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Soil phosphorus content classes and energy cane yield under controlled environmental conditions

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ABSTRACT: Phosphorus (P) plays a crucial role in plant metabolism. However, its specific effect on biomass and stalk production in energy cane in tropical soil regions has not yet been fully clarified. This study aimed to evaluate the effect of P application rates on energy cane yield under two water regimes, determine critical soil P levels, and propose interpretive classifications for agronomic and fertilization recommendations. The experiment was conducted in containers in a controlled environment in a randomized block design with four P application rates (0, 60, 180, and 300 kg ha⁻¹ of P₂O₅ applied as triple superphosphate), two water regimes (full irrigation and water deficit irrigation), and two energy cane varieties (Vertex 2 and Vertex 3) in a 4 × 2 × 2 factorial arrangement with three replications. The following factors were analyzed: biometric evaluations, stalk yield, gross sugar yield, definition of critical soil P levels, and classifications of soil P levels. The application rate of 180 kg ha⁻¹ of P₂O₅ provided the best crop growth and yield (174 Mg ha⁻¹ for Vertex 3 and 181 Mg ha⁻¹ for Vertex 2). Critical soil P levels under the water deficit irrigation and full irrigation conditions, respectively, were 18 and 29 mg dm⁻³ P for the linear model, 19 and 29 mg dm⁻³ P for the quadratic model, and 23 and 31 mg dm⁻³ P for the Inverse Mitscherlich model. Soil P levels for deficit irrigation and full irrigation were classified as very low (up to 16 mg dm⁻³, under both irrigation conditions), low (16–23 or 16–31 mg dm⁻³, resp.), intermediate (24–29 or 32–60 mg dm⁻³, resp.), high (30–58 or 61–120 mg dm⁻³, resp.), and very high (>58 or >120 mg dm⁻³, resp.). Energy cane has a higher P nutritional requirement compared with conventional sugarcane, highlighting the need to revise the phosphorus fertilization recommendation criteria. Therefore, the definition of specific P critical levels and content classifications for energy cane is essential to optimize fertilizer use efficiency, reduce environmental impacts, and promote more sustainable production systems.

Keywords: phosphorus fertilization, relative yield, critical P level, biomass production.

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Received: July 31, 2024

Approved: April 25, 2025

How to cite: Rocha JR, Silva DL, Lima RC, Carvalho ML, Passos IF, Capucin V, Ramos ACV, Silva THB, Bressiani JA, Baptista AS, Lavres J, Abreu Junior CH. Soil phosphorus content classes and energy cane yield under controlled environmental conditions. Rev Bras Cienc Solo. 2025;49nspe1:e0240163.

<https://doi.org/10.36783/18069657rbcs20240163>

Editors: Tales Tiecher 

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INTRODUCTION

Sugarcane (*Saccharum officinarum*) cultivation is one of the most widely practiced agricultural systems in tropical regions. Over the past decade, growing energy demand for sugar and ethanol has led to further expansion of this crop across tropical and subtropical areas (Medorio-García et al., 2020). However, extreme weather events such as droughts, heavy rains, heat waves, and tropical cyclones have threatened harvest yields in recent years, and projections are that rainfall in subtropical areas may decrease by up to 20 % by 2100 (Seneviratne et al., 2021; Furtak and Wolińska, 2023; Kumar et al., 2023).

Energy cane, arising from a significant contribution of the *S. spontaneum* genome, may offer advantages over other crops regarding tolerance to water deficit. It has a system of fine, deep, and robust roots that allows these varieties to access water at depth and promote greater carbon storage. Energy cane thus exhibits greater agricultural yield potential, climate resilience, and environmental sustainability (Knoll et al., 2021). However, studies emphasize that although energy cane has good biomass yield, water deficit during the growth phase, both in plant cane and ratoon cane, along with prolonged dry periods in the first months of development, can affect maximum performance potential (Boschiero et al., 2019; Cruz et al., 2021). In conventional sugarcane, water deficit is also a limiting factor for growth and development, leading to declining yields, which have occurred more frequently in recent years (Teixeira et al., 2021).

Together with the need to understand the response of energy cane under different water availability conditions, it is necessary to know the response of these varieties to fertilization. After nitrogen (N), phosphorus (P) is the main limiting nutrient for plant growth. Plants exhibit high demand for mineral or organic fertilizers to achieve competitive agricultural yields in the market, which may result in challenges regarding the economic and environmental sustainability of phosphorus fertilization (Marchi Soares et al., 2021). Studies indicate that energy cane is a variety that grows in marginal areas with low soil fertility. However, planting in marginal areas may have a negative effect on crop yield, especially regarding conditions of phosphorus fertilization management in tropical soils.

Several factors can affect P uptake by roots, including spatial variability, soil P bioavailability, that is, the proportion of total soil P readily available to plants, and the efficiency of acquisition by the plant. The main mechanism responsible for movement of P from the soil to the roots is diffusion (Arruda et al., 2016). In tropical soils, the main reactions that control P bioavailability are adsorption of Fe and Al (oxy)hydroxides to 1:1 clay minerals, and precipitation with Al and Fe (Nascimento et al., 2018; Withers et al., 2018). However, the low availability of phosphorus resulting from these reactions can be overcome by applying high rates of water-soluble phosphate fertilizers. This includes triple superphosphate (TSP), which rapidly increases P concentration in the soil solution, enhancing plant uptake (Marchi Soares et al., 2022).

In sugarcane production systems in Brazil, P uptake by the plant represents only 0 to 20 % of the amount applied in the first crop cycle, mainly due to the physicochemical properties of tropical soils, which lead to immobilization of the nutrient (Abreu Junior et al., 2003; van Raij, 2004). That shows the agronomic challenge of managing fertilizers in environments where the P applied is rapidly bound by the soil, making it unavailable to plants.

Although satisfactory yields are generally associated with applications of 150 to 180 kg ha⁻¹ of P₂O₅, these rates often exceed actual crop requirements, reflecting the inefficient use of phosphorus fertilizers (Marchi Soares et al., 2022). That shows that yield increases have been achieved with high application rates that are not always justified. This can lead to waste of resources and an environmental impact, highlighting the importance of more rational and technically based management practices. This situation reveals the urgency of adopting more precise management strategies that optimize P availability in

the soil and avoid excessive use of that input. It is essential to progress in formulating recommendations based on response curves, critical levels, and sufficiency classes tailored to each crop and growing condition, as shown in this study on energy cane.

Sugarcane is the primary raw material used for bioethanol production in Brazil. Recently, some breeding programs have focused on the energy cane crop to increase bioenergy yield in mills that produce second-generation ethanol (2G ethanol) (Boschiero et al., 2019). However, a critical knowledge gap lies in the absence of studies evaluating the effect of P application rates on crop variables, such as biomass production, juice yield, and juice quality. In addition, information is lacking on the critical soil P threshold that can lead to an increase or decrease in these variables and on the classes of soil P content to determine the P application rate for the energy cane crop.

We hypothesized that supplying P at adequate rates can increase stalk productivity and, consequently, biomass production by energy cane grown in tropical soils, thereby promoting a more sustainable energy transition. This study aimed to evaluate the effect of phosphorus fertilization on stalk productivity of energy cane under full irrigation and deficit irrigation, determine soil P critical levels, and define the soil P content classifications and P availability.

