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Original Article

Sugarcane productivity and economic viability in response to planting density

Produtividade e viabilidade econômica de cana-de-açúcar em resposta à densidade de plantio

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Abstract

Planting with higher density in sugarcane is one of the practices used to overcome low productivity. However, this planting material is equivalent to 25% of the total cost of production, being one of the main expenses for cultivation. In this sense, the present work aims to evaluate the productivity and economic viability of sugarcane as a function of planting density. The experiment was carried out at Usina Monte Alegre in the municipality of Mamanguape, Paraíba, Brazil, from March 2021 to January 2022 with the variety RB92579. Seven planting density were studied: T1: 7 gems m^{-1}, T2: 10 gems m^{-1}, T3: 12 gems m^{-1}, T4: 11 gems m^{-1}, T5: 15 gems m^{-1}, T6: 17 gems m^{-1}, T7: 24 gems m^{-1}, in randomized blocks with four replications. Growth, productivity and economic viability were evaluated. The highest productivity of cane and sugar, 77.69 ton ha^{-1} and 10.390 ton ha^{-1}, respectively, was with planting density of 17 and 24 gems^{-1}. While the minimum productivity of cane (61.313 ton ha^{-1}) and sugar (7.924 ton ha^{-1}) was recorded at sowing density of 7 and 11 gems^{-1}. However, cultivation density with 7 and 10 gems m^{-1} were the ones that provided the highest profitability around 50%, followed by density of 12, 15 and 17 gems m^{-1} with an average of 45% profit and 11 and 24 gems m^{-1} with the lowest proportion of profit on average 38%. The cultivation with 17 gems m^{-1} of cane provides in cane-plant, variety RB92579, greater productivity with a profit rate of 45%, being the most suitable.

Keywords: *Saccharum officinarum*, cultivation arrangements, production costs.

Resumo

O plantio com maiores densidades na cana-de-açúcar é uma das práticas utilizadas para superar a baixa produtividade. Contudo, esse material de plantio equivale a 25% do custo total de produção, sendo uma das principais despesas para o cultivo. Nesse sentido, o presente trabalho objetiva avaliar a produtividade e viabilidade econômica de cana-de-açúcar em função das densidades de plantio. O experimento foi realizado na Usina Monte Alegre no município de Mamanguape, Paraíba, Brasil, durante março de 2021 a janeiro de 2022 com a variedade RB92579. Sendo estudadas sete densidades de plantio: 7,10, 12, 13, 15, 17 e 24 gemas m^{-1}, em blocos casualizados com quatro repetições. Foram avaliados o crescimento, a produtividade e a viabilidade econômica. A maior produtividade de cana e açúcar, 77,69 ton ha^{-1} e 10,390 ton ha^{-1}, respectivamente, foi obtida com as densidades de plantio de 17 e 24 gemas^{-1}. Enquanto a produtividade mínima de cana (61,313 ton ha^{-1}) e açúcar (7,924 ton ha^{-1}) foi registrada nas densidades de semeadura de 7 e 11 gemas^{-1}. Contudo, as densidades de cultivo com 7 e 10 gemas m^{-1} foram as que proporcionam maior lucratividade em torno de 50%, seguida das densidades 12, 15 e 17 gemas m^{-1} com média de 45% de lucro e 11 e 24 gemas m^{-1} com menor proporção de lucro em média 38%. O cultivo com 17 gemas m^{-1} de cana proporciona em cana planta, variedade RB92579, maior produtividade com índice de lucro de 45%, sendo a mais indicada.

Palavras-chave: *Saccharum officinarum*, arranjos de cultivo, custos de produção.

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is the world's primary source of sugar and bioenergy (Gravina et al., 2021), particularly for many tropical and subtropical countries where it holds significant economic importance (Manimekalai et al., 2022). Brazil is the largest global producer of this crop, followed by India and China. Projections for the 2021/22 crop estimate Brazilian production at 628.1 million tons, with 8.4 million hectares planted, producing 27 billion liters of

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ethanol and 39 million tons of sugar. It also contributes 3.8% of the national electricity generation, solidifying the country as the world's leading player in this agribusiness sector (Gravina et al., 2021).

