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Filter cake in industrial quality and in the physiological and acid phosphatase activities in cane-plant

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ABSTRACT

Sugarcane filter cake, a phosphorus-rich (P) fertilizer, can affect not only P storage in sugarcane (*Saccharum officinarum* L.), but also its metabolism and photosynthesis. In this study, was evaluated the effect of different mineral fertilizers, with and without the use of filter cake, on P levels, gas exchange, acid phosphatase activity, sugar, hydrated alcohol production, and total soluble solids. Sugarcane (variety RB86 7515) was cultivated on dystrophic Typic Haplustox in a randomized complete block design. Three replicates were established in a 3 × 4 × 2 factorial scheme, with three P sources (Triple Superphosphate-TS, Natural Reactive Bayovar Phosphate-BP, and Natural Araxa Phosphate-AP), four rates of P as P_2O_5 (0, 90, 180, and 360 kg ha^{-1}), and the presence or absence of filter cake (7.5 Mg ha^{-1}, dry weight). The levels of foliar P (PCL) were determined, along with the accumulation of P in aerial plant parts (AAP), net CO_2 assimilation (A), stomatal conductance (g_s), transpiration rate (E), acid phosphatase activity (APL), hydrated alcohol, total soluble solids (TSS), total recoverable sugar (TRS), and stalk production. The highest P rate with filter cake yielded the maximum concentration of P in leaves (1.7 g kg^{-1}), leading to the highest P accumulation in aerial plant parts (17.8 kg ha^{-1}), and furthering a sugar production of 197.1 kg t^{-1}, and stalk production (122.6 Mg ha^{-1}). The highest rate of Triple Superphosphate alone or with filter cake yielded the lowest acid phosphatase activity, the highest rate increased the accumulation of P in aerial parts (18.8 kg ha^{-1}), and for stalk production, produced 123.1 Mg ha^{-1} of stalks. The use of Triple Superphosphate associated with filter cake increased the production of sugar (192.5 kg t^{-1}), hydrated alcohol (91.3 L t^{-1}) and total soluble solids (18.4°Brix), while the use of higher P rates, regardless of the source, increased gaseous exchange in sugarcane plants.

1. Introduction

Sugarcane productivity in tropical regions is commonly related to the availability of phosphorus (P), which is a limiting nutrient in these regions. Adequate P levels are essential for photosynthesis and stomatal conductance (Jacob and Lawlor, 1991; Reich et al., 2009). Plants that are P deficient usually have reduced photosynthetic capacity, which is reflected in a low intercellular CO_2 concentration, resulting in decreased stomatal conductance (Aspelmeier and Leuschner, 2004). When stomatal conductance is impaired, the water vapor flux to the atmosphere is reduced, leading to decreased transpiration rates (Gonçalves et al., 2010).

Phosphorus also plays an important role in stimulating root growth (Zhang and Barber, 1992), as it increases the area of root exploration in the soil, thus increasing water absorption and the turgor of guard cells (Kuwahara and Souza, 2009).

As soil has a high capacity for P absorption, usually apply large amounts of high-phosphate fertilizers, which is also a common in many scientific studies (Santos et al., 2009; Caione et al., 2011; Simões Neto et al., 2012). The filter cake, a byproduct of sugar and ethanol production that is generated in large volumes from ground sugarcane, is rich in organic matter and several nutrients, especially P. It can also improve the efficiency of P fertilization when mineral phosphate fertilizers are used as the liberated organic acids compete for the same adsorption sites, decreasing P adsorption to colloids in the clay fraction of soil (Pavinato and Rosolem, 2008). Therefore, filter cake can

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complement the use of mineral fertilization.

Phosphorus levels may influence several biochemical processes, including acid phosphatase activity (E.C.3.1.3.2) (Besford, 1979; Tanksley, 1983; Kuwahara and Souza, 2009). The activity of the enzyme is increased when the plant is deficient in P (Silva and Basso, 1993; Bovi et al., 1998) and could therefore be used to diagnose low P levels. However, using acid phosphatase activity as a biochemical indicator of P nutritional status in sugarcane has not been well studied. Nevertheless, the enzyme may be employed in future studies as a molecular marker for plants that are efficient in reabsorbing compartmentalized P, especially in plants cultivated on soils with deficient levels of P, and it can also be used as a tool for genetic improvement programs. Acid phosphatase activity, along with the other processes in sugarcane that respond to P deficiency, as discussed above, are all good indicators of the effects of P deficiency on plant metabolism and photosynthesis.

Several studies highlight the effects of filter cake application on P levels in sugarcane, in particular, studies have examined specific physiological and nutritional aspects in order to improve the nutritional efficiencies of the crop (Vasconcelos, 2013; Santos et al., 2014; Caione et al., 2015). An adequate supply of P increases both the productivity and quality of sugarcane crops (Korndörfer, 1994; Korndörfer and Melo, 2009; Santos et al., 2010). Thus, the aim of the present study was to evaluate the effect of phosphate fertilizers and filter cake on the physiology, acid phosphatase activity, production, and industrial characteristics of the cane-plant.

2. Materials and methods

2.1. Experimental site, climate, and soil

The experiment was carried out from June 2011 to June 2012 in the Fazenda Santo Antônio, Itajobi, São Paulo State, Brazil (−21°11′ S and −49°1′ W), at an elevation of 469 m. This region typically has a rainy summer and dry winter, with an average annual temperature of 23.2 °C and average annual precipitation of 1328 mm (CEPAGRI, 2015). In this study, was used the sugarcane variety RB86 7515, which has a high growth rate and stature, growth erect, with high stalk density and sucrose content, and has good agricultural productivity (PMGCA, 2008). Meteorological data were obtained from a nearby weather station located in the city of Catanduva-SP (Fig. 1). Throughout the experiment, was verified a period of surplus precipitation followed by an interval of drought.