MATERIALS AND METHODS

The experiment was conducted in a greenhouse in the experimental area of the Biosystems Engineering Department of the Universidade de São Paulo - ESALQ/USP in Piracicaba, Brazil (-22° 43' 30" S and 47° 38' 00" W, at 546 m altitude), over 12 months.

The effects of phosphorus fertilization on energy cane growing were evaluated using a 4 × 2 × 2 factorial arrangement. Four application rates (AR) of P₂O₅ were tested: 0, 60, 180, and 300 kg ha⁻¹ of P₂O₅, applied as triple superphosphate. Two water replenishment conditions (I) consisted of 50 % provision (simulating water deficit) and 100 % provision (full irrigation), based on soil water holding capacity (θ_{cc}). Two energy cane varieties (V) were used: Vertex 3 (intermediate sucrose and fiber levels) (V3) and Vertex 2 (high fiber yield) (V2).

A randomized block experimental design was used with three replications. The experimental plot consisted of a container dm³ (concrete box) of 167 dm³, which was waterproofed and equipped with a drainage system. Each container received a pre-sprouted seedling (PSS) of energy cane, acquired through a partnership with Nuseed Brasil S.A. Nitrogen fertilization consisted of 180 kg ha⁻¹ of N applied as urea, and P fertilization of 300 kg ha⁻¹ of K₂O applied as potassium chloride.

The soil used in the present study was chosen because of its low P content (resin-extractable P, 2-2.5 mg dm⁻³), based on previous analysis (Table 1). Chemical analysis (Table 1) corresponds to samples taken from soil layers of 0.00-0.20, 0.20-0.40, and 0.40-0.60 m. A total of 20 individual samples were collected to form a composite sample. After collection, the samples were air-dried and passed through sieves with 2-mm mesh. Soil samples were chemically analyzed for pH in 0.01 mol L⁻¹ CaCl₂, available phosphorus (resin method), exchangeable calcium, magnesium, and potassium, total acidity (H+Al), organic matter, sulfur, and micronutrients (Cu, Fe, Mn, and Zn) extracted with DTPA at pH 7.3. Boron content was also analyzed using the hot water extraction (van Raij et al., 2001). After the area was chosen, soil was collected using a backhoe, digging to a depth of 0.00-0.60 m to fill the containers.

Substrate was amended before setting up the experiment according to Cantarella et al. (2022). Calcium oxide and magnesium oxide were used at a 3 (Ca):1 (Mg) ratio to increase base saturation to 70 %, as recommended for the sugarcane crop. Soil amendment was prepared using analytical grade reagents containing 97 % CaO and 95 % MgO, with a

final total neutralizing power of 189 %. As the soil was collected to a depth of 0.60 m to fill the containers, calculations for soil amendment were based on soil analysis performed for the 0.00-0.60 m soil layer (Table 1). Thus, considering a base saturation of 49 %, 300 kg ha⁻¹ of the soil amendment was required to adjust the soil reaction, which amounted to 48 g of the amendment for each 167 dm³ container. After application of the amendment, the soil was moistened and incubated for 70 days until transplanting the pre-sprouted seedlings (PSS) of the energy cane varieties.

Nitrogen levels were defined based on the rate of 0.8 kg N per ton of stalks, as recommended for sugarcane growing in the South-Central region of Brazil (Otto et al., 2021), corresponding to an expected stalk productivity of 150 Mg ha⁻¹. Phosphorus and K levels were chosen based on the minimum and maximum levels recommended for sugarcane, considering soil analysis and expected yield (Landell et al., 2012). Nitrogen and K fertilization at the respective rates was split, with 25 % applied at planting of the PSSs, 35 % 30 days after transplanting, and 40 % 60 days after transplanting, as topdressing, on the substrate surface around the plant.

A drip irrigation system consisted of a drip line with five emitters at a 0.20-m spacing and a flow rate of 1.6 L h⁻¹ in each experimental unit. Irrigation management was based on monitoring soil matric potential. The 100 % θ_{cc} water replenishment level was estimated for full irrigation by adding up the water amounts required to increase soil moisture to field capacity (van Genuchten, 1980). For the deficit conditions (50 % θ_{cc}), half the full irrigation replenishment level was applied. Differentiation of the irrigation levels began 40 days after transplanting the PSSs to ensure uniform establishment of the seedlings.

Eight months after transplanting, soil was collected from the 0.00-0.20 m soil layer. Four individual samples were collected per experimental unit: two samples at 0.15 m from the stalk and two at 0.30 m from the stalk. Samples were homogenized to form a composite sample representing each experimental unit. Chemical analysis of the substrates was performed as described for initial soil characterization (van Raij et al., 2001).

The energy cane plants were evaluated at 360 days after transplanting the PSSs, at the time of harvest. Plant height was measured with a tape measure, from the base to the tip of the plant, as well as the height of the diagnostic leaf attachment to the stalk; the diagnostic leaf is the third leaf of the whorl, also known as the TVD (Top Visible Dewlap) or +1 leaf (+1L) (Cantarella et al., 2022). A digital caliper was used to measure stalk diameter at the base of the stalk (0.05 m above the soil). Finally, the number of tillers of each experimental unit was counted.

Table 1. Results of the chemical analysis for fertility purposes of the soil used to fill the experimental plots in the greenhouse (concrete boxes with a volume of 167 dm³)

Layer	pH(CaCl ₂)	SOM	P		K ⁺	Ca ²⁺	Mg ²⁺	H+Al	Al ³⁺	BS	CTC	V%	m%
			resin	SO ₄									
m		g dm ⁻³	mg dm ⁻³		mmol _c dm ⁻³								
0.00-0.20	4.65	6	2		0.55	8	5.5	15.5	5	14.5	30	47.5	26.5
0.20-0.40	4.1	5	2	-	0.5	4	3	16	6	8	24	32	44
0.40-0.60	4.0	5	2	-	0.3	4	3	16	5	7	23	31	41
0.00-0.60	4.4	5	2.5	5.5	0.6	7	5	13	3	13	26	49	19.5
		Cu			Fe		Zn		Mn			B	
		DTPA										(hot water)	
0.00-0.60		0.55			43		0.95		5.15			0.1	

⁽¹⁾ Determination of pH in 0.01 mol L⁻¹ CaCl₂ (1:2.5 v/v); available phosphorus, exchangeable calcium, magnesium, and potassium by the resin method; total acidity (H+Al); Soil organic matter (SOM); sulfur; micronutrients (Cu, Fe, Mn, and Zn) extracted with DTPA at pH 7.3; and B by the hot water method.

Plants were partitioned to quantify biomass, that is, they were separated into components for evaluation (stalk, sheath, top, green leaves, and dry leaves). For stalk yield, immediately after cutting the plant and removing the leaves, stalks suitable for processing were weighed on a semi-analytical digital scale to determine fresh stalk biomass (FSB) from each plot. Classification of stalks suitable for processing was done through visual analysis of the plant; tillers not fully developed were not counted. Tillers with stalk diameters and heights three times smaller than the main stalk were also not counted as suitable for processing.