Currently, Brazil has the largest sugarcane cultivation area in the world. The historical expansion of sugarcane cultivation in the country is a result of public policies aimed at promoting ethanol production from sugarcane to enhance energy security (Carlucci et al., 2021; Wiesberg et al., 2021), making Brazil the most successful fossil fuel replacement program with bioethanol globally (Rossi Neto et al., 2018). Over the past decades, Brazil has not only increased the cultivated area of sugarcane but also sugar, ethanol, and bioelectricity production (Cherubin et al., 2021). It's worth noting that while this crop is primarily produced for sugar and alcohol production, it serves multiple other purposes, generating various value-added byproducts such as molasses (Walter et al., 2014), bagasse (Chunhawong et al., 2018), and other industrial products for chemicals, plastics, paints, synthetics, fibers, insecticides, and detergents (Mehnaz, 2013; Walter et al., 2014).

The planting stage is crucial for sugarcane's performance, and therefore, proper planting techniques are essential to allow plants to fully utilize environmental conditions and reach their optimal potential. Establishing an appropriate plant population is imperative for facilitating light penetration and efficient use of water and nutrients (Samiullah et al., 2015). Planting density plays a fundamental role in maximizing sugarcane productivity as it directly affects the number of stalks, stalk length, and diameter, variables that are positively associated with cane yield per unit area (Ehsanullah et al., 2011). Furthermore, population density influences the survival of tillers until the harvest phase (Bell and Garside, 2005). Therefore, there is a need to identify ideal planting density, aiming not only for productivity gains but also for efficient use of available resources (Nadeem et al., 2018). Under optimal cultivation conditions, sugarcane tends to respond positively in terms of vegetative development (Silva et al., 2023).

In this context, the present study aimed to assess the productivity and economic viability of sugarcane based on planting density.

2. Materials and Methods

2.1. Experimental site

The experiment was conducted from March 2021 to January 2022 at the Monte Alegre Sugar Mill, located in the municipality of Mamanguape, state of Paraíba, Brazil (06°50'20" S and 35°7'33" W). The climate is hot and humid, classified as type As according to the Köppen classification (Alvares et al., 2013), with an average temperature and precipitation of 28°C and 1200 mm, respectively. Daily temperature, humidity, rainfall, and solar radiation data recorded during the experimental period are shown in Figure 1.

The soil in the experimental area is classified as Latosol (Embrapa, 2014). Soil chemical properties characterization (Table 1) was conducted before the start of experimental procedures using samples collected from the 0-0.20 m layer.

2.2. Experimental design and treatments

The experimental design used was randomized complete blocks, with treatments arranged in strips, and four replications. The treatments consisted of seven population density: T1: 7 gems m^{-1} (4.5 tons ha^{-1}), T2: 10 gems m^{-1} (7 tons ha^{-1}), T3: 12 gems m^{-1} (8 tons ha^{-1}), T4: 13 gems m^{-1} (8.5 tons ha^{-1}), T5: 15 gems m^{-1} (9 tons ha^{-1}), T6: 17 gems m^{-1} (12 tons ha^{-1}), T7: 24 gems m^{-1} (15 tons ha^{-1}). Each experimental unit measured 7.5 × 29 m and consisted of three double rows with row spacing of 1.60 × 0.90 m.

2.3. Implementation and experimental conduct

For soil preparation, conventional tillage with plowing and leveling was followed by furrowing the area. Liming was performed with 2.5 tons of dolomitic limestone per hectare. All plots received basal planting fertilizer, with the application of 20 tons of filter cake ha^{-1}, 50 kg N ha^{-1}, 100 kg P ha^{-1}, and 100 kg K ha^{-1}, based on crop recommendations (Ribeiro et al., 1999).

The sugarcane variety used was RB92579, characterized by high productivity and adaptability to adverse environmental conditions, and widely cultivated in the Northeast region (Diniz et al., 2018).

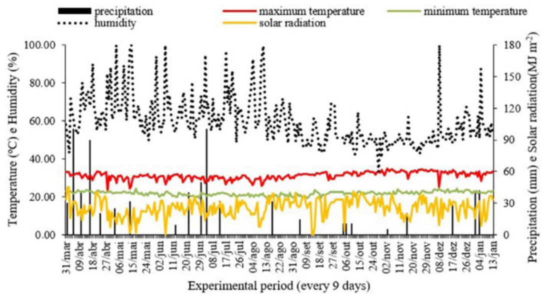

Figure 1. Temperature, humidity, solar radiation, and rainfall data during the field experiment.