The soil of the experimental area is dystrophic Red-Yellow Latosol (EMBRAPA, 2013), which corresponds to the dystrophic Typic Haplustox (USDA, 1999). Twenty composite soil samples (equivalent to 12

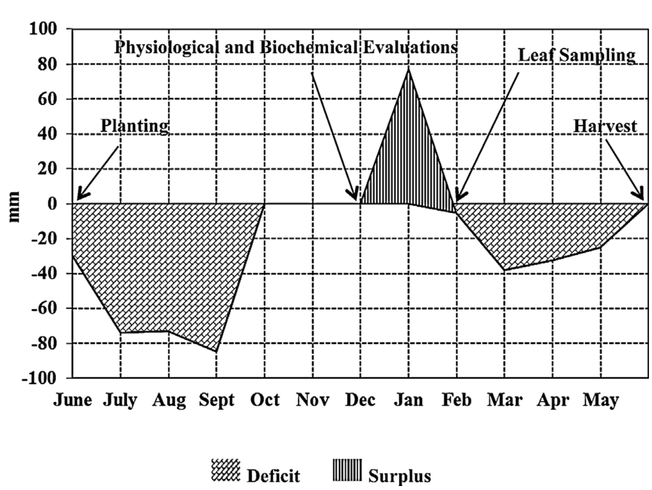

Fig. 1. Water balance from Catanduva, São Paulo State, from June 2011 to June 2012.

Table 1
Chemical and granulometric analysis of soil in the experimental area, Fazenda Santo Antonio, Itajobi, SP, Brazil.

Depth (m)	pH	S.O.M[a]	P	K	Ca	Mg	H + Al	CEC[b]	T[c]	V[d]
	$CaCl_2$	g dm^{-3}	mg dm^{-3}	mmolc dm^{-3}						%
0.00–0.20	6.1	10.0	5.0	1.1	29.0	13.0	10.0	42.3	52.3	81
0.20–0.40	5.6	10.0	4.0	0.9	25.0	9.0	12.0	34.8	46.8	74

Depth (m)	Granulometry			
	Clay	Silt	Fine Sand g kg^{-1}	Coarse Sand
0.00–0.20	209	40	464	287

S.O.M[a]: soil organic matter.
CEC[b]: cation exchange capacity.
T[c]: CEC + (H + Al).
V[d]: base saturation.

simple samples) for the total area were collected, and the results were homogeneous for the entire area.

Both the chemical and particle size analysis of the soil were performed based on the methods of Raij et al. (2001) and Camargo et al. (2009) (Table 1).

2.2. Treatments and crop cultivation

The treatments were defined by different P rates, using 180 kg ha^{-1} of P_2O_5 as the reference rate, which is standard for São Paulo State (Spironello et al., 1997). The experimental design was a randomized complete block design with three replications in a 3 × 4 × 2 factorial scheme. The factors were: three sources of P [Triple Superphosphate (TS; 41% P_2O_5 in citric acid); Natural Reactive Bayovar Phosphate (BP; 14% P_2O_5 in citric acid); and Natural Araxa Phosphate (AP; 4% P_2O_5 in citric acid)]; four P rates (0, 90, 180, and 360 kg ha^{-1}); and presence or absence of filter cake (7.5 Mg ha^{-1} dry matter).

Basic fertilization and coverage were performed following Spironello et al. (1997), by applying 151 kg ha^{-1} of $(NH_4)_2SO_4$, 204 kg ha^{-1} of KCl, and 25 kg ha^{-1} of $ZnSO_4$ and 30 kg ha^{-1} of CH_4N_2O and 160 kg ha^{-1} of KCl respectively. Each plot measured 112.5 m^2 and included five 15 m rows spaced at intervals of 1.5 m, only the three central rows were used (useful area of 67.5 m^2) for the experiment.

The chemical analysis of filter cake was performed based on Alcarde (2009) and the following values were obtained: N (total) 3.4 g kg^{-1}; P_2O_5 (total) 8.2 g kg^{-1}; P_2O_5 (2% citric acid soluble) 7.8 g kg^{-1}; K_2O 2.2 g kg^{-1}; and CaO 12.2 g kg^{-1}. After the filtration process, the filter cake was deposited outside and left to rest for a few days in order to lower the temperature between 60 and 40 °C, when inoculates the microorganisms on the pile. A two-month composting is then performed, with periodic turnings, after this stage, when the compost is mature and cooled then can be used in crops.

All produced filter cake is used during the harvest, its reduces the need fertilizers, furthermore, the milling period extends for almost a year, the production of filter cake occurs continuously so there is no need to stock the product. For sugarcane, the filter cake is applied within the planting furrow or across the total area. In subsequent years (ratoons), it is applied annually in between planting lines.

The filter cake used in this study contained 304.7 g kg^{-1} organic matter (Walkley and Black, 1934), was added 800 mL of BioPack[sc] (which contains organic acids and P-solubilizing microorganisms), with the goal of composting eight tons of filter cake, at a dosage of 100 mL per ton of filter cake, the mixture was composted for eight weeks.

2.3. Analysis of nutritional status, gas exchange, and acid phosphatase activity

At seven months after planting, net CO_2 assimilation (A, μmol m^{-2} s^{-1}), stomatal conductance (g_s, mmol m^{-2} s^{-1}), and transpiration rate (E, mmol m^{-2} s^{-1}) were measured in 12 completely developed and healthy leaves for each treatment (three leaves per plant), using a portable infrared gas analyzer (Li-COR, 2015). Acid phosphatase activity was also measured in the sugarcane leaf +1, using the methodology reported in Pizauro et al. (1988).

At eight months after planting, 15 leaves +1 were collected, the midrib of each leaf was removed, and the middle third of each sampled leaf was processed for analysis (Raij and Cantarella, 1997), samples were dried at 65 °C until a constant weight and were ground in a Wiley mill. To determine P contents in plant tissue, was used the method described by Bataglia et al. (1983), at the time of harvest (12 months), P accumulation in aerial plant parts was calculated by multiplying dry matter by the nutrient content of the aerial parts. To assess stalk production, total recoverable sugar, hydrated alcohol and total soluble solids, data were obtained from 20 plants during harvesting.

2.4. Statistical analysis

Analysis of variance (ANOVA) was performed to assess the effects of fertilizer sources, rate, presence or absence of filter cake, and the interactions among factors. Tukey's test was used to compared mean values at $\alpha = 0.05$, and a polynomial regression analysis was performed for the source of quantitative variation, using the statistical program AgroEstat (Barbosa and Maldonado Junior, 2012).

