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Original Article

Filter cake increases sugarcane yield

A torta de filtro aumenta a produtividade da cana-de-açúcar

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Abstract

Sugarcane cultivation stands out in Brazilian agribusiness, covering more than eight million hectares for the production of sugar, ethanol, and by-products. Fertilization is one of the limiting factors in sugarcane yield, for which filter cake is a viable solution to meet plant nutritional needs. This study aimed to assess the effect of enriched filter cake on gas exchange and yield in RB041443 sugarcane, cultivated in soils of the coastal tablelands of Paraíba, Brazil. The experiment was conducted in the Monte Alegre S/A sugarcane mill, in the municipality of Mamanguape, using a randomized blocks experimental design, with 12 treatments (T1- cake, T2- cake + MAP, T3- cake + gypsum, T4 - cake + phosphate, T5- cake + bagasse, T6- cake + MAP + gypsum, T7- cake + MAP + phosphate, T8- cake + MAP + bagasse, T9- cake + gypsum + phosphate, T10- cake + gypsum + bagasse, T11- cake + phosphate + bagasse, and T12- control (only MAP)), and 4 replications, totaling 48 plots. A significant effect (5% probability) was also observed for the variables number of leaves and tons of stem per hectare (TSH). T1- cake, T4- cake + phosphate, T6- cake + MAP + gypsum and T10- cake + gypsum + bagasse, had the best results for TSH, with yields greater than 140 t ha^{-1}. Regarding stomatal conductance, the highest values were obtained in T6 and T8, which, together with T11, had the highest gs values. Concerning the internal carbon concentration, T1, T2, T6, and T8 stood out. T6 also had a significant effect on transpiration. From this study, it was concluded that the use of enriched filter cake as a base fertilizer in sugarcane culture contributes to increasing the yield of the RB041443 variety, generating positive responses for plant gas exchange, being T1 and T10 indicated to increase the production in the sugar-energy sector.

Keywords: *Saccharum officinarum* L., nutrition, gas exchange.

Resumo

A cultura da cana-de-açúcar ocupa uma posição de destaque para o agronegócio brasileiro, abrangendo mais de oito milhões de hectares na produção de açúcar, etanol e subprodutos. Um dos fatores limitantes na produtividade da cana-de-açúcar é a questão da adubação, sendo a torta de filtro uma solução viável para suprir as necessidades nutricionais da planta. Com esse estudo, objetivou-se avaliar o efeito do uso da torta de filtro enriquecida sob as trocas gasosas e produtividade da variedade de cana-de-açúcar RB041443 cultivada em solos dos tabuleiros costeiros da Paraíba. O experimento foi conduzido na Usina Monte Alegre S/A, no município de Mamanguape-PB, utilizando o delineamento experimental em blocos casualizados com 12 tratamentos (T1- Torta, T2- Torta + MAP, T3- Torta + Gesso, T4 - Torta + Fosfato, T5- Torta + Bagaço, T6- Torta + MAP + Gesso, T7- Torta + MAP + Fosfato, T8- Torta + MAP + Bagaço, T9- Torta + Gesso + Fosfato, T10- Torta + Gesso + Bagaço, T11 - Torta + Fosfato + Bagaço, e T12 - Testemunha (Apenas MAP)), 4 repetições, totalizando 48 parcelas. Efeito significativo a 5% também foi observado para a variável número de folhas e tonelada de colmo por hectare. Para a variável TCH, os melhores resultados foram obtidos nos tratamentos T1- Torta, T4-Torta + Fosfato, T6- Torta + MAP + Gesso e T10- Torta + Gesso + Bagaço, com produtividades superiores a 140 t ha^{-1}. Para a condutância estomática, resultados superiores foram obtidos no T6 e T8, que, junto ao T11, agruparam-se com os maiores valores de gs. Em relação a concentração interna de carbono, destacaram-se os tratamentos T1, T2, T6 e T8. Para a variável transpiração, o T6 apresentou influência significativa da torta de filtro. Com o referido estudo, concluiu-se que a utilização da torta de filtro enriquecida como adubação de fundação na cultura da cana-de-açúcar possibilita aumento no rendimento produtivo da variedade RB 041443, bem como respostas positivas para as trocas gasosas da planta, sendo os tratamentos T1 e T10 indicados para aumentar a produção do setor sucroenergético.