Table 1. Soil Chemical Properties in the Experimental Area. Monte Alegre Mill, Mamanguape, State of Paraíba, Brazil.

pH (in water)	P	K^+	Na^+	H+Al	Al^{3+}	Ca^{2+}	Mg^{2+}	SB	CTC	V	OM	PST
	ppm		meq/100 mL							%		
6.6	64	84	0.27	1.2	0.00	1.3	1.2	2.83	2.83	70.2	1.24	2.91

Note: P and K extracted by Mehlich^{-1}; pH: hydrogen potential; P: phosphorus; K: potassium; Na: sodium; H+Al: potential acidity; Al: aluminum; Ca: calcium; Mg: magnesium; SB: sum of bases; CTC: cation exchange capacity; V: base saturation; OM: organic matter; PST: exchangeable sodium percentage.

2.4. Variables analyzed

Number of tillers per meter: manually counted in a 5 m distance from the two central rows of the plot.

Number of stalks per meter: directly counted in ten meters in the central rows per plot.

Tons of stalks per hectare (TCH): Sugarcane was manually harvested from each plot, weighed using a loader and digital scale, and the data were extrapolated to tons per hectare (fresh basis) according to the Equation 1:

$$TCH = Mass\ of\ stalks\ from\ the\ plot\ (t)\ /\ Plot\ area\ (ha) \quad (1)$$

Recoverable total sugar (ATR): Five stalks per plot were separated and sent to the Monte Alegre Mill Laboratory for analysis according to the CONSECANA (2006) methodology.

Tons of sugar per hectare (TAH): Using ATR values and cane production (TCH), the total recoverable sugar yield per hectare (TAH) was calculated according to the Equation 2:

$$TAH = TCH\ x\ ATR \quad (2)$$

Gross Income (RB): Obtained by multiplying the TCH values by the current price of sugarcane per hectare with a fixed value of (R$ 143.39).

Net Income (RL): Calculated by subtracting RB from the production costs of each treatment (CP). The costs for each planting density are shown in Table 2.

Return Rate (TR): Obtained through the relation (Equation 3):

$$TR = RB / CP \quad (3)$$

Profitability Index (IL): Calculated by the following Equation 4:

$$IL = (RL / RB)\ x\ 100 \quad (4)$$

2.5. Data analysis

The obtained data were subjected to analysis of variance using the F-test at a significance level of 5%. Means were compared using the Scott-Knott test ($p \leq 0.05$) with the R 3.6.3 software through the ExpDes.pt package (Ferreira et al., 2018). Subsequently, a principal component analysis (PCA) was conducted to evaluate the interrelationship between sugarcane's productive aspects and the studied population density using the FactoMineR package (Factor Analysis and Data Mining with R) (Lê et al., 2008).

3. Results

According to the analysis of variance, planting density significantly influenced the number of tillers ($p \leq 0.05$), the number of stalks, tons of stalks per hectare, and sugar per hectare ($p \leq 0.01$), while it did not significantly affect the total recoverable sugar content (Table 3).

The number of tillers grouped the different sugarcane planting arrangements into two groups, with higher tillering in sugarcane planted at a density of 24 gems m^{-1} (T7), 17 gems m^{-1} (T6), and 10 gems m^{-1} (T2). The other planting density had lower values, with a 25.53% reduction in tillering compared to T7, T6, and T2 (Figure 2A).

Sugarcane cultivated at the high planting density T7 had the highest number of stalks, statistically differing from the other planting density (Figure 2B). It showed superiority of 8.56% over 12 gems m-1 (T3), 7.42% over sugarcane with a density of 17 gems m-1 (T6), and 10.03% over sugarcane with a density of 13 gems m^{-1} (T4), which were grouped with intermediate tillering. Meanwhile, reductions of 15.6% were observed for sugarcane with 15 gems m^{-1} (T5), 16.71% for sugarcane cultivated at a population density of 7 gems m^{-1} (T1), and 19.64% for 10 gems m^{-1} (T2), forming the third group with lower tillering. Nevertheless, the number of stalks

Table 2. Total Production Cost for Establishing a Sugarcane Plantation in the State of Paraíba.

	Planting density						
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**
Cost (R$)	4,513.86	5,051.46	5,266.54	5,374.06	5,481.56	6,126.86	6,771.86

T1: 7 gems m^{-1}; T2: 10 gems m^{-1}; T3: 12 gems m^{-1}; T4: 13 gems m^{-1}; T5: 15 gems m^{-1}; T6: 17 gems m^{-1}; T7: 24 gems m^{-1}.

