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RESEARCH ARTICLE

K Dynamics in the Soil–Plant System for Sugarcane Crops: A Current Field Experiment Under Tropical Conditions

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Abstract Sugarcane stands out as the most used renewable energy source in Brazil. Its yield and adaptation respond perfectly to tropical edaphoclimatic conditions. This study evaluates the K dynamics in the soil–plant system for sugarcane crops under tropical conditions. Treatments were arranged in randomized blocks design with five doses of K_2O (0, 50, 100, 150, and 200 kg ha^{-1}) and five replications. The following analyses were performed: K content in the soil, plant uptake, availability and decomposition of sugarcane straw, and K balance in the soil–plant system. Data on response variables were subjected to the analysis of variance and F test at 5% probability. Quantitative factors were subjected to polynomial regression analysis by selecting the model of higher significance. The potassium dose of 200 kg ha^{-1} increased K levels at 0.8 m by 20% relative to the control. After 70 days, 50% of the 79 kg K ha^{-1} was available from sugarcane straw mineralization. The treatment that improved K in soil was 150 kg ha^{-1} of K annual application. This dose causes a positive balance of K in the soil with 133.32 kg ha^{-1} year^{-1}.

Keyword Half-life · Leaching · Potassium balance · Potassium chloride · *Saccharum* spp · Tropical soil

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Introduction

Brazil ranks first in sugarcane production with a grown area of 8.6 million hectares. According to the National Supply Company of Brazil (Companhia Nacional de Abastecimento 2019), sugarcane production is estimated at 620.4 million tons (2018/2019 harvest), and the Goiás State stands out in this scenario ranking the second largest national producer (917.6 thousand hectares, around 70.0 million tons, and average yield of 76.3 t ha^{-1}). The importance of these data is based on the relevance of sugarcane as a raw material for renewable and clean energy. Besides, this data reinforces the need for efforts to study this crop production. Moreover, sugarcane is one of the most important energy crops grown globally, with great biomass and sucrose production traits (Ahorsu et al. 2018; Matsuoka et al. 2014). Sugarcane is part of the history of Brazilian agribusiness production (Pelloso et al. 2020).

Potassium is needed in high amounts by sugarcane (Kwong 2001; Bel-Rhlid et al. 2009; De Lira et al. 2019) and accumulates in the plant cell solution (Ragel et al. 2019). This behavior was reported by several studies on different sugarcane varieties (Otto et al. 2010; Silva et al. 2013; Flores et al. 2014a; Almeida et al. 2015; Pancelli et al. 2015; Watanabe et al. 2016; Freitas et al. 2018). Besides, the Brazilian agribusiness is one of the main consumers of the K_2O manufactured worldwide (around

14%), and 18% are intended for sugarcane crop production (IFA 2018). This information points to the need to improve nutritional management and optimize potassium fertilization practices in sugarcane crops.

Several studies have addressed the issue of K use in sugarcane (Otto et al. 2010; Silva et al. 2013; Jat et al. 2014; De Melo et al. 2016; Velayutham 2017; Freitas et al. 2018), but few have focused only on the K^+ behavior in the soil–plant system considering both plant physiology and soil chemistry (Ferreira et al. 2011; Velayutham 2017). Plants use potassium as an enzymatic activator in photosynthesis, protein synthesis, sucrose translocation, and physiological performance (Watanabe et al. 2016).

Nutrient balance and flow calculations in agricultural production systems provide basic information to assess their sustainability over time (Gustafson et al. 2007). The difference between nutrients applied and nutrients exported by crops indicates the level of soil nutrient capacity (Steiner 2014). This same logical analysis may be applied to the K balance in the soil–plant system.

Studies on the balance and dynamics of K in agroecosystems are important to assess whether the quantities of fertilizers applied annually are being used to maintain soil fertility or intensifying losses in the system. In this sense, this research analyzes the K dynamics in the soil–plant system of sugarcane crops under tropical conditions.

