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Performance and yield estimation of sugarcane varieties for pot still cachaça production

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Abstract

Cachaça is an alcoholic beverage obtained through the distillation of fermented sugarcane juice. It is the sugarcane distillate most consumed in Brazil. Despite the traditional nature and economic importance of cachaça, the production chain in Brazil is not technologically homogeneous; low-yielding varieties of sugarcane with susceptibility to various diseases are common. The pot still cachaças undergo delicate distillation processes in copper pot stills using wild yeast strains for fermentation, and the most exceptional and expensive cachaças can be found on the market in Brazil. The objective of this study was to assess modern sugarcane varieties for the production of pot still cachaça and to propose a new methodology to obtain the expected yield in liters of cachaça per hectare. A randomized block experimental design was used in a 4 (sugarcane varieties) × 3 (harvest times) factorial arrangement, with five replications. At the end of three crop seasons after harvest, the yield components, soluble solids content, and expected cachaça yield were evaluated. The highest levels of soluble solids (°Brix) were for CTC4 and RB966928. Based on data from three crop seasons, the CTC9002 variety showed the highest stalk yield per hectare (SYH). The estimated yield methodology allowed for comprehensive assessment of the main sugarcane production characteristics, providing reliability and practicality in estimating cachaça yield. Based on analysis of yield components and mean cachaça yield (liters/ha) over three crop seasons, CTC9002 is recommended for inclusion in the panel of varieties for cachaça production.

Keywords: brandy, still, alcoholic beverage, crop seasons, *Saccharum* spp.

Abbreviations: JYf - juice yield factor; DEf - distillation efficiency factor; SH – stalk height, SJ- sugarcane juice, DAC– days after cutting, DAT– days after transplanting, SD– stalk diameter, LJ– liters of juice from 10 crushed stalks, PSP– pre-sprouted plantlets, NSM– number of stalks per meter; Q%–yield loss per cycle, ECY– expected cachaça yield, SS_ soluble solids, SYH– stalk yield per hectare.

Introduction

Cachaça is a typical Brazilian spirit produced by fermentation of fresh sugarcane juice and subsequent distillation, reaching 38% to 48% alcohol by volume (ABV) at 20 °C (Brasil, 2022). This beverage is highly valued for its characteristic flavor and aroma, which result from fermentation, distillation, and aging processes in wooden barrels. It is mainly composed of ethanol and water, as well as secondary compounds, such as higher alcohols, acids, esters, acetals, phenols, hydrocarbons, nitrogenous compounds, sulfur compounds, and sugars, among others, which characterize and qualify it (Brasil, 2022; Cardoso et al., 2004).
Sugarcane (*Saccharum* spp.) generates significant economic activity for cachaça producers, especially in the Southeast and Northeast regions of Brazil. Pot still cachaça is classified as such based on the distillation process, as this cachaça is produced exclusively in copper stills and obtained through the distillation of fermented must from raw sugarcane juice (Brasil, 2022). Pot still cachaça is known for its high-quality flavor and aroma and accounts for 30% of Brazilian commercial volume (Santos et al., 2019; Sylvio et al., 2021).
Cachaça is a beverage with considerable cultural, social, and economic impact on Brazilian society. The cachaça sector generates commercial transactions of nearly seven billion Brazilian reals annually, and it is responsible for around 600,000 direct and indirect jobs (Paulo et al., 2016). The states of Pernambuco, São Paulo, Ceará, Minas Gerais, and Paraíba lead production (Ibrac, 2019). The state of Minas Gerais is the main producer of pot still cachaça, representing 50% of Brazilian pod still production and generating income for small and medium-sized properties (Sylvio et al., 2021).
Sugarcane characteristics desired for cachaça production include high stalk yield, medium/low fiber content, high sucrose content, resistance to major pests and diseases, easy stripping of leaves, and a long period of industrial use (Cardoso, 2021). Therefore, selecting varieties adapted to

specific edaphic and climatic growing conditions is essential to establish the ideal sugarcane plantation in production units. However, limited technical and scientific information on varieties with higher agronomic yield for pot still cachaça production still hinders the activity.

The sugarcane variety used in cachaça mills in Brazil is often predominantly RB867515. However, repeated use of the same variety over multiple crop seasons can compromise the yield and longevity of the sugarcane plantation. The crop becomes vulnerable to biotic factors and loses yield when grown in environments that do not meet its specific requirements (Sanches et al., 2019). Thus, it is important to seek new materials to diversify the plantation and ensure its longevity for pot still cachaça production.