Palavras-chave: *Saccharum officinarum* L., nutrição, trocas gasosas.

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1. Introduction

Sugarcane (*Saccharum* spp.) is a crop that occupies a prominent position in Brazil, with great importance in the agribusiness sector (Figueiredo et al., 2022), being highly studied (Monteiro et al., 2021; Rehman et al., 2023). This culture currently covers more than eight million hectares, making Brazil a promising country in the production of sugar, ethanol, and by-products worldwide (Conab, 2021), becoming of great importance, both in the environmental and economic fields. This culture, under ideal cultivation conditions, tends to positively respond in terms of plant development.

Fertilization is one of the most important factors for increasing sugarcane yield so that it meets the needs of the crop during its cycle (Silva et al., 2021). Some by-products from the sugarcane agroindustry are used to increase production at a lower cost, as this process generates a high amount of organic residues, which have been used to improve the soil.

Among these residues, filter cake stands out, which is a by-product derived from the processing of sugarcane, resulting from the vacuum filtration of the sludge retained in the clarifiers. This residue is rich in P, Ca, Cu, Zn, and Fe, has a high C/N ratio, and, in addition to being deficient in K, can also reduce the availability of N in the soil (Korndorfer, 2015).

For each ton of sugarcane processed, an average of 40 kg of filter cake is produced, a compound rich in essential minerals such as calcium, phosphorus, potassium, nitrogen, and organic matter (Santos et al., 2015). Improvements in soil aeration, infiltration, water storage, and neutralization of the impact caused by rain are some benefits of using filter cake; in addition, the high concentrations of phosphorus pentoxide (P_2O_5) and calcium oxide (CaO), in the composition of this product, promote the accumulation of phosphorus and potassium and favor the solubility of natural phosphates (Schmidt Filho et al., 2016).

Considering that sugarcane is very demanding in some nutrients, this research hypothesizes that the use of filter cake increases sugarcane yield. Thus, this study aimed to assess the effect of enriched filter cake on gas exchange and yield in RB041443 sugarcane, cultivated in soils of the coastal tablelands of Paraíba.

2. Material and Methods

The experiment was conducted from December 2019 to January 2021, in an open environment in the agricultural area of the Monte Alegre S/A sugarcane mill, located in the municipality of Mamanguape, Paraíba, Brazil (6° 50' 20" W, 35° 7' 33" N). The climate in the region is classified as As' (tropical rainy), hot and humid (Köppen, 1936), with temperatures from 25 – 27 °C and average rainfall from 1400 – 1800 mm, from autumn to winter.

A randomized block design was used, with twelve treatments and four replications, totaling 48 plots. Each plot was composed of six furrows (0.90 x 1.6 m), measuring 5.9 m wide and 100 m length, and each block comprised the twelve treatments, measuring 70.8 m wide, with 72 rows of sugarcane. The total width of the experimental area was 283.2 m, totaling 288 rows of sugarcane and covering 28,320 m^2. The variety of sugarcane used was RB041443.

The furrows were mechanically opened to a depth of 40 cm and planting was performed manually, using from 15 to 18 buds per linear mete, uniformly distributing medium-sized stems (60 cm) in the furrows, using a double alternate spacing of 0.90 x 1.6 m. One week after planting, a central pivot (70 mm) was used. The chemical attributes of the soil in the experimental area are shown in Table 1.

The soil was prepared by subsoiling, harrowing, and furrowing approximately 80 cm deep. The soil of the experimental area was classified as distrocohesive yellow latosol, which was fertilized with the established sources and doses. The filter cake was subjected to chemical analysis, from which the following results were obtained: pH = 7.44, organic matter (g kg^{-1}) = 13.35, P (mg kg^{-3}) = 130.65, K^+ (mg kg^{-3}) = 192.7, Ca^{2+} ($cmol_c$ dm^{-3}) = 2.24, Mg^{2+} ($cmol_c$ dm^{-3}) = 1.52, Na^+ ($cmol_c$ dm^{-3}) = 0.20, base saturation ($cmol_c$ dm^{-3}) = 4.45, H + Al^{3+} ($cmol_c$ dm^{-3}) = 0.30, Al^{3+} ($cmol_c$ dm^{-3}) = 0.30, and cation exchange capacity ($cmol_c$ dm^{-3}) = 4.75.