Stalk productivity (Mg ha^{-1}) was calculated using equation 1, considering the FSB of the plot, the soil area of the plot, and the total area available for the canopy, considering the plant corridors, equivalent to 20,000 plants per hectare, at a spacing of 1.35×0.37 m, in which the plants were grown in a greenhouse (adapted from Barbosa, 2015).

$$\text{Stalk productivity} = \text{FSB} \times 21 \quad \text{Eq. 1}$$

Stalks passed through a hydraulic press to extract the juice, which was then analyzed for the following technological variables: total soluble solids (Brix), sucrose content (Pol in the juice), fiber, reducing sugars (RS), purity, total reducing sugars (TRS), and total recoverable sugar (TS). Gross sugar yield, or tons of sugar per hectare (TSuH), was calculated using equation 2, based on the values of TRS and of total recoverable sugar (TS), in kg Mg^{-1} .

$$\text{Sugar yield} = \frac{\text{Stalk productivity} \times \text{TRS}}{1000} \quad \text{Eq. 2}$$

Equation 3, adapted from van Raij (2011), is used to calculate relative stalk yield (RY%) and is based on stalk productivity (tons of stalks per hectare) and the soil P content determined by the resin method, described by Abreu et al. (2001). For each P application rate, the stalk productivity obtained was divided by the stalk productivity corresponding to the application rate considered optimal (180 kg ha^{-1}), which often draws near that recommended by Boletim 100 (Cantarella et al., 2022) to achieve high yield in the sugarcane crop.

$$\text{PRC} = \frac{\text{Stalk productivity (at the dose studied)}}{\text{Stalk productivity (at the optimal dose)}} \times 100 \quad \text{Eq. 3}$$

The following mathematical models were used to determine critical levels: Linear-Plateau (Anderson and Nelson, 1965), Quadratic-Plateau (Litell, Freund, and Saas, 1991), and Inverse Mitscherlich (van Raij, 2011), with soil P content corresponding to 90 % of the RSY; for below that point, a steep reduction in yield occurs.

Soil P classes were determined using the graph method based on van Raij (2011), applying the Inverse Mitscherlich model, which associates the soil P levels with relative stalk yield (RSY). Soil P classes were defined as follows: very low (up to 70 % of RSY), low (from 71 to 90 % of the RSY), and intermediate (from 91 to 100 % of the RSY). The RSY higher than 100 % is defined as the high and very high classes, when no response is expected from phosphorus fertilization. The threshold between the high and very high content classes was determined by multiplying the lower limit of the high content class by 2. Analysis was conducted using equation 4.

$$y = a + \frac{b}{x} \quad \text{Eq. 4}$$

The results for checking the assumptions of normality of variance were tested using the Shapiro-Wilk test (Shapiro and Wilk, 1965), and homoscedasticity was verified using Levene's test. Correlations were analyzed using Pearson's correlations. Means were compared using Tukey's test at a 5 % significance level. Analyses were carried out through the R software version v.3.3.4 (R Development Core Team, 2020) using the Exp Des.pt (Ferreira et al., 2014) and ggplot2 (Wickham, 2011) packages.

RESULTS

Total plant height and height of the +1 leaf (TVD) were altered by AR, V, and I, with plant height showing interaction effects from all interactions and TVD showing interaction effects from AR × I and AR × V × I (Figure 1). The number of tillers, number of stalks suitable for processing, stalk diameter, showed no significant interaction effects (Supplementary Material, Table S1).

The effect of the P application rates on the energy cane varieties showed that 60 and 300 kg ha⁻¹ of P₂O₅ led to greater total plant height in the V3 variety. For the V2 variety, the different application rates did not show differences from each other but showed superior growth only in comparison to unfertilized conditions.

Regarding TVD, both cultivars had longer stalks under the application rate of 180 kg ha⁻¹ of P₂O₅, indicating greater growth. The V3 variety had greater total plant height and higher TVD (Figure 1).

Regarding the effect of the P application rates on energy cane plant growth under different water replenishment levels, differences were observed between the plants that did not receive the fertilizer and those that were fertilized, with the greatest growth under full water replenishment. This growth was particularly evident in the V3 variety under both water replenishment conditions.

Phosphorus application rates and water replenishment affected total biomass yield and stalk productivity. The AR × V interaction affected total biomass production, and the AR × I interaction affected both total biomass and stalk productivity. Total sugar yield increased with P application and water replenishment, and there was an effect from the AR × V and AR × I interactions (Table 2).

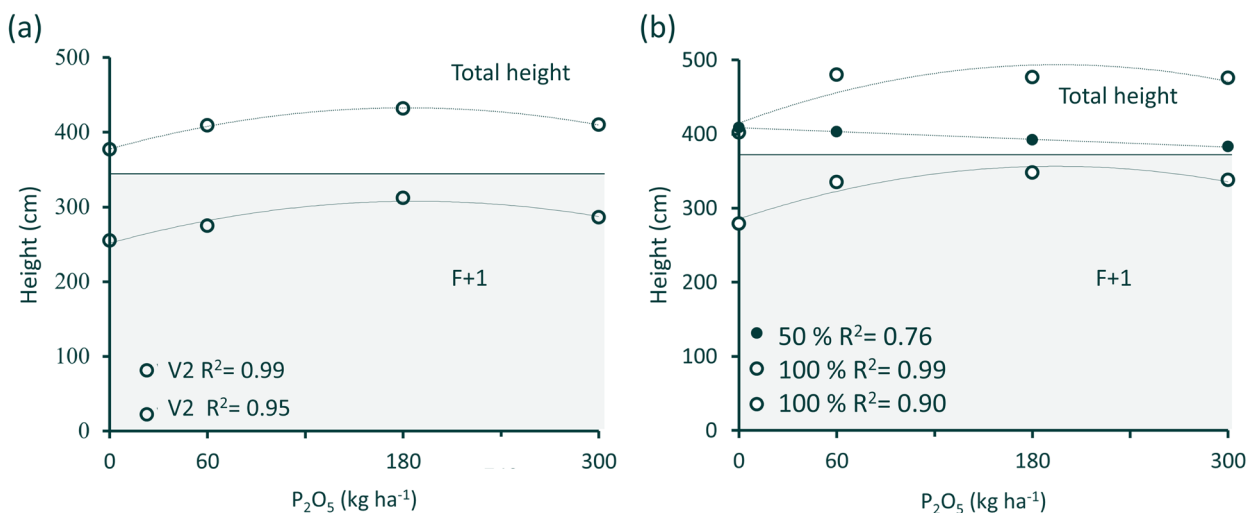


Figure 1. Plant height (a and b) in two energy cane varieties and under two water replacement conditions, as a function of phosphorus fertilization rates. At the top of figures (a and b) are the values for total plant height, and at the bottom are the values for the height of the +1 leaf insertion (TVD). The top parts of the figures show the distribution of points for total plant height, while the bottom parts show the points for the height of the +1 leaf insertion. White circles with black outlines indicate variety V2 (a); black circles with black outlines indicate deficit irrigation - 50 %, and white circles with black outlines indicate full irrigation - 100 % (b)

Table 2. ANOVA results for total biomass productivity (stalk, sheath, green leaves, dry leaves, and top), stalk productivity, juice Brix, fiber content, total recoverable sugars (TRS), and gross sugar yield