Information in the literature for production of this beverage is usually limited to the fermentation processes of the raw material, given the range of investigations focused on juice quality and fermentative yeasts (Moura et al., 2020; Mutton et al., 2020; Stefenon et al., 2021). However, few studies consider agricultural aspects for plantations growing sugarcane for pot still cachaça production, especially regarding a methodology to quantify cachaça yield in liters per hectare for different sugarcane varieties. This aspect is essential for planning the establishment of plantations and for still sizing.

Therefore, the objective of this study is to evaluate the yield performance of modern sugarcane varieties for pot still cachaça production and propose a new methodology to estimate the expected cachaça yield in liters per hectare.

Results and Discussion

Stalks per meter, plant height, and stalk diameter

Significant differences in results were observed among the cultivars evaluated. The best result for the number of stalks per meter (NSM) trait was in CTC4. However, the lowest results for plant height and stalk diameter were for the cultivars CTC9003 and CTC4.

Statistical differences were also observed among the crop seasons. The first stood out for the stalk height variable, the second (2nd) for low variation in yield, and the third (3rd) for the lowest values of the agronomic parameters (Table 1).

The agronomic traits NSM and SH are directly related to SYH. Harvest and milling of one ton of sugarcane yields from 60 to 80 liters of cachaça from copper stills (Pimentel and Andrade, 2020). These agronomic traits are quantitatively linked to the expected cachaça yield (ECY). Another quantitative and qualitative factor is soluble solids content (SS); values above 18 °Brix indicate that the sugarcane is mature (Pimentel and Andrade, 2020). However, during fermentation, added juice should have levels between 14 and 16 °Brix (Campos et al., 2010; Duarte et al., 2011; Schwan et al., 2001), requiring dilutions. Values above this range can inhibit yeast cell activity and favor glycogen accumulation, leading to a decrease in alcohol yield (Maia et al., 1993; Walker, 1998).

The CTC4 variety had the highest value for the number of stalks per meter trait; the other varieties did not differ statistically (Table 1). The number of stalks is directly related to tillering, a factor that affects sugarcane production and is linked to the genetic potential of each variety. Environmental, physiological, and phytotechnical factors are also important (Manhães et al., 2015). Otto et al. (2022) evaluated the suitability of varieties in different planting seasons and reported an average of ten tillers per meter, with stabilization around the fifth month after planting. Therefore, tiller development is of paramount importance in achieving high yield levels; and proper management can lead to high-quality stalks.

The varieties showed stable development of the number of stalks in the first (NSM - 14) and second (NSM - 12) crop season. However, there was a decrease in the third (NSM - 10) crop season (Table 1). This reduction in stalk density can be attributed to loss of vigor, associated with damage to the ratoons by machine traffic during harvest. The reduction is also due to excess straw commonly found in cane fields harvested without burning of crop residue, which creates a microclimate favorable to proliferation of diseases and pests, such as the root froghopper (*Mahanarva* spp.). That leads to yield losses and decreased quality of raw material (Castro et al., 2019; Tweddle et al., 2021).

The varieties showed similar mean values for stalk height (Table 1). Sugarcane growth has a sigmoid pattern; it is initially slow, enters a faster growth phase, and finally slows again (Mischan and Pinho, 2014). The only variety that had a different value was CTC9003, possibly affected by the number of stalks per meter. Silva et al. (2008), indicated that stalk height may be negatively correlated with stalk diameter; thus, sugarcane with a larger diameter may be shorter in height.

During the 360-day evaluation period, the first crop season resulted in the tallest stalks, while the subsequent crop seasons showed similar stalk heights (Table 1). The taller stalks in the first season can be attributed to lower pressure from biotic factors on first-year sugarcane, while the shorter heights in the subsequent seasons may be due to potential damage sustained during the harvesting process, leaving ratoons exposed to pest and disease attacks. As a result, reduction in stalk height may be associated with cracks in the ratoons, which, combined with moisture accumulation in residual straw, favored the attack of opportunistic fungi, such as *Colletotrichum falcatum* Went., causing red rot of the stalks and hindering maximum development of the varieties (Prasanth et al., 2022).