The planting fertilization consisted of applying 15 kg of gypsum per ton of cake, 30 kg of phosphate/ton of cake, 250 kg/ha^{-1} of MAP, 20 t of cake per hectare, and 1 t of bagasse per 5 t of cake. The treatments and amounts of products and by-products per plot are described in Table 2.

The stem diameter was measured using a digital caliper, with values expressed in mm. The number of leaves was determined by counting ten plants in each experimental plot, considering only fully open leaves. The number of internodes, from the base to the apex of the stem, was visually and individually counted. For tillering, the number of stems in the two central furrows of each plot was counted, using 5 m in each row, calculating the average number of stems per linear meter.

Gas exchange analysis was performed 180 days after planting (DAP). Gas exchanges were determined using an infrared gas analyzer (IRGA, LCpro-SD Portable Photosynthesis System, ADC BioScientific, Hoddesdon, ENG). Measurements were made from 8 am to 10 am, using natural light on the abaxial surface of the leaves at room temperature.

Table 1. Soil chemical attributes of the experimental area (0 – 0.20 m and 0.20 – 0.40 m), respectively.

$pH_{(in\ water)}$	P	K Na	H+Al	Al	Ca	Mg	SB	CEC	OM
	ppm		Meq/100mL						%
6.4	13	123 34	3.2	0.07	1.2	0.3	1.96	5.16	1.83
5.7	4	109 32	2.9	0.15	0.7	0.2	1.32	4.22	1.27

(P and K): $Mehlich^{-1}$ Extractor; SB: sum of bases; CEC: cation exchange capacity; OM: organic matter.

Table 2. Treatments and quantities of products and by-products used in the experiment, per plot.

Treatments	Quantities (Kg)
T1 - cake	1440
T2- cake + MAP	1440 + 18
T3- cake + gypsum	1440 + 21.6
T4 - cake + phosphate	1440 + 43.2
T5- cake + bagasse	1440 + 288
T6- cake + MAP + gypsum	1440 + 18 + 21.6
T7- cake + MAP + phosphate	1440 + 18 + 43.2
T8- cake + MAP + bagasse	1440 + 18 + 288
T9- cake + gypsum + phosphate	1440 + 21.6 + 43.2
T10- cake + gypsum + bagasse	1440 + 21.6 + 288
T11 - cake + phosphate + bagasse	1440 + 43.2 + 288
T12 - control (only MAP)	18

Stomatal conductance (gs – mol H_2O m^{-2} s^{-1}), net photosynthesis (A – µmol CO_2 m^{-2} s^{-1}), transpiration (E – mmol H_2O m^{-2} s^{-1}), internal carbon concentration (Ci – µmol CO_2 mol air^{-1}), instantaneous carboxylation efficiency (A/Ci), instantaneous water-use efficiency (WUE), and intrinsic water-use efficiency (iWUE) were assessed.

The number of TSH was obtained from the data of industrializable stems, cutting the entire plot of each treatment. The yield was estimated based on the following Equation 1:

$$TSH = TPM \times 10 \ / \ PUA \tag{1}$$

Where:
TSH - Tons of stem per hectare;
TPM - Total plot mass (kg);
PUA – Plot useful area (m^2);

The number of TSH was determined at the time of harvest using an industrial hook scale to weigh the plants from each plot, with values expressed in kg, which were subsequently applied in the equation described above, following the method proposed by Mariotti and Lascano (1969).

The data were subjected to the Shapiro-Wilk normality and Levene's and Bartlett's variance homogeneity tests. After verifying normality and homogeneity, the data were subjected to analysis of variance by the F test ($p \leq 0.05$) and subsequent test of means by the Scott-Knott criteria, at 5% probability. Cluster grouping using the hierarchical method was also performed. All analyses were performed using R® software, version 3.6.1 (R Core Team, 2019).