Materials and Methods

Study Area

The field experiment was conducted after the first ratoon budding (i.e., after sugarcane plant cutting), var. IAC 91–1099, in production area of the Goiasa Company, located in Bom Jesus de Goiás, Goiás, Brazil (18°2′39.55″ S; 49°30′28.5″ W; altitude 619 m) from June 2017 to May 2018. According to Köppen and Geiger, the region has an Aw-type climate (megathermal) known as tropical savannah, with dry winter (May–September) and rainy summer (October–April) (Alvares et al. 2013).

Temperature and rainfalls were obtained from the weather station closest to the experimental area in June 2017 and May 2018 (Fig. 1).

The soil was classified as Ustox (NRCS 1999) and LATOSSOLO VERMELHO Distrófico (Santos et al. 2018) with a clayey texture (440, 130, 430 g kg^{-1} of clay, silt, and sand, respectively). Samples were collected at several depths (0.0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m) for chemical analyses according to Singh et al. (2005) and Walinga et al. (1995), with adaptations to the tropical conditions according to Teixeira et al. (2017) (Table 1).

Experimental Design and Treatments

The treatments were composed of five doses of K_2O: 0 (control); 50; 100; 150, and 200 kg ha^{-1}, using potassium chloride (KCl, 58% K_2O) as the source. The experiment was arranged in a randomized complete block design with five replications, totalizing 25 experimental plots. Each plot consisted of five rows, 1.5 m spaced from each other and 10 m long. The useful area was the three central rows, excluding 0.5 m from each border.

The research was carried out in June 2017, thirty days after harvesting the sugarcane. Manual application of potassium doses was performed on the surface and beside the cultivation row without fertilizer incorporation, as indicated by Flores et al. (2014a). Other mineral sources combined were applied to maintain the plant nutritional requirements: 100 kg of ammonium nitrate ha^{-1} (NH_4NO_3, 33% N) and 30 kg mono ammonium phosphate ($NH_4H_2PO_4$, 48% P_2O_5).

Potassium Leaching Evaluation

Sugarcane developed for 330 days. After harvesting, soil samples were collected in triplicate from each plot at four different soil layers: 0.0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m. The soil samples were air-dried, ground, and sieved through a 2-mm mesh. Then, the soil analysis was performed according to Teixeira et al. (2017) to determine the exchangeable potassium by Mehlich-1.

Straw Release and Potassium Decomposition Time

Decomposition rates and the K release were evaluated in each experimental plot at 0, 60, 120, 180, 240, and 300 days after fertilizer application (DAF) and the sprouting of the first plant. Nylon litterbags (0.20 × 0.15 m) were filled with stripped sugarcane, corresponding to each analysis date. Potassium rates were determined according to Silva (2009).

We measured the straw production per hectare in a representative random area (0.25 m^2) to determine the amount of straw to be put into each litterbag; the volume was proportional to a hectare. The moisture was analyzed for future adjustment.

After the degradation time, litterbag straw residues were weighed and dried until they reach constant mass in a forced air oven at 60 °C to determine the remaining dry phytomass. Subsequently, samples were milled to determine K contents at the Fertilizer Analysis Laboratory, Soil Sector, Universidade Federal de Goiás, Brazil, as predicted by the method described by Silva (2009).

An exponential mathematical model described by Stanford and Smith (1972) was proposed to describe straw