With regard to stalk diameter, CTC4 exhibited the lowest value, and CTC9003, CTC9002, and RB966928 had the highest values (Table 1). The low diameter value in CTC4 may be attributable to negative correlation of stalk diameter with stalk height, as elongation may occur at the expense of storage in some instances. However, it is important to select varieties with a larger diameter, as this parameter is directly related to sucrose accumulation through the storage capacity of the parenchyma cells in the stalk (Marafon, 2012).

Stalk diameter showed stability throughout the crop seasons (Table 1). This stability in stalk diameter can be attributed to the favorable temperature range of 20-33 °C (Figure 1) during the phase of maximum vegetative development (120-240 DAC). The ideal base temperature for crop growth is around 25-35 °C (Manhães et al., 2015). Bonnett et al. (2006) reported that high temperatures can lead to reduction in stalk diameter.

Guerra et al. (2014) worked with RB867515 and described that high temperature induces an increase in sugarcane height but reduces stalk diameter, possibly due to excessive plant respiration (Diola and Santos, 2012). However, this may vary, depending on the intrinsic genetic characteristics of the variety, affecting production factors such as stalk diameter.

Soluble solids

The CTC4 and RB966928 varieties had the highest soluble solids content, but all varieties had values above 15 °Brix (Table 1). The soluble solids content obtained falls within the standard for sugarcane at the time of harvest (above 15 °Brix), which is an important sugarcane maturity and quality indicator. Therefore, it can be inferred that the low

Table 1. Number of stalks per meter (NSM), stalk height (SH), stalk diameter (SH), soluble solids (SS), and stalk yield per hectare (SYH) (in tons hectare^{-1}) of sugarcane varieties (CTC4, CTC9003, CTC9002, and RB 966928) over three crop seasons.

Variety	NSM	SH (m)	SD (cm)	SS (°Brix)	SYH
CTC4	14.53 a[1]	2.23 a	2.21 b	18.73 a	89.17 b
CTC9003	12.54 b	2.03 b	2.43 a	18.11 b	84.74 b
CTC9002	11.49 b	2.29 a	2.63 a	18.15 b	105.77 a
RB966928	10.43 b	2.27 a	2.51 a	19.36 a	88.91 b
Crop season					
1st	14.00 a	2.34 a	2.44 a	19.28 a	105.30 a
2nd	12.62 a	2.16 b	2.45 a	19.33 a	94.35 a
3rd	10.13 b	2.11 b	2.45 a	17.16 b	76.79 b
Overall mean	12.25	2.20	2.50	18.59	92.15
C.V. (%)	20.8	10.1	16.6	7.0	21.7

[1] Values followed by the same letters in the column do not differ according to the Scott-Knott test ($p \leq 0.05$).

Table 2. Liters of juice from 10 crushed stalks (LJ), sugarcane juice (in thousand liters per hectare) (SJ), and expected cachaça yield (one thousand liters per hectare) (ECY) of sugarcane varieties, mean of three harvests.

Variety	LJ	SJ	ECY
CTC4	5.90 b[1]	57.20 a	14.98 a
CTC9003	5.35 b	44.85 a	11.76 a
CTC9002	9.20 a	68.76 a	17.42 a
RB966928	7.70 a	53.79 a	14.65 a
Overall mean	7.04	56.15	14.71
C.V. (%)	15.09	12.87	17.40

LJ: liters of juice from 10 crushed stalks, SJ: cane juice yield (in thousand liters per hectare), ECY: Expected cachaça yield (in thousand liters per hectare). [1] Values followed by the same letters in the column, do not differ according to the Scott-Knott test ($p \leq 0.05$).

temperatures and rainfall during the maturation period (240-360 DAC) up to harvest (April-July) contributed to the high quality of the raw material. These environmental factors favor the accumulation of sucrose in sugarcane, as they reduce nutrient uptake, stabilize plant growth, maintain a positive balance between fixed and consumed carbon, and promote the conversion of reducing sugars into sucrose through dehydration of plant tissues (Araújo et al., 2016; Pereira et al., 2017).

The soluble solids content declined only in the third crop season (Table 1), and this can be attributed to the incidence of the sugarcane borer (*Diatrea saccharalis*) during the maturation phase. The soluble solids content in sugarcane is predominantly composed of sucrose, which can decline through the action of soluble acid invertase when plants are attacked by the borer. The borer creates holes in the stalk, which can serve as an entry point for secondary phytopathogenic fungi, such as *Colletotrichum falcatum*, *Fusarium moniliforme*, and *F. subglutinans*, causing red rot disease (Sathyabhama et al., 2016). Injury caused by the insects, combined with the presence of phytopathogenic microorganisms, can lead to a decrease in sugar content through inversion of stored sucrose in the plant. Additionally, contamination of the sugarcane juice by these microorganisms makes for a more challenging fermentation process (Dinardo-Miranda et al., 2012).