3. Results

The analysis of variance (ANOVA) showed a significant effect of the treatments at 1% probability by the F test for the variables stem diameter, number of internodes, and tillering. A significant effect was also observed for the number of leaves and tons of stem per hectare, at 5% probability.

For the variable TSH, two distinct groups were formed, represented by the letters "a" and "b", with better results obtained with T1 (cake), T4 (cake + phosphate), T6 (cake + MAP + gypsum), and T10 (cake + gypsum + bagasse), which provided yields greater than 140 t ha^{-1} (Figure 1A).

Two groups with different characteristics were formed for the number of internodes, and T1 (cake), T3 (cake + gypsum), T5 (cake + bagasse), T7 (cake + MAP + phosphate), and T10 (cake + gypsum + bagasse) had the highest values (>12.6 internodes) (Figure 1B).

For stem diameter, three distinct groups were formed, represented by the letters "a", "b" and "c" (Figure 1C), and T1 (cake) and T2 (cake + bagasse) had the highest stem diameters, with 2.435 and 2.46 cm, respectively.

The number of tillers showed variable responses to the different treatments, forming four groups (Figure 1D). The highest results for this variable were obtained with the associated use of cake + phosphate (T4), cake + gypsum + bagasse (T10), and cake + phosphate + bagasse (T11).

Results similar to those found for TSH and number of internodes were also observed for the number of leaves, for which only one group was formed (Figure 1E). For this variable, higher results in absolute means were obtained with T5 (cake + bagasse), T10 (cake + gypsum + bagasse), T11 (cake + phosphate + bagasse), and T12 (only MAP), which resulted in mean values equal to or more than five leaves.

Regarding gas exchange, T11 (cake + phosphate + bagasse) and T12 (control) had the highest values of photosynthetic rate (A) (Figure 2A).

For stomatal conductance (gs), better results were also obtained with T6 (cake + MAP + gypsum) and T8 (cake + MAP + bagasse), which together with T11 (cake + phosphate + bagasse) had the highest gs values, statistically differing from the other treatments (Figure 2B). The values found for this crop are lower, which can be attributed to the evaluation period of the experiment, performed in the dry season, at 180 DAP, in late July, when the rains began to cease in the study region.

Concerning the internal carbon concentration (Ci) (Figure 2C), two groups were formed, in which T1 (cake), T2 (cake + MAP), T6 (cake + MAP + gypsum), and T8 (cake + MAP + bagasse) stood out. In addition, the use of enriched filter cake significantly influenced the sugarcane transpiration (E) (Figure 2D), with the formation of two distinct groups, in which T6 (in absolute means) was the most prominent, followed by T1 (cake), T4 (cake + phosphate), T7 (cake + MAP + phosphate), and T9 (cake + gypsum + phosphate) with lower values.

For the instantaneous carboxylation efficiency (A/Ci) (Figure 2E), three groups were formed, and T11 (cake + phosphate + bagasse) and T12 (control) had the best results, providing the highest values for this variable, which is used to identify the action of non-stomatal factors that interfere with CO_2 assimilation rates.

T1 (cake), T2 (cake + MAP), T6 (cake + MAP + gypsum), and T8 (cake + MAP + bagasse) provided lower instantaneous water use efficiency (WUE), which grouped with the lowest averages (Figure 2F). This variable indicates the amount of carbon assimilation regarding water use and is considered a key factor to improve crop yields, as low water availability is the most important environmental factor for limiting agricultural production.