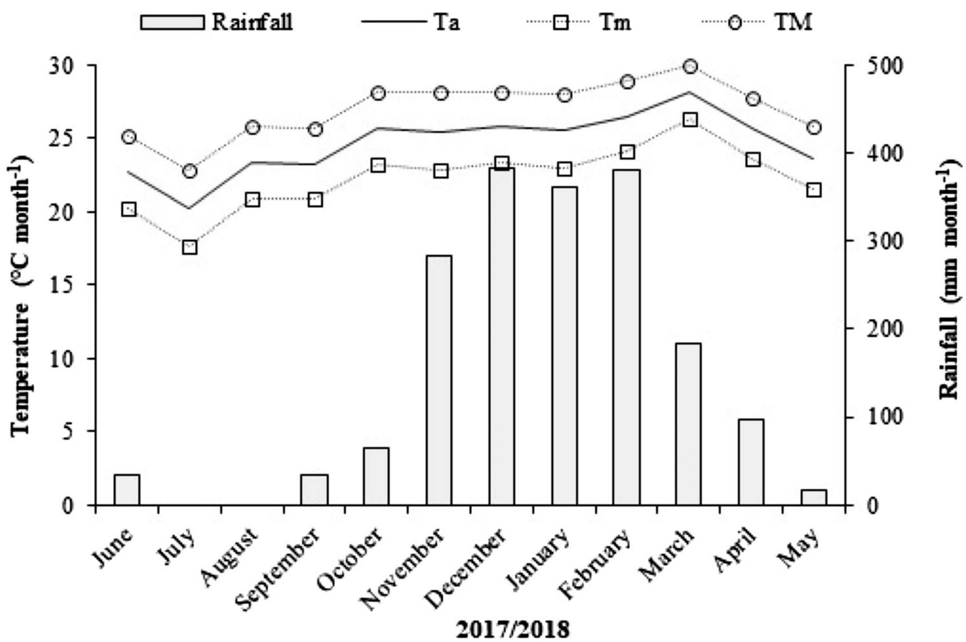

Fig. 1 Air temperature maximum (TM), minimum (Tm) and average (Ta), and rainfall per month, from June/2017 to May/2018, in the Setor Alvorada, Goiasa Sugar-Power Plant, county of Bom Jesus de Goiás, GO, Brazil

Table 1 Physical and chemical characteristics of soil used in the study before experiment

Deep (m)	Clay	Silt	Sand	pH[a]	OM	P	K^+	Ca^{2+}	Mg^{2+}	H + Al	BC	CEC	V
0.0–0.2	44.0	13.0	43.0	5.5	26.8	13.0	0.20	4.3	1.7	4.1	6.2	10.3	60.2
0.2–0.4	45.0	14.0	41.0	5.1	12.1	10.2	0.11	2.7	1.1	4.2	3.9	8.1	48.2
0.4–0.6	46.0	13.0	41.0	4.8	12.1	2.6	0.10	2.4	1.1	4.3	3.6	7.9	45.6
0.6–0.8	47.0	13.0	40.0	4.7	10.7	2.3	0.05	1.0	0.6	4.0	1.8	5.8	31.6

[a]In water

OM = organic matter of soil (g dm^{-3}); P = phosphorus (mg dm^{-3}); K^+ = potassium ($cmol_c$ dm^{-3}); Ca^{2+} = calcium ($cmol_c$ dm^{-3}); Mg^{2+} = magnesium ($cmol_c$ dm^{-3}); H + Al = exchange acidity ($cmol_c$ dm^{-3}); SB = total base cation ($cmol_c$ dm^{-3}); CEC = cation exchange capacity ($cmol_c$ dm^{-3}). V = bases saturations (%)

decomposition with adjustments of k-value (half-life time) as t½ = 0.693/k (Paul 2007).

K plant accumulation

Sugarcane harvesting was performed manually 330 days after sprouting. Sugarcane energy stalks were analyzed to determine yield according to Gheller (1999) and Simões et al. (2005) per plot with data expressed as t ha^{-1}. Leaves and stalks were analyzed separately to determine fresh phytomass. Fresh material (400 g) was collected and dried until constant mass in a forced-air oven set at 70 °C (for approximately 120 h). Afterward, samples were weighed and milled (2 mm), and potassium contents were determined (Silva 2009).

K exportations were estimated for stem and top leaves according to Flores et al. (2020), Eq. 1:

$$K_E = \frac{(Y \cdot K_{ST})}{1000} \quad (1)$$

where K_E is K exportation quantity of sugarcane stalks (kg ha^{-1}); Y is the stalk yield (kg ha^{-1}); K_{ST} is K concentration in sugarcane stalks (g kg^{-1}) per treatment.