Dose P ₂ O ₅	Total biomass		Stalk productivity		Brix		Fiber		TRS		Sugar Yield	
kg ha ⁻¹	Mg ha ⁻¹		Mg ha ⁻¹				%		Mg ha ⁻¹		Mg ha ⁻¹	
	V3	V2	V3	V2	V3	V2	V3	V2	V3	V2	V3	V2
0	118.16 ^{bA}	89.66 ^{cB}	70 ^{cA}	68.66 ^{cA}	13.76 ^{aA}	9.76 ^{aB}	12.92 ^{NS}	13.59 ^{NS}	67.22 ^{cA}	70.97 ^{cA}	4.46 ^{cA}	4.7 ^{cA}
60	129.66 ^{bA}	138.33 ^{bA}	119.33 ^{bA}	116.33 ^{bA}	14.06 ^{aA}	12.75 ^{bB}	13.02 ^{NS}	14.72 ^{NS}	77.36 ^{aA}	76.19 ^{bcA}	8.8 ^{cA}	9.1 ^{cA}
180	174.5 ^{aA}	181 ^{aA}	153.33 ^{aA}	145.33 ^{aA}	13.53 ^{aA}	11.16 ^{bB}	12.83 ^{NS}	14.22 ^{NS}	69.93 ^{abB}	80.79 ^{abA}	10.68 ^{abB}	12.23 ^{aA}
300	190.16 ^{aA}	184.33 ^{aA}	146.66 ^{aA}	149.66 ^{aA}	13.88 ^{aA}	11.14 ^{bB}	13.26 ^{NS}	14.05 ^{NS}	69.9 ^{abB}	87.5 ^{aA}	10.6 ^{abB}	13.05 ^{aA}
	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %
0	65.16 ^{cB}	142.66 ^{bA}	45.66 ^{bB}	93 ^{cA}	11.6 ^{NS}	11.92 ^{NS}	12.99 ^{NS}	13.52 ^{NS}	73.54 ^{abA}	64.64 ^{bB}	3.36 ^{bB}	5.8 ^{cA}
60	109.5 ^{bB}	158.5 ^{bA}	94.5 ^{ab}	141.16 ^{bA}	13.65 ^{NS}	13.16 ^{NS}	13.75 ^{NS}	14 ^{NS}	81.53 ^{aA}	72.02 ^{bB}	7.71 ^{abB}	10.18 ^{bA}
180	135 ^{ab}	236.16 ^{aA}	107.66 ^{ab}	191 ^{aA}	13.08 ^{NS}	11.6 ^{NS}	13.6 ^{NS}	13.45 ^{NS}	69.7 ^{bB}	81.02 ^{aA}	7.53 ^{abB}	15.38 ^{aA}
300	133 ^{ab}	225.83 ^{aA}	103.66 ^{ab}	192.66 ^{aA}	13.2 ^{NS}	11.83 ^{NS}	13.43 ^{NS}	13.88 ^{NS}	75.77 ^{abB}	81.62 ^{aA}	7.93 ^{abB}	15.71 ^{aA}
	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %	50 %	100 %
V3	186.97 ^{aA}	194.58 ^{aA}	151.42 ^{aA}	157.57 ^{aA}	14.49 ^{aA}	13.11 ^{ab}	13.13 ^{NS}	12.89 ^{NS}	77.47 ^{aA}	64.73 ^{bB}	6.75 ^{abB}	10.51 ^{bA}
V2	109.8 ^{bA}	111.45 ^{aA}	88.43 ^{bA}	87.18 ^{bA}	11.26 ^{bA}	11.13 ^{aA}	13.76 ^{NS}	14.53 ^{NS}	72.8 ^{bB}	84.92 ^{aA}	6.51 ^{abB}	13.02 ^{aA}
D	0.0001**		0.0001**		0.0043**		0.5485 ^{NS}		0.0009**		0.0001**	
V	0.24 ^{NS}		0.37 ^{NS}		0.0001**		0.0008**		0.001**		0.004**	
I	0.0001**		0.0001**		0.0154**		0.384 ^{NS}		0.8419 ^{NS}		0.0001**	
D x V	0.0069**		0.51 ^{NS}		0.0244**		0.5831 ^{NS}		0.001**		0.0261**	
D x I	0.0005**		0.0001**		0.1242 ^{NS}		0.8591 ^{NS}		0.0001**		0.0001**	
V x I	0.0407**		0.0115**		0.0406**		0.1052 ^{NS}		0.0001**		0.0001**	
D x V x I	0.058 ^{NS}		0.013 ^{NS}		0.0596 ^{NS}		0.857 ^{NS}		0.0001**		0.0001**	
CV (%)	9.37		7.39		15.26		7.75		7.13		10.65	

V3 (Vertex 3), V2 (Vertex 2). D: doses; V: variety; I: irrigation. * and (p≤0.05); ** (p≤0.01); and NS: not significant. The F-test was applied. Tukey's test was applied. Lowercase letters indicate significant differences within the same variety or irrigation condition across the four levels of potassium fertilization (column). Uppercase letters indicate significant differences between varieties or irrigation conditions at the same phosphorus fertilization dose (row). n = 3.

The Brix levels of the juice were affected by the P application rates, by the energy cane varieties, and by the water replenishment levels; and effects were observed for the AR × V and AR × I interactions. Only the varieties differed for fiber content under the water replenishment conditions, without interactive effects among the treatments. The TS, in turn, did not change with the irrigation differences; however, it was affected by all the other factors and by the AR × V × I interaction. The TSuH was affected by AR, V, and I, as well as by all the AR × V × I interactions (Table 2).

The application rates of 180 and 300 kg ha⁻¹ of P₂O₅ led to the largest accumulations of fresh biomass in the energy cane varieties. The V3 achieved average yields of 174 and 190 Mg ha⁻¹, and V2 achieved yields of 181 and 184 Mg ha⁻¹ (Table 2), representing increases of up to 62 % for V3 and 48 % for V2 compared to unfertilized plants. For stalk yield, the increases were up to 48 % for V3 and 46 % for V2. The V3 was the variety with the highest total biomass yield and stalk productivity per hectare under phosphorus fertilization.

For Brix and fiber, the P application rates did not significantly affect the response of the varieties, and irrigation levels likewise did not significantly affect Brix and fiber according to the fertilizer application rates. However, for V2, Brix was lower without P fertilization compared with plants that received fertilizer (Table 2).

The application rates that brought about higher gross sugar yields were 180 and 300 kg ha⁻¹ of P₂O₅, with average yields of 10 Mg ha⁻¹ for the V3 variety and 13 and 12 Mg ha⁻¹ for the V2 variety. Phosphorus fertilization resulted in an increase of up to 42 % for V3 and 36 % for V2 compared with plants that did not receive the fertilizer (Table 2 and Figure 2).