3. Results and discussion

3.1. Effects of fertilizer and filter cake on P concentrations in sugarcane leaves + 1

Foliar P levels were affected by the interaction of the filter cake with sources and rates of P (Table 2). The use of TS and BP resulted in higher foliar P when compared with the use of AP, particularly when TS and BP were combined with filter cake (Fig. 2a).

The combination of TS with filter cake resulted in the P increase, reaching up to 1.7 g kg^{-1} (Fig. 2a). The resulting values are within the range considered suitable for sugarcane cultivation (1.5–3.0 g kg^{-1}), as reported in a previous study (Raij and Cantarella, 1997).

Foliar P concentrations increased linearly with an increased rate of mineral fertilizer, particularly when filter cake was applied (Fig. 2b), reaching a maximum concentration of 1.7 g kg^{-1}. The application of TS in the absence of filter cake resulted in an average foliar P concentration of 1.5 g kg^{-1}, a result lower than that observed by Kuwahara and Souza (2009) who verified P concentrations in leaves from 2.1 to 3.4 g kg^{-1}, for the application of TS to brachiaria (*Brachiaria brizantha* L.) cv. MG-5 Vitória cultivated on Red-Yellow Argisol (EMBRAPA, 2013).

In contrast to the present study, Lima (2011) observed that the application of organic sources alone (filter cake in combination with crushed sugarcane) for the cultivar RB86 7515 in Red-Yellow Latosol (EMBRAPA, 2013), promoted greater increases in foliar P than those obtained from the combined use of organic sources and mineral fertilizers. Similarly, other studies have failed to find that the application of filter cake enhances the effectiveness of mineral fertilizers.

The exclusive application of TS to sugarcane (variety RB75 126) cultivated on Yellow Argisol (EMBRAPA, 2013) resulted in a higher foliar P content, when compared with the use of filter cake together with bagasse and ash (Santos et al., 2009). Meanwhile, no differences were found in foliar P concentrations among sugarcane plants treated with mineral P (TS) at a rate of 119 kg ha^{-1} P_2O_5 and plants treated with 92 kg ha^{-1} of TS and 15 Mg ha^{-1} of filter cake (Bokhtiar et al., 2008).

In the present study, the effect of the mineral fertilizer with the application of filter cake may be related to the release of amino acids from the filter cake, which can saturate and/or block P adsorption sites on soil particles, thus increasing its availability to plants (Lee and Kim, 2007).

3.2. Effects of fertilizer and filter cake on acid phosphatase activity in sugarcane leaves

Acid phosphatase activity in sugarcane leaves was affected by the interaction of filter cake with P sources and rates (Table 2). Because acid phosphatase activity increases as P decreases, the enzyme's activity is considered an indicator of P levels in plants (McLachlan et al., 1987; Silva and Basso, 1993; Yun and Kaeppler, 2001).

The application of P in the forms of TS and BP produced greater reductions in acid phosphatase activity, when compared with the use of AP (Fig. 3), especially when applications were associated with the filter cake (Fig. 3a). The use of TS rates in combination with filter cake resulted in the lowest acid phosphatase activity (Fig. 3b). This treatment produced an activity level of 166.9 mol min^{-1} mg^{-1} (Fig. 3a) and 163.3 mol min^{-1} mg^{-1} at the highest P application rate (Fig. 3b).

In addition, acid phosphatase activity was significantly negatively correlated with P concentration in both plants and aerial plant parts (Table 3).

3.3. Effects of fertilizer and filter cake on P accumulation in sugarcane aerial plant parts

Phosphorus accumulation in aerial plant parts (leaves and stalks) was influenced by the interaction of the filter cake both with P sources and rates, as well as by sources and rates (Table 2). The increased concentration of P in aerial parts was positively correlated with P content in the plant (Table 3), when the mineral fertilizer was applied alone (TS), an accumulation of 13.6 kg ha^{-1} of P was verified in the aerial parts (Fig. 4a). This value is lower than that reported by Franco et al. (2008), who found an accumulation of 19 kg ha^{-1} of P in sugarcane aerial parts (variety SP81 3250) cultivated in Red Latosol (EMBRAPA, 2013).

These differences are likely the result of different environmental conditions during the cultivation period between the present and above mentioned study. The application of filter cake and TS resulted in the highest P accumulation in aerial parts, at 15.1 kg ha^{-1} (Fig. 4a), which led to the highest foliar P content for this treatment (Fig. 2a).

Phosphorus levels in aerial parts were similar among the different rates and increased linearly with nutrient accumulation, especially in the presence of the filter cake (Fig. 4b). The greatest accumulation of P in aerial plant parts was 17.8 kg ha^{-1}, obtained by combining 360 kg ha^{-1} of P_2O_5 (the highest P rate) with filter cake (Fig. 4b).

With the application of 150 kg ha^{-1} of P_2O_5 to the RB92 579 variety, Calheiros et al. (2011) noticed a P accumulation of 14.3 kg ha^{-1} in aerial plant parts. In other studies, 32 kg ha^{-1} of P accumulated in the aerial parts of the variety SP81 3250 cultivated in Red Latosol (EMBRAPA, 2013), and fertilized with 120 kg ha^{-1} of P_2O_5 (Franco et al., 2008). Meanwhile, with the application of TS at a rate of 150 kg ha^{-1} of P_2O_5 to RB86 7515 grown in Yellow Latosol (EMBRAPA, 2013), a P accumulation of 14.5 kg ha^{-1} in aerial plant parts was observed (Calheiros et al., 2012). In the present study, TS stood out from the other P sources (Fig. 4c); the application of 360 kg ha^{-1} of P_2O_5 in the form of TS resulted in the greatest accumulation of P in aerial plant parts (18.8 kg ha^{-1}). The greatest accumulation of P verified for this treatment combination is also associated with the greatest increase in foliar P concentration (Fig. 2b).

Table 2
Average values of P concentrations in sugarcane leaves, acid phosphatase in leaves, accumulation of P in aerial parts (leaves and stalks), photosynthesis, stomatal condutance, transpiration, stalk production, total recoverable sugar, hydrated alcohol and total soluble solids (°Brix) as function of fertilization with different sources and rates of P in the absence and presence of sugarcane filter cake.