K Balance

The mathematical analysis was performed for two situations: (1) soil balance (S_B), considering $K_{initial}$ and K_{final} from 0.0 to 0.8 m soil depth, and K_{straw} of sugarcane between June 2017 and May 2018, as K accumulated in top leaves. All calculations were performed following Eq. 2, adapted by Ferreira et al. (2011):

$$S_B = (K_{final} + K_{Straw.f} + K_{acum}) - (K_{initial} + K_{Straw.i}) \quad (2)$$

where $K_{initial}$—K content in the soil before the experiment; K_{final}—K extractable by Mehlich-1 after one crop production cycle up to the 0.8 m depth; $K_{Straw.i}$—K initially present in sugarcane straws; $K_{Straw.f}$—K remaining in straws until the end of the experiment; K_{acum}—the K accumulated in the top leaves until harvesting.

The (2) “crop balance” (C_B)—the *input* of K from fertilizer and the *output* of K exported by sugarcane production, is calculated by Eq. 3.

$$C_B = (K_A - K_E) \quad (3)$$

where K_A—K applied on each production cycle (kg ha^{-1}); K_E—K exported by harvested sugarcane (kg ha^{-1}).

Statistical Analysis

Data were submitted to the analysis of variance and F test at 5% of probability using the AgroEstat software (Barbosa and Maldonado Júnior 2015). When significant, they were submitted to polynomial regression analysis. Linear and quadratic mathematical models were tested by applying the models with the best data adjustments. The magnitude of the significant regression coefficients at a 5% probability by the t-test was used as a model choice criterion. When significant, the maximum and minimum points were obtained by deriving the equations.

Results

K Content in Soil

K content in soil was affected by the amount of potassium applied at all soil depths (0.0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m) (Fig. 2) in different forms. However, all of them were adjusted to a second-order polynomial equation (Fig. 3). Moreover, at the 0.0–0.2 soil layer, we observed a K maximum content of 0.24 $cmol_c$ dm^{-3} with the 150 kg K_2O ha^{-1} application.

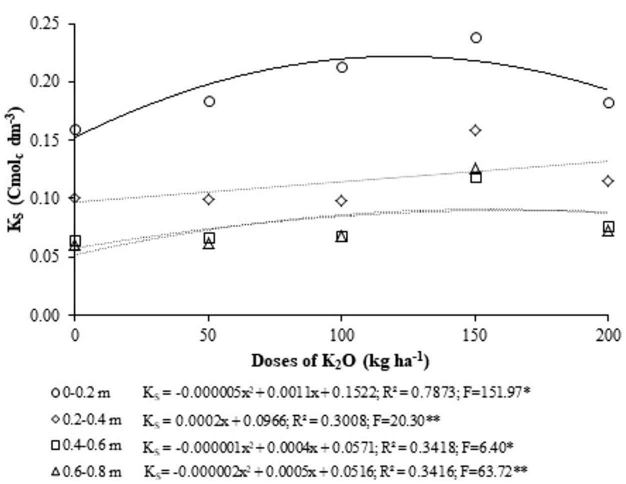

Fig. 2 K content exchange in soil (Ks) 330 days after sprouting (DAS). Data demonstrated by layers (0.0–0.2, 0.2–0.4, 0.4–0.6 and 0.6–0.8 m) and by dose K_2O application. * significance level of 0.05 and ** significance level of 0.01, both with F-test probability

Another key point to remember is that the R-square in this study indicates that 78% of the K variation in the soil (Ks) is explained by variations in doses on the surface (0.0–0.2 m). The highest K concentration in the soil surface may also be explained by successive applications of this macronutrient in a clayey soil (440 g kg^{-1}) and by the high cation exchange capacity (CEC) (10.3 $cmol_c$ dm^{-3}) (Table 1). The coefficient of determination decreased around 34% concerning the dependent variable (K soil content). The observed variation can explain this. For the whole soil profile, the most evident concentration was 150 kg K_2O ha^{-1} with an inflection behavior at this point.