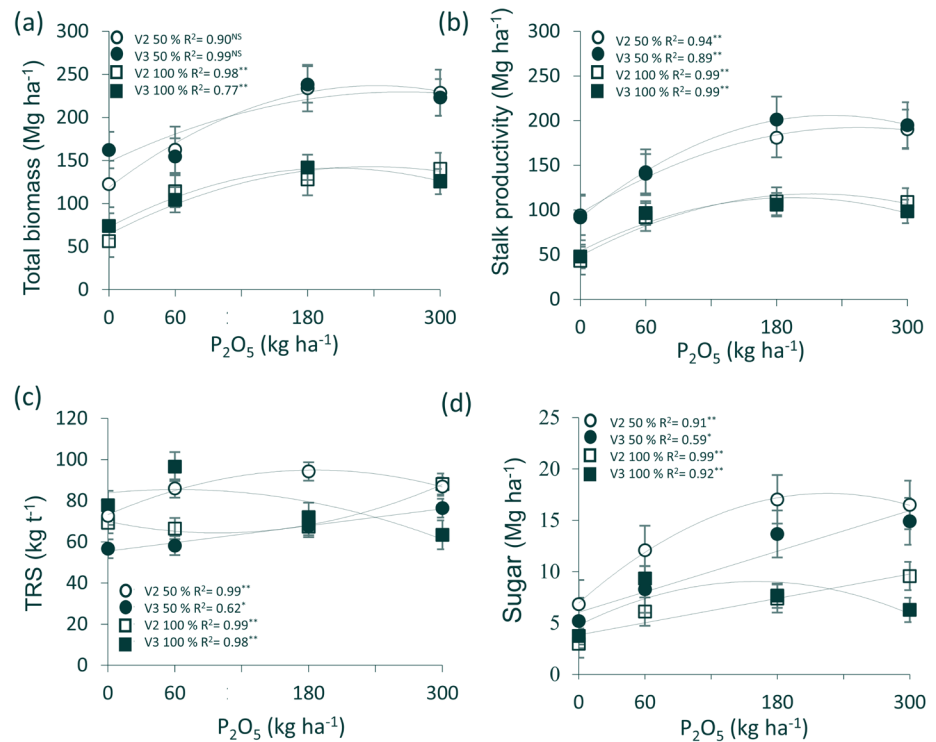


Figure 2. Total biomass productivity (a); stalk productivity (b); total recoverable sugars (TRS) (c); and gross sugar yield (d) in two energy cane varieties and under two water replacement conditions, as a function of phosphorus fertilization rates. White circles with black outlines indicate V2 grown under deficit irrigation - 50 %; black circles with black outlines indicate V3 grown under deficit irrigation - 50 %; white squares with black outlines indicate V2 grown under full irrigation - 100 %; and black squares with black outlines indicate V3 grown under full irrigation - 100 %.

Water replenishment similarly affected total biomass yield and stalk productivity as a function of P₂O₅ application rates (Table 2). Biomass yield increased by up to 48 and 42 % under water deficit conditions (50 % water replenishment) and by up to 63 and 48 % under full irrigation, comparing the plants that received the application rates of 180 and 300 kg ha⁻¹ of P₂O₅ to plants that did not receive fertilizer. Full water replenishment resulted in higher yields compared with water deficit conditions.

Water replenishment as a function of the P application rates also had a direct effect on gross sugar yield, leading to an increase of up to 42 % under 50 % water deficit conditions and up to 36 % under full irrigation conditions when comparing the higher P supply conditions with the unfertilized plant conditions. Growing under full irrigation conditions led to higher gross sugar yields than the water deficit conditions for V3 and V2. However, the varieties did not exhibit significant differences within the same level of water replenishment.

Total biomass showed a higher yield at the P application rate of 180 kg ha⁻¹ of P₂O₅ for both deficit and full irrigation (Figure 2a) (Table 2). The optimal application rates were 235 and 243 kg ha⁻¹ of P₂O₅ for V2 and 209 and 276 kg ha⁻¹ of P₂O₅ for V3 under deficit irrigation and full irrigation conditions, respectively (Figure 2a). Total stalk productivity exhibited a second-degree polynomial fit, higher yields, and better technological quality under full irrigation conditions (Figure 2b). Optimal application rates were 216 and 251 kg ha⁻¹ of P₂O₅ for V2 and 192 and 296 kg ha⁻¹ of P₂O₅ for V3 under the 50 and 100 % water replenishment conditions, respectively (Figure 2b).

The effect of the application rates on TS peaked at the application rate of 60 kg ha⁻¹ for V3 under water deficit conditions. For V2, the highest values of TS were observed at the application rate of 180 kg ha⁻¹ of P₂O₅, with maximum yield at the application rate of 194 kg ha⁻¹ of P₂O₅ under full irrigation conditions (Figure 2c).

The TSuH fit a second-degree polynomial response to P application rates for V3, with the highest TSuH at 132 kg ha⁻¹ of P₂O₅ under water deficit conditions, and a linear increase from the application rates under full irrigation conditions. For V2, the TSuH showed a linear response as application rates increased under 50 % irrigation conditions and showed a quadratic effect from the application rates under 100 % irrigation conditions, peaking at the application rate of 180 kg ha⁻¹ of P₂O₅ (Figure 2d).

For the growing conditions, whether deficit irrigation or full irrigation, the relative stalk productivity response to soil P levels was obtained to determine the critical levels in the models tested. For the Linear-Plateau model (Figures 3a and 3b) under the water deficit and full irrigation growing conditions, a linear increase in relative yield is observed as soil P concentrations increase, up to the point at which the curve stabilizes, representing a plateau set at 90 % of maximum yield. The critical levels of 18 and 29 mg dm⁻³ P were defined for the two growing conditions. For the Quadratic-Plateau model (Figures 3c and 3d), relative yield showed a curvilinear response, with a progressive increase until reaching the plateau corresponding to 90 % of maximum yield. Under water deficit, the estimated critical level was 19 mg dm⁻³ P (Figure 3c). Under full irrigation conditions, the critical level was 29 mg dm⁻³ (Figure 3d).

