum in the state of Veracruz. The highest stem biomass and sugar productivity were obtained during the June, July and August planting dates. The most notable genotypes were RB-Cañero, due to its higher biomass productivity, and RB-Cañaveral, due to its higher sugar concentration in the juice, which suggests a lower volume of biomass to be transported to the sugar mill and, consequently, lower transportation costs.

The optimal planting period for sweet sorghum in Veracruz is from June to August. When combined with early and intermediate genotypes, this allows the sugar mills' harvest period to be extended by at least a month and a half, from December 1 to April 30, which is typically the sugarcane harvest period.

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