Table 3. Summary of Analysis of Variance for the number of tillers, number of stalks, stalks per hectare (TCH), total recoverable sugar (ATR), and total recoverable sugar per hectare (TAH) of sugarcane as a function of planting density.

FV	GL	Number of tillers	Number of stalks	TCH	ATR	TAH
Block	3	14.555^{ns}	1.056^{ns}	54.862^{ns}	9.363^{ns}	703888.074^{ns}
Density	6	61.449^{*}	2.270^{**}	193.445^{**}	79.520ns	4621055.602^{**}
Error	18	16.185	0.160	19.496	38.772	441898.915
CV (%)		19.62	4.00	6.37	4.76	7.33
Mean		20.50	9.99	69.29	130.73	9.065

^{ns}, **, *not significant and significant at 1% and 5%, respectively, by the F-test. FV: sources of variation; GL: degrees of freedom; CV: coefficient of variation.

values falls within the range for the studied variety (7.7–11.0 stalks m^{-2}) (Dias et al., 2020).

Regarding tons of stalks per hectare (TCH) (Figure 2C) and tons of sugar per hectare (TAH) (Figure 2D), three distinct groups were formed, with higher productivity achieved in denser canes (T6 and T7) with average values of TCH and TAH of 77.69 tons ha^{-1} and 10.390 tons ha^{-1}, respectively. Intermediate productivities were observed in canes from density T2, T3, and T5, with respective average values of TCH and TAH of 68.99 tons ha^{-1} and 8.942 tons ha^{-1}. Canes planted at T4 and T1 with lower productivity had corresponding average values of 61.313 tons ha^{-1} for TCH and 7.924 tons ha^{-1} for TAH.

Concerning economic parameters, according to the analysis of variance, all were significantly influenced ($p \leq 0.01$) by planting density (Table 4), demonstrating differences in economic profitability depending on the density.

Gross income was higher at density T7 and T6, intermediate in planting density T2, T3, and T5, and lower in T1 and T4 (Figure 3A), corroborating with what was observed in TCH, as gross income calculation is based on multiplying TCH by the current value of the gross ton of sugarcane. Regarding net income, only planting density T4 had the lowest income value, being statistically lower than the other density (Figure 3B).

In the return rate, planting density were grouped into three categories: T1 and T2 promoted the highest return, T3, T5, and T6 had intermediate rates, while the rest had low economic returns (Figure 3C). Consequently, the profitability index showed that planting density T1 and T2 provide the highest profitability, around 50%, T3, T5, and T6 with an average profit of 45%, and T4 and T7 with a lower profit margin, averaging 38% (Figure 3D).

The principal component analysis (PCA) explained 88.6% of the original data variance in the first two axes (CP1 and CP2) (Figure 4). In axis 1, which accounted for 52.3% of the data explanation, a significant association was observed between TAH ($r = 0.97$; $p<0.01$), ATR ($r = 0.94$; $p<0.01$), RB ($r = 0.94$; $p<0.05$), and the number of tillers ($r = 0.86$; $p<0.05$). Treatments T6 and T7, which presented the best values for these variables, stood out in this axis (Figure 4).

In axis 2, which gathered 36.3% of the explanation of the original variance, a significant association was found between the profitability index ($r = 0.96$; $p<0.01$), economic