Treatments	PCL[a] g kg^{-1}	APL[b] nmol min^{-1} mg^{-1}	AAP[c] kg ha^{-1}	A[d] μmol m^{-2} s^{-1}	g_s[e] mmol m^{-2} s^{-1}	E[f]	Stalk Production Mg ha^{-1}	TRS[g] kg t^{-1}	Hydrated alcohol L t^{-1}	°Brix %
Sugarcane filter cake (F)										
Presence	1.56^{a}	178.8^{b}	12.9^{a}	25.6	205.0	2.6	120.8^{a}	176.9^{a}	90.35^{a}	17.55^{a}
Absence	1.46^{b}	196.1^{a}	10.3^{b}	21.7	181.8	2.5	112.8^{b}	169.2^{b}	88.44^{b}	17.14^{b}
MSD (5%)	0.02	3.64	0.71	4.15	10.54	0.35	4.37	6.80	1.69	0.25
F test	37.61^{**}	91.77^{**}	54.72^{**}	3.76	2.07	0.13	13.48^{**}	5.25^{*}	5.23^{*}	10.71^{**}
Sources (S)										
Triple Superphosphate (TS)	1.61^{a}	177.5^{c}	14.3^{a}	22.8	180.2	2.5	117.5	173.6	89.6	17.40
Bayovar Phosphate (BP)	1.49^{b}	189.7^{b}	10.8^{b}	25.1	193.3	2.5	115.9	172.6	89.6	17.34
Araxa Phosphate (AP)	1.42^{c}	195.2^{a}	9.8^{c}	23.0	206.2	2.5	117.0	172.9	89.0	17.30
MSD (5%)	0.04	5.37	1.05	6.12	10.92	0.52	6.44	10.33	2.50	0.37
F test	47.13^{**}	33.76^{**}	61.25^{**}	0.53	0.84	0.03	0.18	0.03	0.19	0.21
Rates (R)										
0 kg ha^{-1} P_2O_5	1.27	196.3	6.0	23.1	90.0	1.2	105.1	154.8	86.8	16.90
90 kg ha^{-1} P_2O_5	1.42	195.5	10.0	23.8	182.1	2.5	110.7	164.0	88.6	17.25
180 kg ha^{-1} P_2O_5	1.51	188.2	11.6	24.0	196.5	2.5	117.1	172.4	89.2	17.30
360 kg ha^{-1} P_2O_5	1.58	178.8	13.3	27.7	201.7	2.6	122.6	182.7	90.3	17.50
MSD (5%)	0.48	5.80	1.40	6.65	12.7	0.60	6.95	10.4	3.67	0.39
F test	30.54^{**}	28.64^{**}	29.40^{**}	3.92^{*}	4.29^{*}	7.0^{*}	10.13^{**}	10.34^{**}	1.40	1.30
				F Test						
(F) × (S)	4.17^{*}	5.56^{**}	4.69^{*}	1.18	0.10	0.57	1.39	2.37	1.15	2.23
(F) × (R)	5.64^{**}	1.82	6.98^{**}	3.17	1.31	1.32	11.88^{**}	12.43^{**}	0.08	0.64
(S) × (R)	2.47	2.81^{*}	4.06^{**}	1.15	1.02	2.54	12.19^{**}	9.38^{**}	2.80^{*}	5.32^{**}
(F) × (S) × (R)	1.12	2.86^{*}	4.00^{**}	0.78	0.36	2.02	8.66^{**}	7.27^{**}	1.25	1.04
Average Residue Square	0.05	43.81	1.67	56.91	3.73	0.41	6.31	15.30	9.42	0.22
C.V. (%)	4.0	3.5	11.4	32.0	32.4	25.4	6.8	7.2	3.4	2.70

$^{**;*}$ Significant at $p < 0.01$ and $p < 0.5$ respectively.
PCL[a]: Phosphorus concentrations in leaves.
APL[b]: acid phosphatase in leaves.
AAP[c]: accumulation in aerial parts.
A[d]: photosynthesis.
g_s[e]: stomatal conductance.
E[f]: transpiration.
TRS[g]: total recoverable sugar.

3.4. Effects of fertilizer and filter cake on gaseous exchange in sugarcane plants

Increased P levels led to increased photosynthesis, stomatal conductance, and transpiration (Table 2). Photosynthesis rates were highly correlated with stomatal conductance and plant transpiration (Table 3).

The induction of photosynthetic activity, stomatal conductance, and transpiration due to P has been verified in rice (*Oryza sativa* L.), brachiaria, sugarcane, and barley (*Hordeum vulgare* L.) plants (Yong-fu et al., 2006; Kuwahara and Souza, 2009; Sato et al., 2010; Zribi et al., 2011). The observed low rates of photosynthesis are due to a decrease in ATP synthesis in chloroplasts, resulting from the limited availability of free cytoplasmic inorganic P (P_i). P_i is replaced by the triose P of the chloroplast in the case of P transporters, which use P_i as a substrate