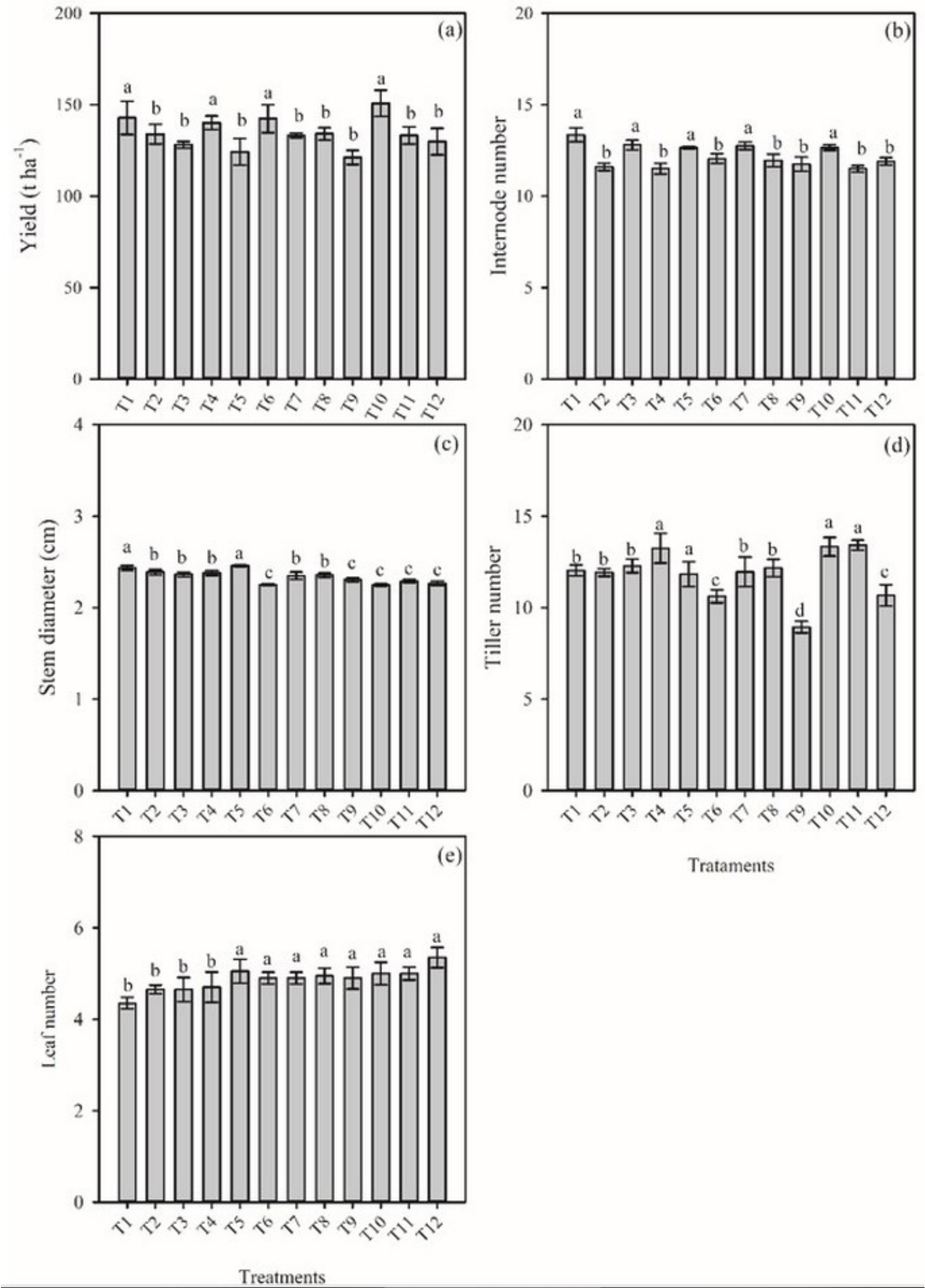

Figure 1. Yield (a), number of internodes (b), stem diameter (c), number of tillers (d), and number of leaves (e) in sugarcane subjected to different treatments combined with enriched filter cake. (T1- cake, T2- cake + MAP, T3- cake + gypsum, T4 - cake + phosphate, T5- cake + bagasse, T6- cake + MAP + gypsum, T7- cake + MAP + phosphate, T8- cake + MAP + bagasse, T9- cake + gypsum + phosphate, T10- cake + gypsum + bagasse, T11- cake + phosphate + bagasse, and T12- control (only MAP)).

For intrinsic water-use efficiency (iWUE), T4 (cake + phosphate), T7 (cake + MAP +phosphate), and T9 (cake + gypsum + phosphate) (Figure 2G) had the best results, whereas T2 (cake + MAP), T6 (cake + MAP + gypsum), and T8 (cake + MAP + bagasse) provided the lowest values.