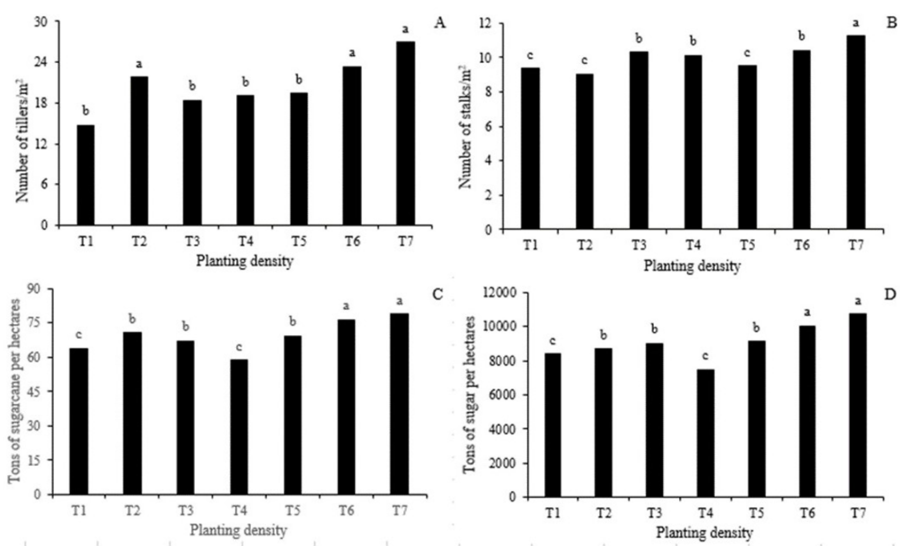

Figure 2. Mean results of the number of tillers (A), number of stalks (B), stalks per hectare (C), and sugar tonnage per hectare (D) of sugarcane as a function of planting density. T1: 7 gems m^{-1}, T2: 10 gems m^{-1}, T3: 12 gems m^{-1}, T4: 13 gems m^{-1}, T5: 15 gems m^{-1}, T6: 17 gems m^{-1}, T7: 24 gems m^{-1}. Bars with the same letters do not differ from each other by the Scott-Knott test at a 5% probability level.

Table 4. Summary of the Analysis of Variance for gross income (RB), net income (RL), return rate (TR), and profitability index (IL) of sugarcane as a function of planting density.

FV	GL	RB	RL	TR	IL
Block	3	1128441.899^{ns}	1128441.899^{ns}	0.0385^{ns}	36.279^{ns}
Density	6	3977754.311**	1664122.299**	0.1076**	104.324**
Erro**r**	18	400989.239	400989.239	0.0133	12.425
CV (%)		6.37	14.32	6.36	7.96
Mean		9934.93	4422.61	1.81	44.28

^{ns}Not significant; **significant at 1%, respectively, by the F-test. FV: Source of variation; GL: Degrees of freedom; CV: Coefficient of variation.

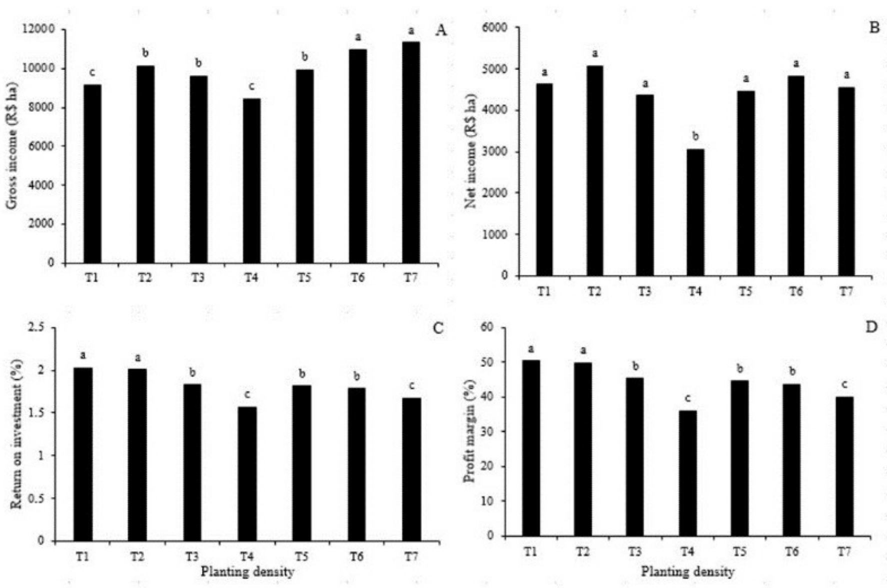

Figure 3. Mean results of Gross Income (A), Net Income (B), Return Rate (C), and Profit margin (D) of sugarcane as a function of planting density. T1: 7 gems m^{-1}, T2: 10 gems m^{-1}, T3: 12 gems m^{-1}, T4: 13 gems m^{-1}, T5: 15 gems m^{-1}, T6: 17 gems m^{-1}, T7: 24 gems m^{-1}. Bars with the same letters do not differ from each other by the Scott-Knott test at a 5% probability level.

return rate (r = 0.94; p<0.01), and net income (r = 0.90; p<0.01). In this axis, treatments T1 and T2 performed the best, contrasting with T4, which had lower performance for these variables. In this context, planting density T4 yielded the lowest economic return and productivity, making it less suitable for sugarcane cultivation.