Stalks per hectare

The CTC9002 variety showed a significant difference, obtaining the highest stalk yield; the other cultivars did not reach an mean of 100 tons of stalks per hectare in the three crop seasons (Table 1). This result follows from the response observed for stalk diameter and height, confirming consistent yield performance of the CTC9002 variety. Nevertheless, all varieties showed yield above the Brazilian average of 69.35 t ha^{-1} (Conab, 2023). This highlights the significant effect of adequate mean monthly rainfall during tillering (140 mm), a crucial phase for ensuring high yields (Coelho et al., 2018). Peloia et al. (2019) highlight that rainfall during the budding and tillering phases is a determining factor for yield.

The data show a standard pattern of yield decline per cycle (Q%) from the first to the second crop season (Q = 10.3%). However, there was a significant drop in yield in the third crop season (Q = 18.6%) compared to the previous season (Table 1). This indicates that the longevity of the sugarcane field was compromised, since the yield decline index exceeded the acceptable limit (Q = 5-10%) for reduction in raw material from one crop season to the next for all the agricultural seasons analyzed (Landell, 2017). These reductions, especially in the last season, can be attributed to low rainfall during the growing season. In this context, the factors described above were crucial in bringing about an early decline in yield for this young sugarcane field.

Approximately 75% of sugarcane dry matter accumulation is obtained in the high growth phase, which is more sensitive to water restriction (Smit and Singels, 2006). Based on that, the abrupt decline in mean yield from the second to the third crop season is understandable, because even though sugarcane has the ability to compensate for water deficits that are not so severe through stomatal closure and a deep root system (Hu et al., 2019), the mean rainfall in the sugarcane field of the third crop season had only 980.25 mm rainfall in the maximum vegetative growth phase (Figure 1). Silva et al. (2012) worked with sugarcane in the second cycle and described that sugarcane at that growth stage requires more than 1000 mm of rainfall.

Cachaça yield

The results show that there were no significant differences ($p \leq 0.05$) among the varieties evaluated in the parameters that include expected cachaça yield (ECY) (Table 2). However, the RB966928 and CTC9002 varieties showed a high volume of liters of juice from ten crushed stalks (LJ), a trait that has a positive impact on final yield.

CTC 9002 had the best performance in terms of tons of stalks per hectare (104.9 t ha^{-1}), and that may have ensured the high mean value for expected cachaça yield (ECY). Although there were no significant differences in the estimated yields, this variety may still be an alternative for growing sugarcane directed to pot still cachaça production, due to its high stalk yield.

Table 3. Volume of water to be added to the juice for adjustment to 15° Brix (soluble solids content, SS) (total volume 1000 liters).

°Brix of the Original Juice	Desired °Brix 15		Juice yield / extraction efficiency factor (JYf)
	water	juice	
16	65	935	1.0695
17	125	875	1.1429
18	180	820	1.2195
19	225	775	1.2903
20	265	735	1.3605
21	300	700	1.4286
22	340	660	1.5152
23	370	630	1.5873
24	400	600	1.6667
25	425	575	1.7391

Source: Adapted from Souza et al. (2013).

Higher storage of sucrose in the sugarcane stalks may indeed be directly linked to their larger size and diameter, providing a greater number of parenchyma cells, as sucrose is specifically stored in vacuoles and in the surrounding apoplast of the stalk parenchyma cells (Wang et al., 2013). This characteristic contributed to the mean performance of 17.42 thousand liters per hectare of cachaça for the CTC9002 variety (Table 2). It should be noted that the estimated cachaça yield in the present study does not divide the distillate into "head", "heart", and "tail" cuts. Rather, separation is based on the specific product desired for the market.

In this context, stalk yield per hectare (SYH) directly affected the estimated cachaça yield from the CTC9002 variety. Although there was no statistically significant difference, it resulted in an mean of 48% more liters of cachaça compared to the variety with the lowest mean stalk yield (CTC9003). This is attributable to the fact that high stalk yield, combined with soluble solids content, regulates both the dilution of the juice and the amount of must directed to fermentation, consequently affecting cachaça production (Medeiros et al., 2017). The data obtained from this study identified promising varieties that can contribute to higher cachaça yields, promote diversity in sugarcane growing, and boost production in pot still cachaça distilleries. Moreover, it suggests a methodology for quantifying cachaça in liters per hectare, which can help producers determine the yield of their varieties.