According to the hierarchical clustering, the treatments were grouped into two groups, from the most important to the least important regarding the variables stem diameter, number of internodes, number of leaves, number of tillers, and yield (Figure 3). T1 and T10 were the most important treatments considering the clustering of the study variables. Furthermore, the analysis revealed that T9, T6, T12, T5, T3, T7, T2, T4, T8 and T11 grouped together forming a second group.

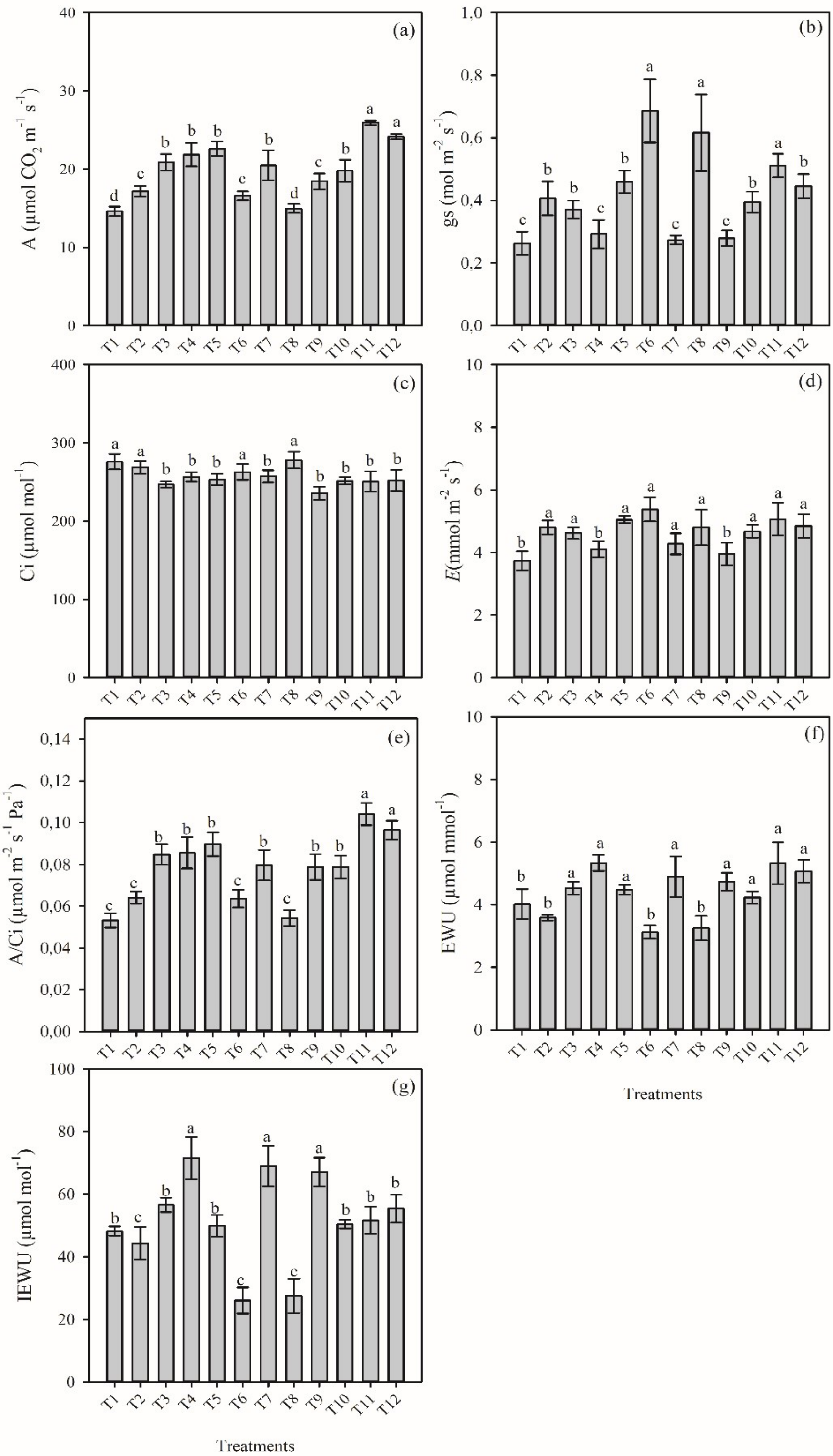

Figure 2. CO_2 assimilation (a), stomatal conductance (b), internal carbon concentration (c), transpiration (d), instantaneous carboxylation efficiency (e), instantaneous water use efficiency (f), and intrinsic water use efficiency (g) in sugarcane subjected to different treatments with enriched filter cake. Means followed by the same letter do not differ statistically from each other, according to the Scott-Knott test, at 5% probability. (T1- cake, T2- cake + MAP, T3- cake + gypsum, T4 - cake + phosphate, T5- cake + bagasse, T6- cake + MAP + gypsum, T7- cake + MAP + phosphate, T8- cake + MAP + bagasse, T9- cake + gypsum + phosphate, T10- cake + gypsum + bagasse, T11- cake + phosphate + bagasse, and T12- control (only MAP)).

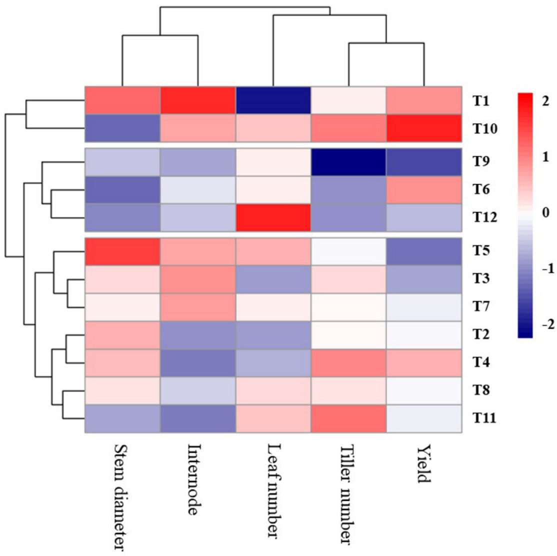

Figure 3. Hierarchical cluster and heatmap analysis with the 12 treatments as a function of the variables stem diameter, number pf internodes number, number of leaves, number of tillers, and yield. The red and blue colors represent the importance, from the most to the least, respectively. (T1- cake, T2- cake + MAP, T3- cake + gypsum, T4 - cake + phosphate, T5- cake + bagasse, T6- cake + MAP + gypsum, T7- cake + MAP + phosphate, T8- cake + MAP + bagasse, T9- cake + gypsum + phosphate, T10- cake + gypsum + bagasse, T11- cake + phosphate + bagasse, and T12- control (only MAP)).

4. Discussion