The 0.2–0.4 deep soil profile behaves like a 0.0–0.2 soil layer, and the maximum K content was close to 0.12 $cmol_c$ dm^{-3}. Data increased by 15% compared to those in control at the same depth. On the other hand, the R-square points to around 30% of K_2O dose variation in the soil profile to explain K content exchange in the soil. To understand this, the depth soil profile seems not to be influenced by K_2O application in 330 days. The great resistance of penetration can also explain such behavior in the soil profile (Fig. 4). The most critical resistance was at around 0.6 m deep, configuring a physical offside zone.

A decreasing gradient of K concentration was observed in the soil profile (0.0–0.8 m) considering K applications (Figs. 2 and 3). Two phenomena may explain these results: (1) the expressive negative charge on clay surfaces, which may bind K^+ temporarily, and (2) the influence of rainfalls, which gave rise to a leaching phenomenon and consequently K movement along with the soil profile. Between October 2017 and April 2018, rainfalls were expressive (close to 1,654 mm, 236 mm monthly average) (Fig. 1).

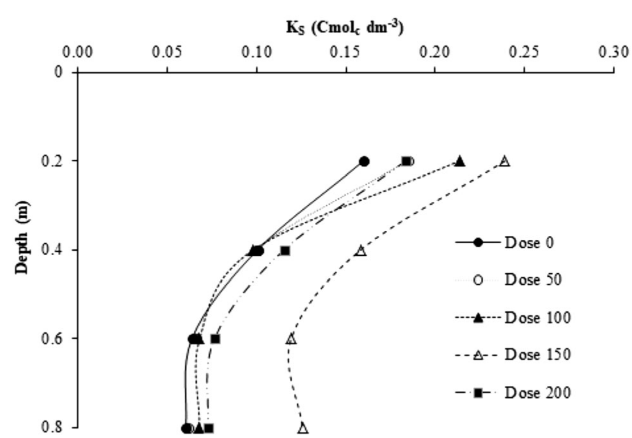

Fig. 3 Accumulated potassium in soil depth (Ks), after 330 days after sprouting (DAS), concerning potassium dose application on soil

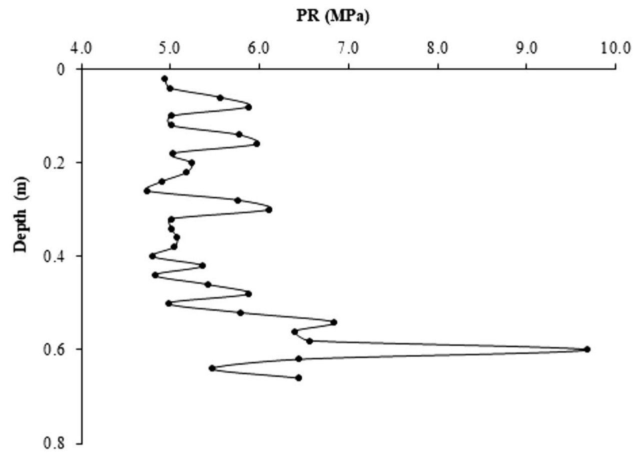

Fig. 4 Soil penetration resistance (PR) in experimental field (June, 2017). Humidity variation around 27.51%, 24.76%, 24.83% and 18.98% on 0.0–0.2, 0.2–0.4, 0.4–0.6 and 0.6–0.8 m depth, respectively

After the sugarcane production cycle (330 days), at a depth of 0.6–0.8 m, and comparing the dose of 150 K_2O with the control, it is possible to verify a great improvement (60%) in K contents (see Table 1 and Fig. 2: initial 0.05 and final 0.08 $cmol_c$ dm^{-3}). At the 0.4–0.6 m depth, we observed a 20% reduction in K exchange.

Despite that, except for the surface behavior, no other curve shows a response relationship depending on the input of the application of different K_2O doses. To that end, this present study suggests that the K^+ present on the system is not lost by leaching before 330 days of analysis.