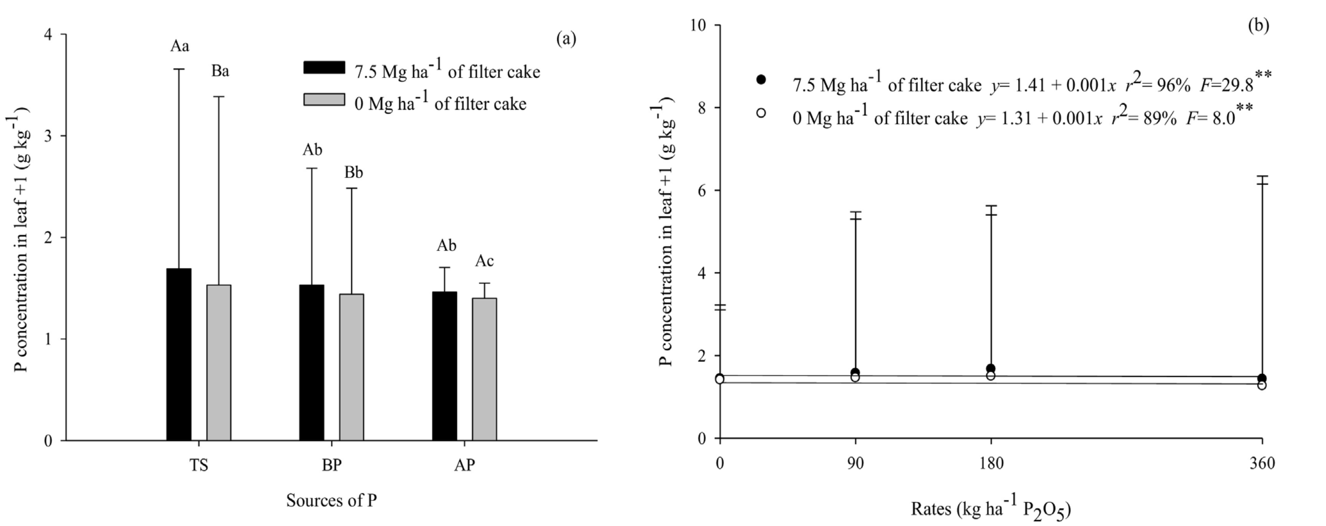

Fig. 2. Phosphorus (P) concentrations in sugarcane leaves as a function of P sources in the absence and presence of sugarcane filter cake (a); P rates in the absence and presence of sugarcane filter cake (b). Capital letters refer to the presence of sugarcane filter cake and lowercase letters refer to P sources, with significance by the *F* test (5% probability) and MSD (5%) for sugarcane filter cake (0.05) and P sources (0.06). ** – Significant by the *F* test, 1% probability.

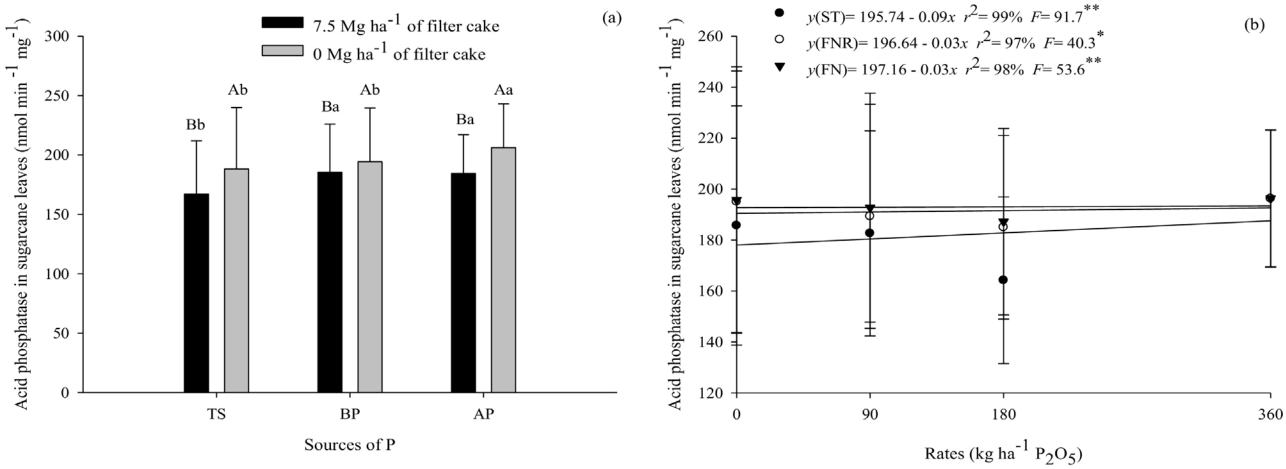

Fig. 3. Acid phosphatase in sugarcane leaves, as a function of P sources in the absence and presence of sugarcane filter cake (a) as a function of P rates as Triple Superphosphate-TS, Bayovar Phosphate-BP and Araxa Phosphate-AP (b). Capital letters refer to sugarcane filter cake and lowercase ones refer to P sources by the Tukey test (5% probability) and MSD (5%) for sugarcane filter cake (6.30) and for P sources (7.59). ** and * – Significant by the *F* test, 1% and 5% probability, respectively.

Table 3
Correlation coefficients among foliar P concentration, acid phosphatase levels, P concentration in aerial parts, photosynthesis (A), stomatal conductance (g_s), and transpiration (E) in sugarcane.

Attributes	Foliar P	Acid phosphatase	P in aerial parts	A	g_s
Acid phosphatase	−0.66**	–	–	–	–
P in aerial parts	0.76**	−0.67**	–	–	–
A	0.15	−0.02	0.20	–	–
g_s	0.07	0.02	0.06	0.66**	–
E	0.16	0.03	−0.04	0.40**	0.63**

** Significant at $p < 0.01$.

(Flügge et al., 2003). In addition, P deficiency in plants reduce the number and efficiency of thylakoids and stromal processes, affecting photosynthesis (Lauer et al., 1989; Chiera et al., 2002).

In terms of productivity, low P supplies result in reduced leaf area, limiting leaf expansion (Chiera et al., 2002). The P uptake led to a greater leaf area, resulting in higher stalk yields, as a direct result of the increase in transpiration activity, which also corroborates with the showed in the present study (Santos et al., 2009).

3.5. Effects of mineral fertilizer and filter cake on stalk production, total recoverable sugar, hydrated alcohol, and total soluble solids in sugarcane plants

Filter cake interactions with P sources and rates influenced stalk production (Table 2), the application of filter cake with the highest P rate produced 122.6 Mg ha^{-1} of stalks, a result higher than that obtained with the use of 360 kg ha^{-1} of P_2O_5, which resulted in 118.4 Mg ha^{-1} of stalks (Fig. 5a). This result may be related to the P content in the compost (equivalent to 52 kg ha^{-1} of P_2O_5) and to high values of P obtained with the application of filter cake.

The significant stalk production observed with the use of filter cake was found for a sugarcane system harvested at 12 months. Thus, it may not be comparable with ratoon-cane systems, as they are different cropping systems in which plants grow and develop differently, suggesting that the evaluation of ratoon culture is necessary.