The results evidenced the potential use of enriched filter cake, which contributes to increasing the final yield of sugarcane and the economic gains of the producer due to the higher number of tillers produced (Zeng et al., 2020). In addition, competition between tillers for water, light and space increases when the plants reach their maximum tiller production, causing the death of younger tillers (Manhães et al., 2015).

The better results of using cake and bagasse in comparison with the control and the other treatments can be explained by the fact that the addition of sugarcane bagasse, ground in the filter cake purification and obtainment, causes rapid decomposition and high availability of nutrients, which are essential for the growth and development of sugarcane, with high levels of organic matter, consequently increasing the diameter of sugarcane stems (Nolla et al., 2015).

The results found in this study are promising, especially when considering that the average yield of sugarcane in 2020 was 75.60 t ha^{-1} in Brazil and 56.47 t ha^{-1} in the state of Paraíba (SIDRA, 2021).

Our results regarding the number of internodes portray the importance of using treatments with the presence of gypsum, bagasse and phosphate together with the cake, which may have favored greater availability of water, environmental factors and soil nutrients for the plants (Arantes, 2012). In addition, it is noteworthy that a greater number of internodes is desirable if there is also a greater plant length, considering that small internodes directly affected crop yield (Chen et al., 2020). Likewise, such characteristics were observed for the number of leaves, which may be related to the high amount of organic matter added to the soil, leading to a positive crop efficiency (Miranda-Stalder and Burnquist, 2019). In summary, treatments with gypsum, sugarcane bagasse and phosphate may have influenced these variables by improving the distribution and depth of the roots, allowing access to a greater layer of water stored in the soil (Pereira, 2021), as well as when present with organic matter, organic compounds, as in the case of filter cake, increase the agronomic characteristics of sugarcane (Santiago and Rossetto, 2009).