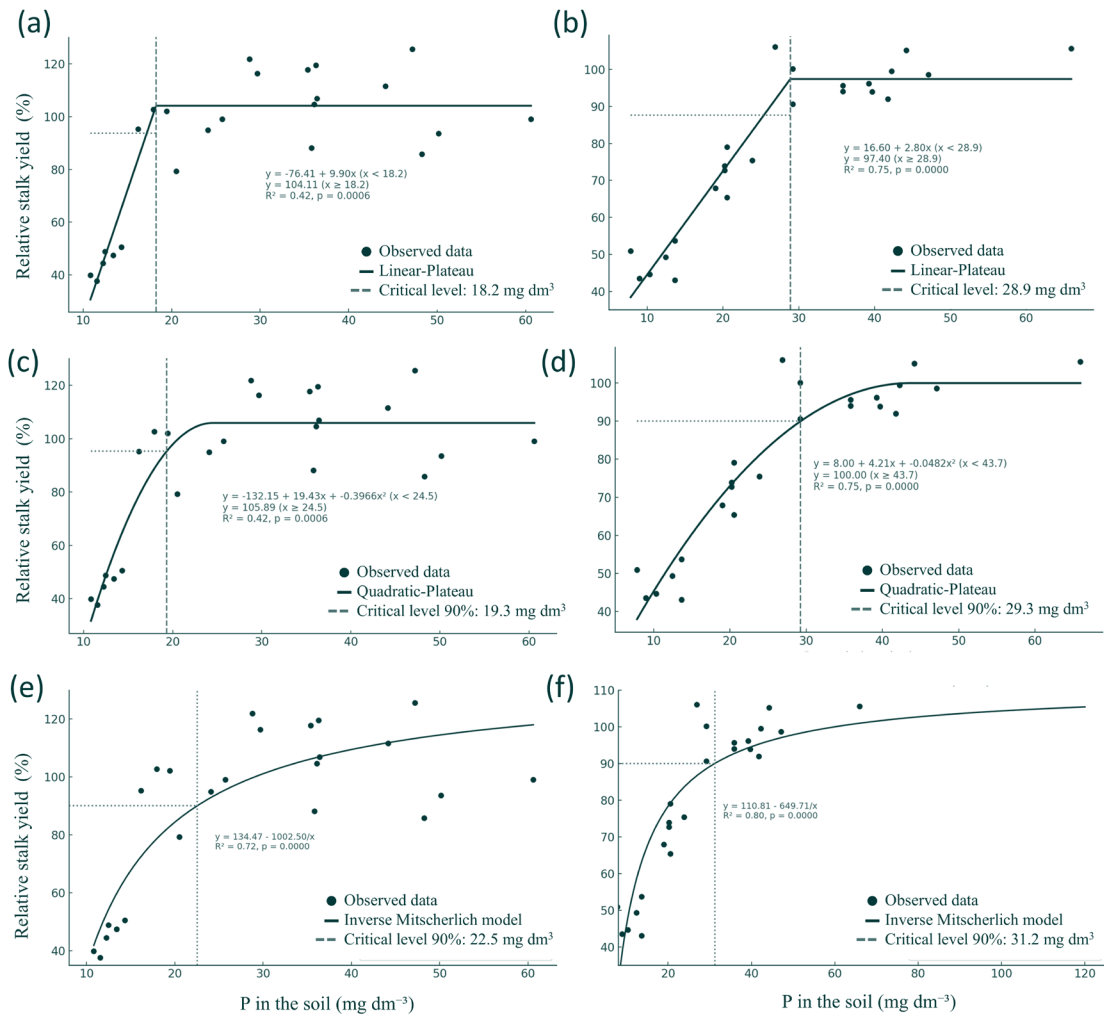


Figure 3. Calibration curves of relative yield as a function of soil P concentration (mg dm⁻³), fitted using different statistical models. The models presented include: (a and b) Linear-Plateau under deficit irrigation and full irrigation conditions; (c and d) Quadratic-Plateau under deficit irrigation and full irrigation conditions; and Inverse Mitscherlich based on the model proposed by van Raij (e and f) under deficit irrigation and full irrigation conditions. The points represent experimental data, and the fitted lines correspond to the regression equations used for modeling. Vertical lines indicate the critical soil P values estimated to achieve the target yield.

For both of the models, the correlation coefficients were 42 % ($p < 0.001$) under water deficit conditions and 75 % ($p < 0.001$) under full irrigation conditions, indicating that full irrigation experimental conditions exhibit greater association between P available in the soil and energy cane yield; in other words, the model is appropriate for describing the data trend (Figures 3c and 3d).

The results fit well ($R^2 \geq 0.7$, $p < 0.001$) in the model proposed by van Raij (Figures 3e and 3f), indicating that the Inverse Mitscherlich equation adequately describes the relative yield response to soil phosphorus content for energy cane under both irrigation conditions studied. Critical soil P levels, defined as the concentration required to achieve 90 % of maximum relative yield, were estimated to be 23 mg dm⁻³ under water deficit and 31 mg dm⁻³ under full irrigation conditions.

Soil P concentrations were placed in five classes regarding relative stalk productivity of energy cane (Table 3 and Figure 4). Under water deficit conditions, soil P content below 16 mg dm⁻³ was considered very low; from 16 to 23 mg dm⁻³, low; from 24 to 29 mg dm⁻³, intermediate; from 30 to 58 mg dm⁻³, high; and above 58 mg dm⁻³, very high. For classification of soil P content under full irrigation conditions, content below 16 mg dm⁻³ was considered very low; from 16 to 31 mg dm⁻³, low; from 32 to 60 mg dm⁻³, intermediate; from 61 to 120 mg dm⁻³, high; and above 120 mg dm⁻³, very high.

Table 3. Classification of available soil phosphorus levels (mg dm⁻³) based on the relative stalk yield of energy cane under two water conditions

Phosphorus level class	Relative yield %	50 %	100 %
		P in the soil mg dm ⁻³	
Very low	<70	<16	<16
Low	71-90	16-23	16-31
Medium	91-100	24-29	32-60
High	>100	30-58	61-120
Very height*	>100	>58	>120
Critical level		23	31

The determination of the ranges was performed graphically according to the method proposed by van Raij (2011), considering the critical level as the concentration required to achieve 90 % of the maximum relative yield. * By definition, the very high level class begins at twice the upper limit of the high level class.

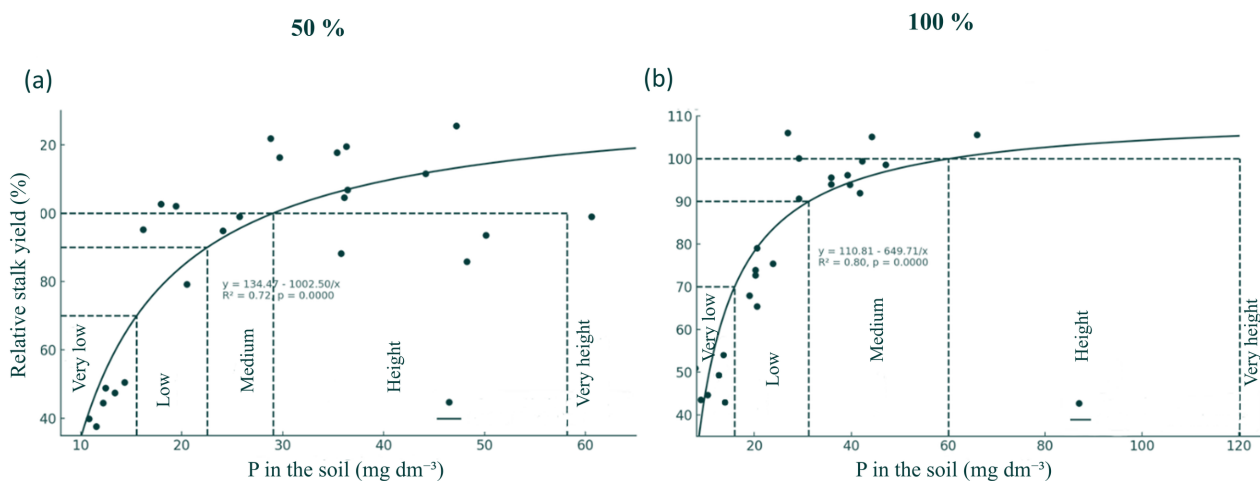


Figure 4. Classification of soil P levels related to the relative stalk yield of energy cane based on the Inverse Mitscherlich model, under deficit irrigation conditions (50 % water replacement) and full irrigation (100 % water replacement). (a) <16 mg dm⁻³ was considered very low; between 16 and 23 mg dm⁻³, low; between 24 and 29 mg dm⁻³, medium; between 30 and 58 mg dm⁻³, high; and >58 mg dm⁻³, very high. (b) <16 mg dm⁻³ was considered very low; between 16 and 31 mg dm⁻³, low; between 32 and 60 mg dm⁻³, medium; between 61 and 120 mg dm⁻³, high; and >120 mg dm⁻³, very high.