Straw Decomposition and Potassium Release Time

Around 13,333 kg of dried phytomass ha^{-1} of straw is produced as cover by the IAC 91–1099 variety during the first harvest period. Straw decomposition fitted the exponential model (Fig. 5a). Several rainfall events impacted the time of decomposition. In this way, decomposition was analyzed considering the time and mass reduction. Until 120 days, there was a stable decomposition capacity, and a subtle intensification was observed after 120 days and after sprouting. This effect may be due to the rainfall period when rains began in the region (September 2017: 35 mm) and intensifies in October 2017 (65 mm) (Fig. 1).

In the following months, up to the end of the experiment (April), rainfalls sometimes have intensified (283, 382, 360, 184, and 97 mm). The temperature recorded an average of 26 ± 2 °C during the rainy period (October 2017 until April 2018) and 23 °C during the dry period (August and September 2017).

In 300 days, dry phytomass reduced by 49.0% (6,537.83 kg ha^{-1}) compared with the initial conditions (Fig. 5a). These results demonstrate how the vegetation type and inputs drive the dynamics of K release. In the present study, the constant of decomposition was 0.002 g day^{-1}, with a half-life time of 346.5 days.

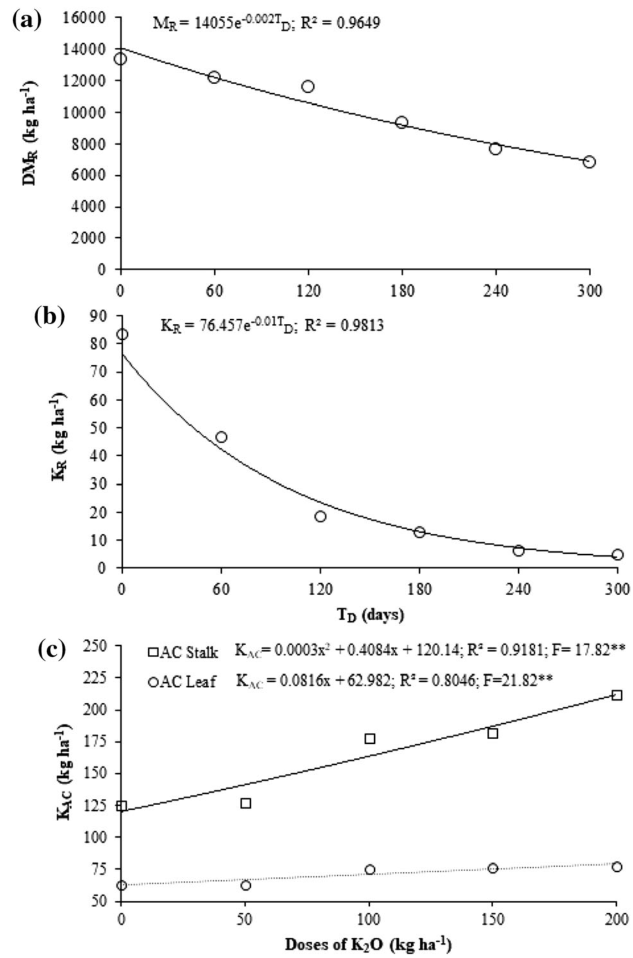

Fig. 5 Remaining dry mass (DM_R) in sugarcane straw (kg ha^{-1}) with 300 days of decomposition observation (time decomposition—T_D) (**a**). Remaining K content (K_R) in sugarcane straw (kg ha^{-1}) with 300 days of experimental field (time decomposition—T_D) (**b**). K accumulation (K_{AC}) in leaves and stalks, according to potassium fertilizer dose application (**c**). ** significance level of 0.01 with F-test probability

Around 79.2 kg of K ha^{-1} was released from sugarcane straw, which, compared to the initial conditions, represents a 94.4% increase. The constant release corresponds to 0.01 g of K day^{-1}, 70 days of half-life, and release to the soil–plant system from sugarcane straw (Fig. 5b).