It is noteworthy that regardless of the agricultural season, the CTC4 variety had the largest number of plants per meter, but also had the smallest stalk diameter, confirming the inverse relationship between these factors. Furthermore, CTC9003 had the lowest plant height and CTC9002 had the highest stalk yield. The soluble solids content (°Brix) exhibited higher than mean values for all varieties, indicating a high concentration of sucrose in the cane juice, which is a desirable trait for cachaça production. Based on the data from three crop seasons, CTC9002 and RB966928 had the highest yields of juice from ten crushed stalks (LJ).

Materials and Methods

Location and experimental design

The experiment was carried out in an area of the Cachaçaria Bocaina company, on highway BR-265, KM 349, in the municipality of Lavras, state of Minas Gerais, at an altitude of 916.19 m (21°14'00'' S and 45°00'00'' W). The climate of the region is type Cwa, according to the Köppen classification, with average annual rainfall of 1500 mm. Meteorological conditions were collected throughout the experimental period (Figure 1).

Experimental conduction and evaluated characteristics

The soil of the experimental area was classified as a *Latossolo vermelho* (Santos et al., 2018). Before implementing the field project, soil samples were collected at a depth of 0-20 cm to determine soil chemical and physical characteristics: pH (H_2O) 5.8, O.M. 2.83 dag.kg^{-1}, P 1.19 mg.dm^{-3}, K 47.89 mg.dm^{-3}, H + Al 2.44 cmolc.dm^{-3}, Al 0.15 cmolc.dm^{-3}, Ca 2.92 cmolc.dm^{-3}, Mg 1.18 cmolc.dm^{-3}, SB 4.22 cmolc.dm^{-3}, CEC (T) 6.66 cmolc.dm^{-3}, V 63.79%, m 3.43%, Zn 3.43 mg.dm^{-3}, Fe 32.32 mg.dm^{-3}, Mn 7.69 mg.dm^{-3}, Cu 1.59 mg.dm^{-3}, B 0.1 mg.dm^{-3}, S 5.84 mg.dm^{-3}, clay 58 dag.kg^{-1}, silt 32 dag.kg^{-1}, and sand 10 dag.kg^{-1}.

The experiment was conducted in a randomized block design in a 4 × 3 factorial arrangement with five replications. The first factor corresponded to four sugarcane varieties (RB966928, CTC4, CTC9002, and CTC9003) and the second factor to three harvest times (30/06/2020, 21/06/2021, and 02/07/2022). Plots consisted of three 5-meter rows, spaced at 1.5 m, for a total area of 22.5 m^2. The area of the plot used for data collection was 6.0 m^2, considering the central row, excluding 0.5 m from the ends.

Soil tillage consisted of plowing, and subsequently, furrows were opened. The crop was planted on 23 March 2019 using pre-sprouted plantlets (PSP), distributing ten plantlets in each 5-meter row, spaced at 0.5 meters. For fertilization at planting, 600 kg ha^{-1} of the formulation 04-14-08 was used. At 120 days after transplanting (DAT), top-dressing of 200 kg ha^{-1} of the 20-00-20 fertilizer formulation was applied. For the two subsequent ratoon cane cycles, top-dressing of 400 kg ha^{-1} of the 20-00-30 fertilizer formulation was used at 120 days after cutting (DAC). Manual weeding was performed throughout the experimental period to keep the area free of weeds.

At the time of harvest (in all three seasons), 10 stalks were randomly selected from the area of each plot used for data collection, and the heart tips and straw were removed. The following parameters were determined: stalk height (SH); number of stalks per meter (NSM), which was counted along three meters of the central row; stalk diameter (SD), measured using calipers (evaluated in the lower third of the stalks); soluble solids content (°Brix), according to the Consecana methodology (2006) (SS); and stalk yield per hectare (SYH), which was determined by weighing ten industrializable stalks per plot (W10) and multiplying that by the number of stalks per meter (NSM) in the data collection area, considering the spacing (E). After weighing and counting the stalks, Equation 1 was used on the data:

$$SYH = \frac{W10 \times NSM}{S} \quad (1)$$

For cachaça yield over the three agricultural years, a new methodology is proposed for estimation, based on the