DISCUSSION

Total plant height and TVD in energy cane differ from those found by Albuquerque et al. (2016), who evaluated the effects of P application rates and P sources on sugarcane cultivars and found that +1 leaf height was not affected by the phosphorus application rates or sources. Likewise, the results regarding stalk diameter are consistent with those obtained by Caione et al. (2011), who studied P application methods and P application rates in forage sugarcane and found no effect of phosphorus fertilizer on stalk diameter. Similar results were reported by Pasuch et al. (2012), who evaluated the development, yield, and bromatological composition of first ratoon sugarcane in response to P sources and application rates and likewise did not find effects on stalk diameter. These reports, together with the data obtained in the present study, reinforce that, for energy cane, P management should be tailored to optimize specific traits, such as total yield and plant height, even if not all variables respond directly to the P application rate.

Phosphorus application rates and irrigation levels affected tillering and the number of stalks (Table S1), which differs from the results of Coelho et al. (2018), whose study showed no effect of irrigation on the number of stalks, except under extreme and severe water deficit conditions. These results suggest that in energy cane, water management should be integrated with P fertilization planning to ensure greater production efficiency, particularly in agricultural systems facing climate challenges.

In addition, Malavolta (1980) highlighted that P deficiency is a limiting factor for plant tillering. Moreover, a more recent study also indicated that adequate use of P increases tillering (Caione et al., 2013; Fernandes et al., 2023). In this context, data from the literature are consistent with the present study, showing that phosphorus fertilization and irrigation contribute to more efficient tillering, which is essential for maximizing crop yield and, consequently, increasing the economic potential and sustainability of the sugar-energy sector.

Varieties V2 and V3 (Figure 2) exhibited maximum total biomass yields of 190 and 184 Mg ha⁻¹, and stalk yields of 153 and 149 Mg ha⁻¹, respectively, under full irrigation. Similar values were reported by Boschiero et al. (2023), who observed mean total biomass of 184 Mg ha⁻¹ using 130 kg ha⁻¹ of P₂O₅ in a study involving 24 energy cane genotypes under rainfed conditions. Our results show mean biomass values higher than those found for conventional sugarcane varieties, which range from 80 to 100 Mg ha⁻¹ (Carvalho-Netto et al., 2014; Meena et al., 2020; Yang et al., 2021), highlighting the high potential of the V2 and V3 varieties for the biomass market.

The higher biomass yield observed in the energy cane varieties compared with the conventional varieties can be attributed to their morphology, particularly to tillering (Supplementary Material, Table S1). The energy cane varieties show morphological traits more closely related to those of *Saccharum spontaneum*, such as higher fiber content, lower sucrose content, and greater root biomass per area and depth (Matsuoka, 2014), which enhances water and nutrient uptake. These attributes strengthen the potential of these varieties for sustainable production systems, optimizing resource use and expanding their economic viability in the biomass market.

Full irrigation affected biomass production, as the average total biomass yields ranged from 65 to 133 Mg ha⁻¹ under water deficit and from 142 to 225 Mg ha⁻¹ under full irrigation. These data show that the maximum yield under water deficit was equivalent to the minimum yield under full irrigation. This contrast highlights the positive impact of adequate water supply on the performance of the energy cane crop.

These results are consistent with the literature, which shows that water stress negatively affects plant development, in both plant shoots and roots (Khalil et al., 2020; Kang et al., 2022; Sánchez-Bermúdez et al., 2022). In extreme cases, as in areas with scant rainfall,

average energy cane yield was only 40 Mg ha⁻¹ (Fedenko et al., 2013), emphasizing the combined effect of water deficiency and low soil P availability. These findings highlight the importance of water management and phosphorus fertilization to maximize the yield potential of energy cane, especially in regions with irregular rainfall.

Although the plants received the same volume of water in the first 40 days of growth, and the differentiation of water regimes began only after this period, which is considered critical, the root system of these varieties in the first crop cycle may require more time to be established and have a better response regarding biomass production in accordance with phosphorus fertilization. Although energy cane has a more extensive root system than sugarcane in the adult stage, in the bud-sprouting stage, the root system develops more slowly, occurring over 2 to 5 weeks (Abreu et al., 2020). First, the shoot develops, and then photoassimilates are allocated to root growth. This sprouting period is essential for crop establishment after transplanting the PSSs. The first 30 days after transplanting seedlings is the most critical phase.

Although the soil available P levels under water deficit conditions were equivalent to those under full irrigation conditions (Supplementary Material, Table S1), the lack of water impeded the P uptake process (data not shown). Phosphorus movement in the soil is governed by diffusion, which is the movement of ions along a concentration gradient, which accounts for more than 94 % of root-ion contact. Water stress conditions can hinder the diffusive flow of inorganic phosphorus in the soil solution toward the plant root. Under severe stress conditions, this flow is nearly interrupted, causing significant yield losses (Robinson et al., 2011; Prado, 2020). In other words, higher total plant biomass and stalk yields under irrigated conditions are associated with better growing conditions, which led to better root growth in both depth and area, and with localized fertilization, which increased the area of contact between phosphate fertilizer ions and root hairs, increasing P uptake and enabling greater biomass accumulations.

In the present study, the highest sugar yields were observed under the application rate of 180 kg ha⁻¹ of P₂O₅ under full irrigation and 60 kg ha⁻¹ of P₂O₅ under water deficit, showing that these varieties require more fertilization and irrigation management studies (Table 2). In sugarcane, the biggest increases in sugar production and yield from plant cane are generally obtained with P₂O₅ application rates greater than 180 kg ha⁻¹ (Sundara et al., 2002). The response in the energy cane crop may have occurred because the plants had not yet established their root system in the first crop cycle. Moreover, energy cane has deeper and more extensive roots that occupy a larger area, due to the greater presence of rhizomes in these varieties than in conventional ones (Abreu et al., 2020). Therefore, the higher yield obtained from P application rates lower than 180 kg ha⁻¹ of P₂O₅ may be linked to this characteristic of growth and establishment of the energy cane root system.

In the determination of critical levels, the results showed that P availability in the soil and its relationship with energy cane yield are strongly affected by the water regime and by the model used (Figure 3). Critical levels estimated in the Linear-Plateau (18 and 28 mg dm⁻³) and Quadratic-Plateau (19 and 29 mg dm⁻³) models under the water deficit and full irrigation conditions, respectively, were lower than the critical levels obtained using the Inverse Mitscherlich model, which estimated 23 mg dm⁻³ under water deficit conditions and, notably, 31 mg dm⁻³ under full irrigation.

Phosphorus rate effect was more accentuated under full irrigation conditions. Under water deficit conditions, our results suggest that although the response to P rates is lower, the presence of the nutrient still plays an essential role in maintaining adequate yield, preventing yield decline. This response had already been reported for sugarcane by Silva et al. (2019), who found that phosphorus fertilization is more efficient in soils with adequate water availability, due to enhanced P diffusion in the soil. Our results confirm this trend, suggesting that P availability directly depends on soil moisture; full irrigation led to higher P critical values and higher yields than water deficit conditions.

The response observed in the Linear-Plateau and Quadratic-Plateau models agrees with studies that recommend calibrating soil tests using methods that consider the P critical level required to achieve 90 % of maximum yield. However, the Quadratic-Plateau model showed greater precision in determining critical soil phosphorus levels, and it is a model widely used for perennial and semi-perennial crops, including sugarcane (Slaton et al., 2024).