Caione et al. (2015) verified that the association between 180 kg ha^{-1} of P_2O_5 and filter cake (7.5 Mg ha^{-1}, dry weight), produced greater quantities of stalks (239.4 Mg ha^{-1}) in sugarcane CTC 15 cultivated in eutrophic Red Argisol. Additionally, Shankaraiah and Kalyana (2005) observed that the application of 15 Mg ha^{-1} (dry weight) of filter cake enriched with microorganisms that solubilize P, produced a 21% increase in stalk productivity while reducing the need for chemical fertilizers by 50%.

Regarding the interaction of sources and rates of P, a linear response was found for stalk production, with the highest values found for TS (123.1 Mg ha^{-1}) and BP (106.2 Mg ha^{-1}), suggesting that these sources are more efficient than AP (Fig. 5b). No effect was identified with the use of AP.

The greater stalk production obtained using BP and TS may be correlated to both the increased P in leaf (Fig. 2a) and the accumulation of the element in aerial plant parts (18.8 kg ha^{-1}; Fig. 4c). Moda et al. (2015) verified a stalk production of 189.6 Mg ha^{-1} in the variety RB 855453 applying 360 kg ha^{-1} of P_2O_5 as Triple Superphosphate, although no effect occurred using the same Araxa Phosphate rates, producing a stalk yield of 153.2 Mg ha^{-1}. Highlighting the importance of phosphate fertilization for sugarcane, Caione et al. (2013) found an increase of 34% in stalk production by applying 100 kg ha^{-1} of P_2O_5 as Triple Superphosphate to variety IAC86-2480, cultivated in Typic Latosol.

The P rates associated with filter cake had a linear effect on total recoverable sugar (TRS), both in the presence and absence of the compost, with the rate of 360 kg ha^{-1} P_2O_5 resulting in a production of 197.1 and 176.1 kg t^{-1} of sugar, respectively (Fig. 6a). TRS also displayed a linear effect for both sources and rates of P, where the rate of 360 kg ha^{-1} P_2O_5 (TS) produced a TRS of 192.5 kg t^{-1}, while at the same rate, BP and AP sources displayed a TRS of 191 and 186.5 kg t^{-1}, respectively (Fig. 6b).

With the exclusive application of 135 kg ha^{-1} P_2O_5 (Triple Superphosphate) on variety CTC 3 in a Dark Red Latosol, Vazquez et al. (2015) observed a TRS of 152.7 kg t^{-1} of sugar; using only 10 Mg ha^{-1} of filter cake, the authors verified a TRS of 139.7 kg t^{-1}.

The variation between TRS values obtained for the filter cake treatment support the study by Almeida Júnior et al. (2011), who observed that the chemical composition of filter cake is dependent on both the variety and maturity of sugarcane, soil type, and juice clarification process, among other factors.

Albuquerque et al. (2016) when applying 114 kg ha^{-1} of P_2O_5 (Triple Superphosphate), verified a TRS of 161.6 kg t^{-1} for variety RB92579, grown in dystrophic Yellow Latosol. This value is lower than the result verified in the present study and that obtained by Franco et al. (2010), who used 180 kg ha^{-1} P_2O_5 for variety RB 85-5536 grown in dystrophic Argisol and found a production of 163 kg t^{-1} of recoverable sugar.

Chiba et al. (2009) also found lower values of TRS compared with the present study, reporting 153.4 kg t^{-1} of TRS for variety SP83 2847