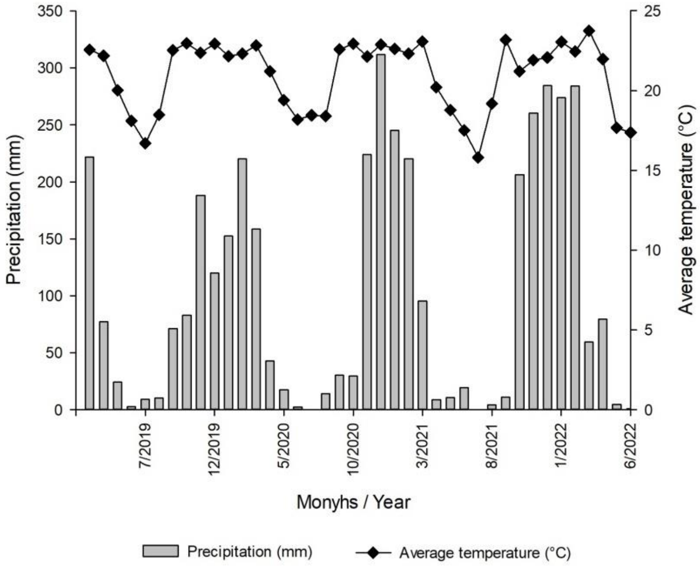

Fig 1. Rainfall (mm); Months / Year; Rainfall (mm). Mean temperature (°C) and monthly rainfall (mm) over the three agricultural seasons (March 2017 to June 2022) of the experiment. Lavras, Minas Gerais, Brazil. Source: INMET Estação Meteorológica Convencional de Lavras, MG, Brazil.

varieties of sugarcane and considering the cane juice production. The estimation of sugarcane juice (SJ, in thousand liters per hectare) was calculated using Equation 2:

$$SJ = \frac{LJ \times NSM}{S}, \quad (2)$$

where:

LJ = liters of juice from 10 crushed sugarcane stalks;
NSM = number of stalks per linear meter;
S = spacing between sugarcane rows in the field (in meters).
Considering Equation 2, the number of stalks per linear meter was estimated in the field at the time of harvest, corresponding to measurement in the central row within a range of 3 (three) meters for each experimental replication. Finally, 10 stalks were randomly collected from each variety, and the cane juice was mechanically extracted using the CPB 10 × 14 inch mill at a rotation speed of 4800 rpm.

After cane juice extraction, the expected cachaça yield (ECY, in thousand liters per hectare) was obtained, which was calculated using the following equation:

$$ECY = SJ \times JYf \times DEf, \quad (3)$$

where:

SJ = sugarcane juice (in thousand liters per hectare);
JYf = juice yield factor, standardized to 15 °Brix;
DEf = distillation efficiency factor.

The juice yield (extraction efficiency) factor (JYf) for adjustment to 15 °Brix (Equation 3), with water dilution, was based on the Cruz de Cobenze diagram, according to Souza et al. (2013), which is represented in Table 3.

To calculate the juice yield factor (JYf), the following equation was considered:

$$JYf = \frac{Vi}{Vf}, \quad (4)$$

where:

Vi = initial volume of juice (1000 liters);
Vf = volume of juice in relation to the desired °Brix and original °Brix (Table 3).

Finally, the "still efficiency" variable (DEf) considers an pot still with a cylindrical column equipped with plates and a dephlegmator, with a 20% yield rate (Souza et al., 2013). This means that for every 1000 liters of sugarcane “wine” (fermented must), 200 liters of cachaça are obtained, considering all three phases (heads, hearts, and tails).

Statistical analysis

The mean values of agronomic performance and estimated cachaça yield from the three agricultural years were analyzed for normality using the Shapiro-Wilk test and for homogeneity of variance using the Bartlett test. Subsequently, analysis of variance was performed on the data using the F-test ($p < 0.05$). Based on the data obtained, the Scott-Knott test was employed, with a significance level of 5%; analyses were performed using the Sisvar® software (Ferreira, 2019).

Conclusion

Based on the data from three crop seasons, the CTC9002 variety had the best performance in terms of stalk yield per hectare (SYH), indicating its potential for use in cachaça production units. The estimated yield methodology allowed for incorporation of the main yield traits of sugarcane, providing reliability and practicality in estimating cachaça yield per variety on the property.

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Conflict of interest

The authors declare no conflict of interest.

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