The applicability of the Linear-Plateau model (Figures 3a and 3b) may be more limited in long-cycle crops such as energy cane, since crop growth over successive cuttings may modify the response to phosphorus. Quadratic models may more adequately represent the response to phosphorus in perennial crops as they better reflect the residual effect of fertilizer over the production cycles (Slaton et al., 2024). In the present study, the Quadratic-Plateau model showed that under full irrigation, the yield response to phosphorus showed a progressive increase before stabilization, which may be related to enhanced P uptake efficiency over time.

Determination of critical soil P levels is essential for proper management of phosphorus fertilization, as it is related to the minimum soil nutrient concentration required for the plant to achieve a yield near its maximum yield potential, generally defined as 90 % of relative yield (Figure 3). To achieve the ideal P levels observed in this study, the phosphorus buffering capacity (PBC) of the soil must be considered, which varies according to soil texture and directly affects the P application rate. Typical PBC values range from 6 to 19 kg ha⁻¹ of P₂O₅ per mg dm⁻³ of P in the soil, depending on soil particle size (Sousa and Lobato, 2004). Fertilization calibration based on such critical values may contribute to more efficient use of phosphorus fertilizers, reducing waste and environmental impacts while maximizing agronomic and economic returns in the energy cane crop. However, critical soil P levels are not the basis for fertilization recommendation purposes; rather, P recommendation classes are used (van Raij, 2011).

Classes of soil nutrient levels have traditionally been used as a basis for fertilization recommendation, such as established in Boletim 100 of the Instituto Agronômico de Campinas (IAC). For sugarcane, a perennial crop, soil P levels are classified as follows: very low (<5 mg dm⁻³), low (5–16 mg dm⁻³), intermediate (16–40 mg dm⁻³), high (41–60 mg dm⁻³), and very high (>60 mg dm⁻³) (Quaggio et al., 2022). Classes of soil P levels for energy cane (Figure 3 and Table 4) show wider ranges and higher values compared with those established for sugarcane.

It is important to highlight that the critical P levels estimated using the Linear-Plateau and Quadratic-Plateau models are in the low soil P content class under both water replenishment conditions (Table 3). This result strengthens the hypothesis of greater nutritional requirements for energy cane, which is related to its high biomass yield capacity.

Classification of soil nutrient levels for fertilization purposes allows an absolute number obtained from soil analysis to be transformed into an agronomic diagnosis, indicating whether there is a need for phosphorus fertilization and the rate to be applied. This avoids unnecessary expenses by optimizing the use of fertilizers and promotes environmental sustainability, as phosphorus fertilization in soils with very high P can lead to residual accumulation and the risk of contaminating bodies of water through eutrophication. Therefore, determining soil P content classes is essential for translating technical data into practical application, making fertilization management efficient, cost-effective, and sustainable. Without this classification, it is not possible to establish objective criteria for fertilizer recommendation.

Results obtained from this study show that, considering a relative yield of 70 %, soil P levels required for energy cane are around twice as high as those required for sugarcane. This indicates that energy cane has a slower response to initial phosphorus fertilization, requiring higher available P levels in the soil to achieve intermediate yield.

Crop response to phosphorus fertilization tends to be more pronounced in soils with low initial P levels, whereas in P-enriched soils, additional inputs result in less expressive yield increases (Silva and van Raij, 1999). For energy cane, soil P levels higher than 58 mg dm⁻³ (under water deficit) and 120 mg dm⁻³ (under full irrigation) (Figure 3 and Table 4) did not lead to significant yield increases. This lack of response is characterized as a depreciative effect of the fertilizer, as P accumulation in the soil exceeds plant requirements and is no longer converted into yield gains. This response corresponds to the concept of the agronomic critical level (Wu et al., 2020) and highlights the importance of establishing well-defined sufficiency ranges to avoid fertilizer waste and environmental impacts.

Soil P availability ranges in this study represent the phosphorus fertilization zones for energy cane under different water conditions. The results indicate that the interpretation of soil P levels should be tailored to the physiological reality of the crop. It is essential to consider its high nutrient demand to ensure agronomic efficiency and sustainability in fertilizer management. A further consideration is that the phosphorus fertilization recommendation classes for energy cane are higher than those currently adopted for sugarcane.

Soil P content classes (Figure 3 and Table 4) are important for the energy cane crop, considering that the sugarcane-producing regions and potential areas for energy cane production are mainly located in tropical regions, with predominance of highly weathered soils of low fertility (Abreu Junior et al., 2003), such as Latossolos (Figure 4). Under these conditions, around 90 % of the soluble P added to the soil, whether from mineral or organic fertilizers, is adsorbed by the solid phase, reinforcing the need for substantial applications of phosphorus fertilizers to meet crop nutritional requirements (Correia et al., 2023).

Further studies under field conditions should be carried out to calibrate classes of nutrient levels, and this study serves as a foundation for this definition in the energy cane crop grown under tropical conditions. Analysis of the different classes of soil phosphorus levels enabled the determination of the relationship between the soil P level and the need, or lack thereof, for phosphorus fertilization, leading to an understanding of energy cane nutrient requirements in tropical soils. This study contributes to enhancing knowledge in soil science and promoting more sustainable agricultural practices, particularly in growing energy cane as a bioenergy crop.

CONCLUSIONS

Phosphorus fertilization has a significant impact on energy cane yield. The rate of 180 kg ha⁻¹ P resulted in the best growth and yield of the crop. The critical P levels estimated using the Quadratic Plateau model were 29 mg dm⁻³ under full irrigation and 19 mg dm⁻³ under deficit irrigation, considering 90 % of the relative yield as a reference. The critical levels obtained using the Linear-Plateau and Quadratic-Plateau models are within the low soil P availability class, defined based on the relationship between relative energy cane yield and soil P levels, according to the Inverse Mitscherlich model. The threshold values for interpretation of the soil P availability classes for energy cane were higher than those traditionally used for sugarcane, showing the higher nutritional requirements of the crop, particularly in high biomass yield and stalk productivity systems. Our results reinforce the importance of establishing specific sufficiency ranges for energy cane, tailored to the water availability conditions and the observed agronomic response.

SUPPLEMENTARY MATERIAL

Supplementary data to this article can be found online at https://www.rbcjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-49-spe1-e0240163/1806-9657-rbcs-49-spe1-e0240163-suppl01.pdf.

DATA AVAILABILITY

The data will be provided upon request.




FUNDING




This study was funded by the São Paulo Research Foundation (FAPESP), grant numbers 2020/03271-9, 2021/10058-2, 2022/08391-8 and 2024/10755-3; the National Council for Scientific and Technological Development (CNPq), grant number 311203/2021-3 and 303230/2025-8; and the Coordination for the Improvement of Higher Education Personnel (CAPES) – Finance Code 001.




ACKNOWLEDGMENTS



We thank FAPESP for the financial support; Nuseed S.A. for providing the plant material and the TT3 and TT4 fellowships that contributed to the successful execution of the experiment; CENA/USP; ESALQ/USP; the Department of Biosystems Engineering; the Department of Crop Production (LPV); and the Sugar-Energy Technology and Bioenergy Laboratory (LTSBio) of ESALQ.





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