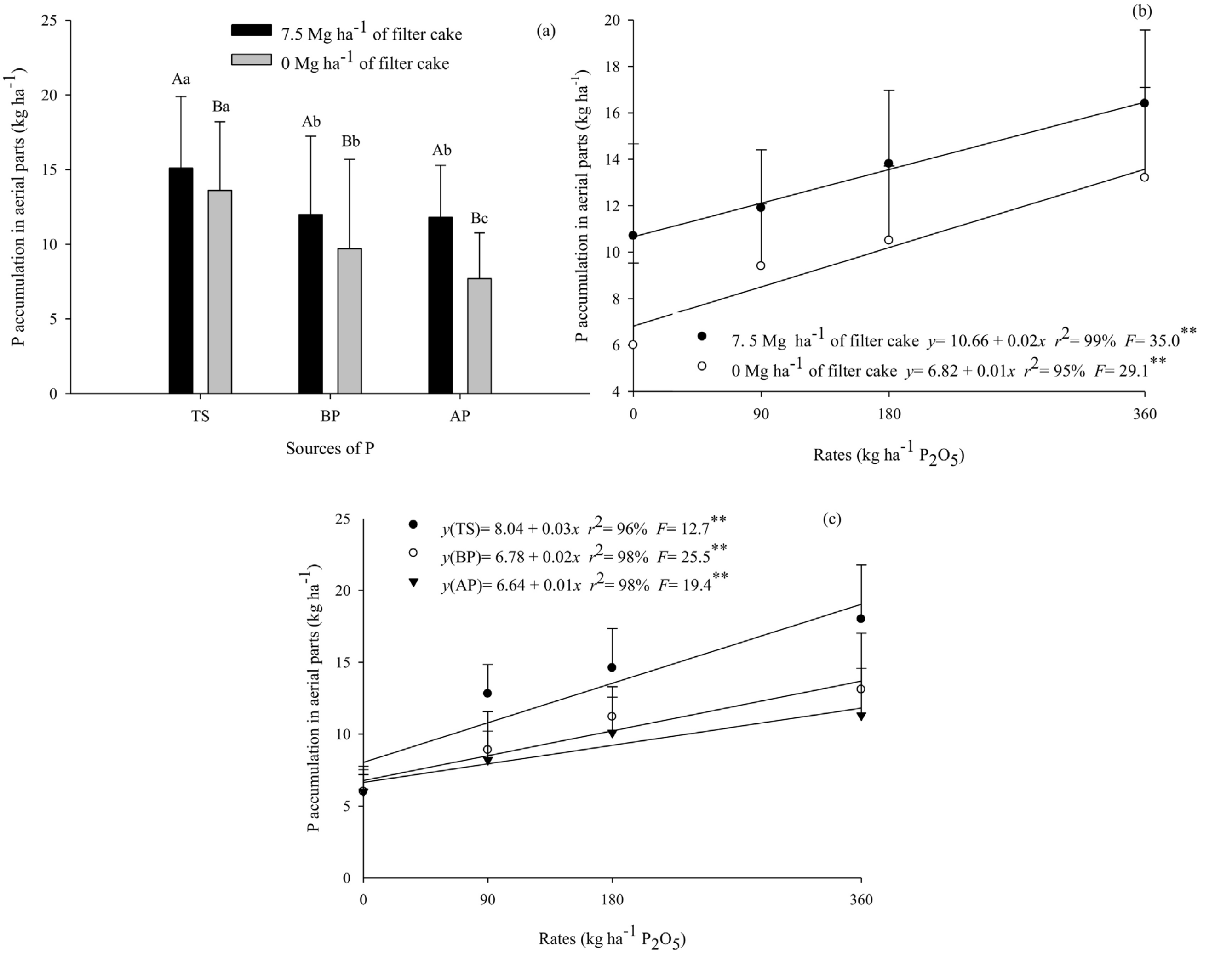

Fig. 4. Phosphorus accumulation in sugarcane aerial parts, as a function of P sources in the absence and presence of sugarcane filter cake (a) as a function of P rates in the absence and presence of sugarcane filter cake (b) and as a function of P rates as Triple Superphosphate-TS, Bayovar Phosphate-BP and Araxa Phosphate-AP (c). Capital letters refer to sugarcane filter cake and lowercase ones refer to P sources by the Tukey test (5% probability) and MSD (5%) for sugarcane filter cake (1.23) and for P sources (1.48). ** and * – Significant by the *F* test, 1% and 5% probability, respectively.

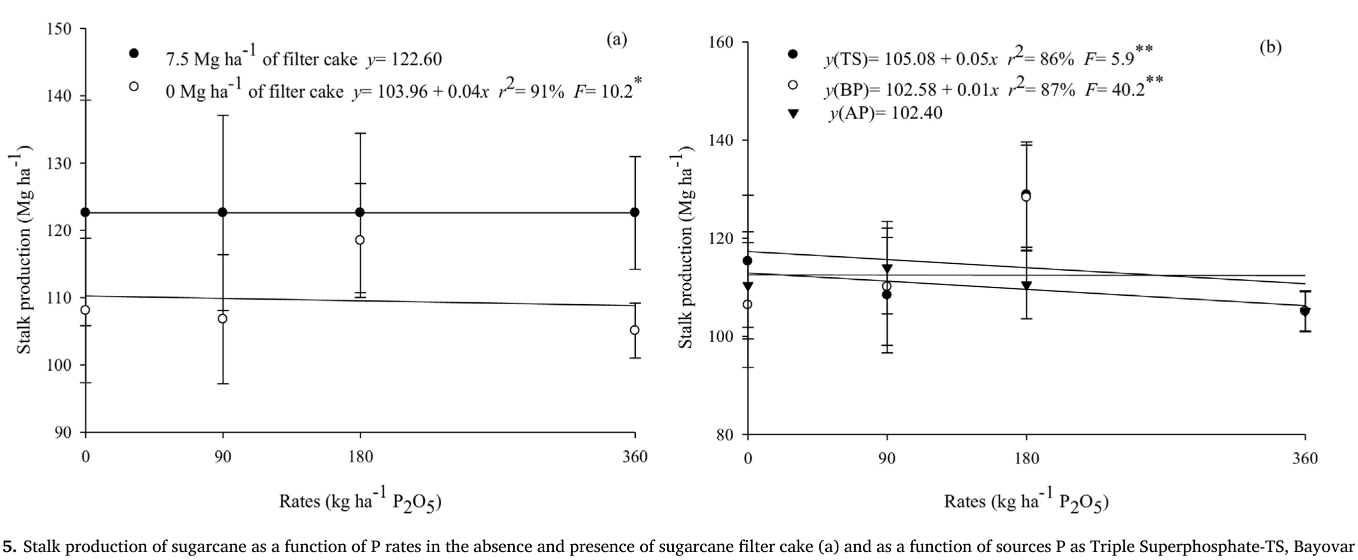

Fig. 5. Stalk production of sugarcane as a function of P rates in the absence and presence of sugarcane filter cake (a) and as a function of sources P as Triple Superphosphate-TS, Bayovar Phosphate-BP and Araxa Phosphate-AP (b). ** and * – Significant by the *F* test with a 1 and 5% probability, respectively.

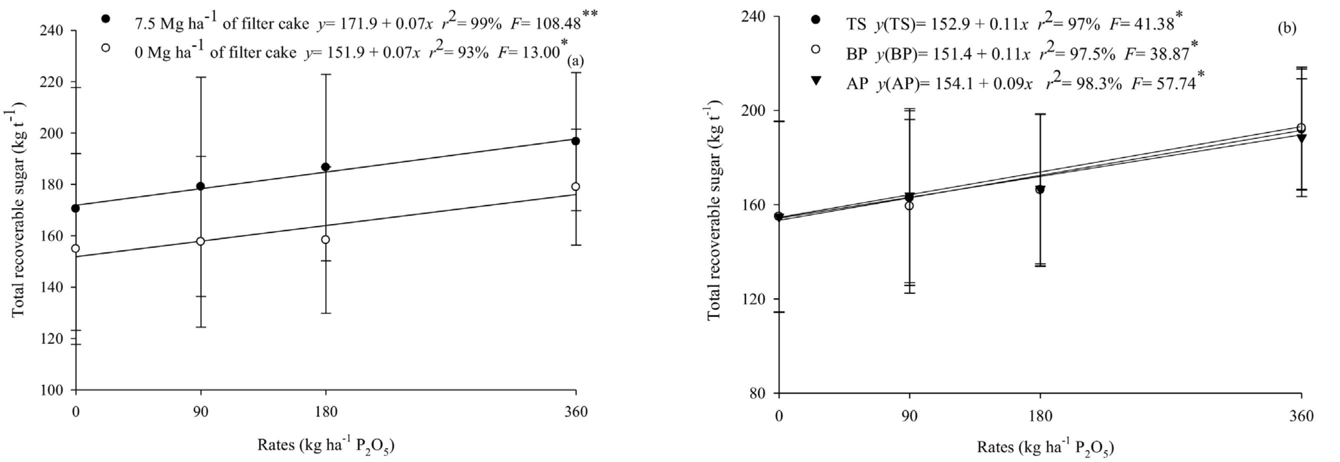

Fig. 6. Total recoverable sugar as a function of P rates in the absence and presence of sugarcane filter cake (a) and as a function of sources P as Triple Superphosphate-TS, Bayovar Phosphate-BP and Araxa Phosphate-AP (b). ** and * – Significant by the *F* test with a 1 and 5% probability, respectively.

with the application of 180 kg ha^{-1} of P_2O_5 (Triple Superphosphate) in Red-Yellow Argisol.