4. Discussion

The higher tillering in denser cultivations, as noted by Pawar et al. (2005), is attributed to a greater contribution of germination/survival percentage, reaching around 81.33%. This is due to the increased number of gems placed at planting, influencing the increase in the proportion of tillers 120 days after planting.

The number of stalks in conditions of high density is generally reduced due to competition for light, water, and nutrients, which also decreases the size and consequently the mass of stalks (Panziera et al., 2022). However, in this study, it was noticeable that higher density, with 27 gems m^{-1} at planting, resulted in a higher number and production of stalks, indicating efficient light interception by the canopy under these conditions. This finding contradicts the conclusion of Chiluwal et al. (2018), who found that more spaced sugarcane plants contained a higher number and production of stalks. Another factor that may have influenced these results is that the RB92579 variety is highly productive and adapted to abiotic stress conditions (Diniz et al., 2018).

The use of reduced spacing had a positive impact with a higher increase in total sugarcane production per unit area, in line with the study by Rossi Neto et al. (2018). Likely, the change in planting arrangement positively influenced

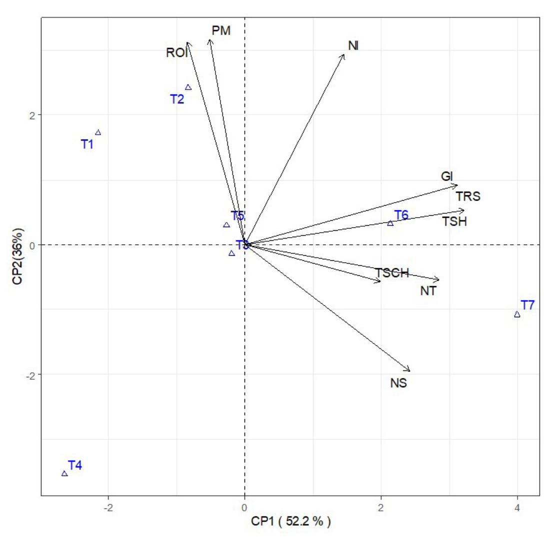

Figure 4. Principal Component Analysis. T1: 7 gems m^{-1}, T2: 10 gems m^{-1}, T3: 12 gems m^{-1}, T4: 13 gems m^{-1}, T5: 15 gems m^{-1}, T6: 17 gems m^{-1}, T7: 24 gems m^{-1}. Gross Income (GI), Net Income (NI), Number of tillers (NT), Number of stalks (NS), Return on investment (ROI), Profit margin (PM), Tons of sugarcane per hectares (TSCH), Total Recoverable Sugar (TRS), and Tons of sugar per hectares (TSH).

root distribution, altering access to soil resources, which could subsequently impact crop productivity.

Furthermore, canopy development and light interception, essential factors for stalk and sugar yield accumulation in current sugarcane cultivation models, change with crop arrangements and spacings, increasing in denser cultivations in the RB 92579 variety (Dias et al., 2020).

In terms of return rate, the planting density applied in treatment T7 required a large number of gems for cultivation (27 gems m^{-1}), leading to an increase in production costs. Since the shoots can account for almost 30% of production costs (Mohanty and Nayak, 2011), this negatively affected the economic return rate, making cultivation at this density economically unviable.

The return rate and profitability index are related to production costs, gross income, and net income, and they can assist producers in decision-making regarding the need for investment. It also helps identify the occurrence of economic return, considering that the utility and success of any technique depend on economic viability and associated costs (Shah et al., 2013). Thus, despite the T7 density promoting higher TCH and TAH values, the high production cost does not support a good economic return. In contrast, treatment T6 may be a more promising cultivation alternative, as it provides both high productivity and a profit of nearly 50%.

In summary, in denser cultivations (T6 and T7), there was higher tillering and stalk numbers, which directly influenced stalk and sugar production per hectare, consistent with the findings of Esteban et al. (2019) on sugarcane yield under different planting spacings. Increased productivity in narrower planting spacings is attributed to a larger area effectively occupied by cultivation due to a higher number of stalks per hectare and a reduction in gaps.

5. Conclusions

Sugarcane cultivated with higher density (17 and 24 gems m^{-1}) in plant cane, variety RB92579, achieves greater growth and productivity.

The minimum sugarcane and sugar productivity is recorded at planting density of 7 and 13 gems m^{-1} in plant cane, variety RB92579.

Cultivation with 17 gems m^{-1} of sugarcane provides greater productivity with a profitability index of 45% in plant cane, variety RB92579.

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