The results provide evidence that confirms the high mobility of K on plants and the contribution of straw decomposition as a potassium source. Furthermore, the results also evidence the absorption capacity of K in different plant compartments; that is, sugarcane stalks are trapping more K ions than leaves (Fig. 5c). Compared to the control (without K_2O application), potassium fertilization affects top leaves in sugarcane (Table 2), promoting an increase of around 21.4% of K accumulation at the end of the experiment. Conversely, the sugarcane stalk increased 70% compared to the control treatment (Table 2). Once again, the most remarkable result is the absorption.

Considerable attention must be paid to the relation between sugarcane stalks and leaves ($K_{stalk\ accumulation}$: $K_{leaves\ accumulation}$). Without potassium fertilizer application, sugarcane stalks concentrate 1.96 times K from the soil due to previous fertilizer applications. This behavior was noted in almost every dose, except for 200 kg K_2O ha^{-1}, which had a 2.75 times ratio.

K Balance

Considering K_2O fertilizer application, the initial K^+ content in all treatments and conditions was the same. However, data shown in Table 1 indicate a gradient K^+ content following soil depth (0.20, 0.11, 0.10 and 0.05 $cmol_c\ dm^{-3}$).

Concerning K balance (Table 3), data show a negative tendency to all K_2O doses studied, except for 150 kg K_2O ha^{-1}, which was the only positive balance (133.32 kg K ha^{-1}). A positive balance may indicate the remaining K^+ in the system for two reasons: (1) losses by leaching and (2) sorption of negative soil charges. The second reason meets this study's condition due to clayey soil characteristics and high CEC.

Treatments without K fertilization have the highest negative balance (−81.11 kg ha^{-1}). The plots had the lowest K content in soil at the end of the experiment (May 2018), with 299.7 kg ha^{-1}, and the lowest total K content in the final evaluation (368.29 kg ha^{-1}). The balance was negative for the doses 50 and 100 kg K_2O ha^{-1}: −61.13 and −21.14 kg ha^{-1}. These results show a reverse relation between K doses and the K content observed in the soil.

Table 2 Stalk production and potassium accumulation in leaves (kg ha^{-1}) according to potassium fertilizer dose application (kg ha^{-1})

Doses of K_2O	K accumulation	
	Leaf	Stalk
kg ha^{-1}	kg ha^{-1}	
0	63.47	124.76
50	63.13	127.04
100	75.28	178.27
150	76.81	181.55
200	77.04	212.23
F test	21.82**	4.86**
V.C. (%)	8.69	23.32

**Significance level of 0.01 with F-test probability

The highest dose (200 kg K_2O ha^{-1}), even with a negative balance (−17.48 kg ha^{-1}), provides better development compared with the other treatments (0, 50, and 100 kg K_2O ha^{-1}). Another suggestive behavior involves losses by runoff or leaching, but it is supported by K_2O fertilizers applied on the surface due to the high concentrations applied.

A negative balance was observed in the field for all K doses studied. The annual exportation reinforces that by the sugarcane stalks, which was higher than its own metabolic needs. In other words, high K doses applications stimulate a high uptake by sugarcane stalks and high system exportation. However, high doses and exportation provide inversely proportional losses in absolute terms: −133.92 (0 kg K_2O ha^{-1}), −85.54 (50 kg K_2O ha^{-1}), −95.27 (100 kg K_2O ha^{-1}), −57.05 (150 kg K_2O ha^{-1}), and −46.23 (200 kg K_2O ha^{-1}).

Given the results achieved and the exportation of K balance in the sugarcane crop, K fertilizers exceed crop production requirements (Table 3). However, by using a mechanic harvest, this leads to a higher quantity of potassium in the system by straw degradation, besides initial K content in the soil, and it is possible to verify a positive balance in the soil at the dose of 150 kg K_2O ha^{-1} (133.32 kg K ha^{-1} $year^{-1}$).

When data are analyzed in compliance with sustainability principles, the dose with a positive balance was 150 kg K_2O ha^{-1} without depleting K reserves. It is important to pay attention to the soil type and climate conditions to provide the best use conditions as already proposed.