According to Montanari et al. (2014), the production of total recoverable sugars presents a positive linear relation with P content in sugarcane. It is therefore noteworthy that the treatments that displayed greater P accumulation in plants were filter cake associated with P rates (Fig. 4b), and P sources and rates (Fig. 4c).

The interaction of rates and sources of P promoted a quadratic effect in the production of hydrated alcohol, with the best response obtained with the application of 265.8 kg ha^{-1} P_2O_5 of TS, which produced 91.3 L t^{-1} (Fig. 7). For BP and AP sources, the greater rates of 314.3 and 363.1 kg ha^{-1} P_2O_5 produced 90.2 L t^{-1}.

Adequate levels of N and P in sugarcane are responsible for maximum efficiency in the production of alcohol (Fadel et al., 2014); however, although a few studies assess alcohol production in relation to the use of N and K, there is a lack of scientific analysis of the relation between P and alcohol production. There is, therefore, a clear need for research that assesses the importance of P for increasing the production of hydrated alcohol.

The total soluble solids levels were elevated with increasing rates of P. For TS, the response was quadratic, with a value of 18.4°Brix at the rate of 334.4 kg ha^{-1} P_2O_5. Both BP and AP sources promoted linear effects for this variable, with 17.9 and 17.6°Brix, respectively, at the rate of 360 kg ha^{-1} of P_2O_5 (Fig. 8).

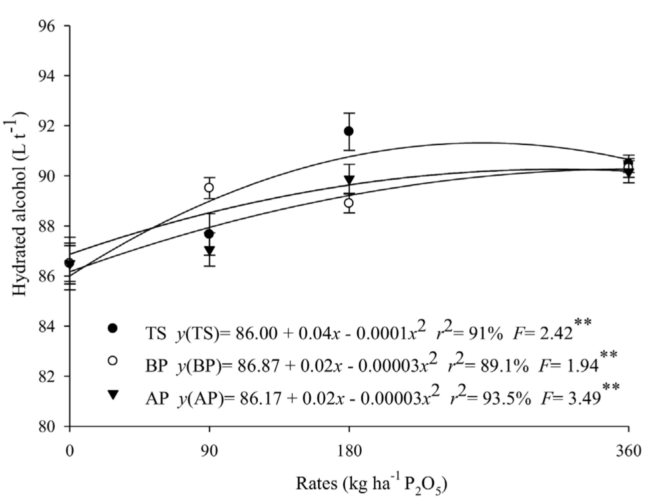

Fig. 7. Hydrated alcohol production of sugarcane as a function of P sources as Triple Superphosphate-TS, Bayovar Phosphate-BP, Araxa Phosphate-AP and P rates. ** and * – Significant by the *F* test with a 1 and 5% probability, respectively.

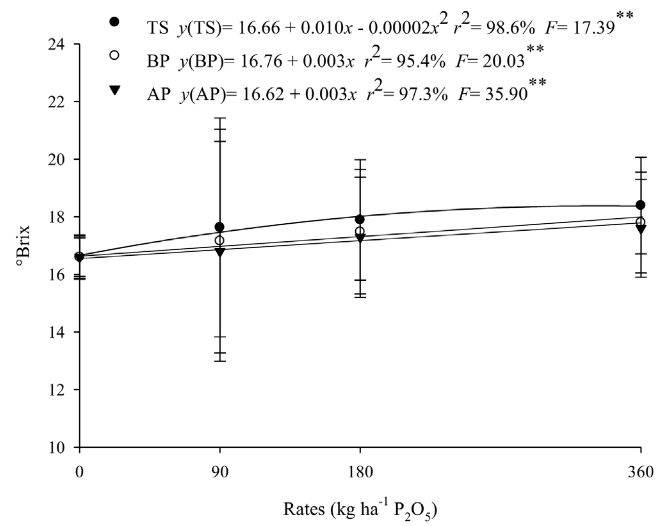

Fig. 8. Total soluble solids as a function of P sources as Triple Superphosphate-TS, Bayovar Phosphate-BP and Araxa Phosphate-AP and P rates. ** and * – Significant by the *F* test with a 1 and 5% probability, respectively.

Using the same sugarcane variety (RB 86 7515), grown in dystrophic Argisol, Santos et al. (2014) verified no effects of P rates (Triple Superphosphate) on total soluble solids. However, with the application of 100 kg ha^{-1} P_2O_5 to varieties IAC 86 2480 and SP 79 1011 grown in Red-Yellow Latosol, Caione et al. (2011) observed an increase of 20.4 and 22.8%, respectively, in total soluble solids. These results support the conclusion of Silveira et al. (2012), who argue that the behavior of most sugarcane genotypes is variable in relation to soil and climatic conditions.

4. Conclusion

The application of P in combination with filter cake increased P content in sugarcane leaves and resulted in its accumulation in aerial plant parts. By using higher P rates in the form of Triple Superphosphate or in combination with filter cake, a decreased acid phosphatase activity was observed, indicating that these treatments supplied adequate P during cellular metabolism. It should be highlighted that acid phosphatase has proved to be a reliable parameter to assess adequate nutritional management of P in sugarcane, thus having significant potential in genetic improvement programs for this crop.

The use of Triple Superphosphate associated with filter cake increased the production of sugar, hydrated alcohol, and total soluble solids. stalk production was greater with the use of filter cake associated the highest P rate and the highest rate of Triple Superphosphate and, while the use of higher P rates, regardless of the source, increased gaseous exchange in sugarcane plants.

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