With regard to gas exchange, Gonçalves (2018) found similar values, evidencing that organomineral fertilization has advantages over mineral fertilization regarding photosynthetic rate. This author also found that the use of filter cake in sugarcane led to an average photosynthetic rate of approximately 16.82 µmol m^{-2} s^{-1}, in the first crop cycle, in addition to positive values when compared to the control, showing the efficiency of using this enriched residue.

This research also showed that the internal concentration of carbon (Ci) tends to be influenced by factors that reduce the influx of CO2 into the inner space of the leaves due to the decrease in stomatal conductance, however, we obtained promising results with T1-cake, T2 -cake + MAP, T6-cake + MAP + gypsum and T8-cake + MAP + bagasse, causing the plants not to close their stomata, absorbing more light and energy (Ometto et al., 2003; Faria et al., 2013). With regard to sugarcane transpiration (E), our results showed a lower transpiration activity in treatments T1- cake, T4- cake + phosphate and T9- cake + gypsum + phosphate, probably due to soil water restriction and to the ineffectiveness of treatments in mitigating stress (Barboza and Teixeira Filho, 2017). However, we observed positive results for the other treatments, mainly T6-cake + MAP + gypsum, probably due to the union of the products, causing the plants to open their stomata and making transpiration (E) more favorable, which reflected in a higher value of (E) (Tatagiba et al., 2015).

As for the instantaneous water use efficiency (WUE), higher values are desirable, such as those observed in this study for the treatments, in particular, T4- cake + phosphate, T7- cake + MAP + phosphate and T11- cake + phosphate + bagasse, as they indicate potential to generate a greater water gain. carbon and, consequently, greater biomass production in relation to the amount of water used by the crop, i.e., greater production of dry matter per gram of transpired water or fixation of more carbon per gram of transpired water (Leakey et al., 2019).

Regarding the intrinsic water use efficiency (iWUE), it is important to note that increases in this variable, in particular, for treatments T4- cake + phosphate, T7- cake + MAP + phosphate and T9- cake + gypsum + phosphate, may be related to the plant strategy to close stomata, in order to reduce water stress, but without a corresponding reduction in photosynthetic rates (Yi et al., 2019).

According to the results, the instantaneous carboxylation efficiency (A/Ci) provided by the study treatments may be related to an increase in the activity of ribulose-1,5-bisphosphate carboxylase-oxygenase (Rubisco) in these plants (Lima et al., 2022).

T1 and T10 provided the highest yields, which may be related to the effects of treatments that assume importance on the chemical properties of the soil, increasing the availability of nutrients, in the CEC (cation exchange capacity), and reduction in the levels of exchangeable aluminum. In both treatments, the highest yield positively correlated with the number of internodes and the lowest number of leaves compared to the control (T12). In the harvest phase, the increased number of leaves had a negative effect on yield, as seen in T12 and T11; however, this effect was observed only for specific treatments. These divergent effects may be associated with the composition of each treatment, which may have reflected in different stages of development. The increased number of leaves is essential for yield because stimulates the supply of assimilates in the tillering and growth phases, before harvest. Nevertheless, when there is a maximum accumulation of sugars in the stem, the leaves may become drains and the stems sources, which may be the reason for the lower production with an increase in the number of leaves in the final phase. Because of this, the sugarcane plants reduce the assimilation of CO_2 in the harvest phase, as identified in T1 and T10. On the other hand, T11 and T12 resulted in higher rates of CO_2 assimilation, which may be associated with the hypothesis that treatments have different phenological stages. Thus, T1 and T10 may be associated with yield anticipation, whereas T11 and T12 can influence the harvest delay.

5. Conclusion

The use of enriched filter cake as a base fertilizer in sugarcane cultivation contributed to increasing the yield and gas exchange.

T1 (cake) and T10 (cake + gypsum + bagasse) can be indicated to increase production in the sugar-energy sector.

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