Potassium leaching losses were not significant in this study. The author believes this is caused by the clayey texture, high CEC, and the strong physicochemical interaction with negative clay charges. However, the results confirm that K remains available to plant absorption.

Discussion

K content in the soil

K content is explained by the dose variation of K_2O application on the soil surface. To understand K^+ dynamics in the soil–plant system, this study hypothesizes that potassium behaves differently according to dose variation. It is clear that potassium availability depends on crop production type and usability of nutrients (Franzaring et al. 2017) in its physiological pathways. A strong relation between rainfall events and K^+ leaching was reported in the literature (El-Tilib et al. 2004; Flores et al. 2014a, b; Jat et al. 2014; Amisnaipa et al. 2016; Cavalcante et al. 2016; Velayutham 2017).

Table 3 K balance in soil and sugarcane crop production, according to potassium dose application, considering until 0.8 m depth (agricultural year 2017/2018)

	Doses of K_2O				
	0	50	100	150	200
Soil Balance	………………………….. K (kg ha^{-1}) …………………………				
June/17					
K soil[a]	365.40	365.40	365.40	365.40	365.40
K straw[b]	84.00	84.00	84.00	84.00	84.00
Total (1)[c]	449.40	449.40	449.40	449.40	449.40
May/18					
K soil[a]	299.70	321.00	349.00	501.00	349.00
K straw[d]	68.59	67.27	79.26	81.72	82.92
Total (2)[e]	368.29	388.27	428.26	582.72	431.92
Final balance[f]	−81.11	−61.13	−21.14	133.32	−17.48
Field balance	………………………….. K (kg ha^{-1}) …………………………				
Input					
Doses of K_2O[g]	0.00	41.50	83.00	124.50	166.00
Output					
Harvested stalk[h]	133.92	127.04	178.27	181.55	212.23
Final field balance	−133.92	−85.54	−95.27	−57.05	−46.23

[a]In 0.0–0.8 soil depth. [b]Sugarcane straw K content before field experiment. [c]K total initial (K soil + K sugarcane straw). [d]Remaining amount K content on sugarcane straw (final of the crop production + K accumulated in the pointer at the moment of the harvest). [e]K final (K soil + K sugarcane straw). [f]Total (2)—total (1). [g]K_2O doses (0, 50, 100, 150 and 200 kg ha^{-1}) applied by KCl form. [h]K exported by sugarcane stalk

The 20% reduction of exchangeable K at 0.4–0.6 m depth may have occurred due to nutrient displacement to deeper soil layers. That is strong evidence of the higher concentrations at 0.6–0.8 m or uptake directly by the plant. More than 80% of sugarcane root phytomass is in-between the surface and 0.6 m depth of soil (Farias et al. 2008; Flores et al. 2020).

The relation between plant nutrition, the chemical composition of the plant, and the shape of yield curves have been extensively studied (FAO 1981; Raij and Cantarella 1996; Pastor and Bridgham 1999; Flores et al. 2014a; Jat et al. 2014; Amisnaipa et al. 2016; Velayutham 2017). When comparing our results to older studies, these findings corroborate the same suggestions of curve behavior. Our data demonstrated that K^+ content increases with increased resource availability, with an inflection point at 150 kg ha^{-1} (Fig. 2), fitting a polynomial disposition (Velayutham 2017). Pastor and Bridgham (1999) referred to this behavior as a type of horizontal asymptote, and resource response efficiency is then unimodal.

The region of this study is known for having a retouched plain surface landscape and soil with natural fertility rich in nutrients (CPRM - Serviço Geológico do Brasil 2010). Due to sedimentary rocks, specially basalts, sandstones, diabase, and gabbro (Amaral Filho et al. 1999; Riccomini et al. 2005), it may be composed of micas and feldspars (Haldar and Tišljar 2014), which in turn tends to form kaolinite (Manning 2010; Haldar and Tišljar 2014).

Although preliminary, this information suggests that kaolinite is an agent of physicochemical interaction with potassium. The value of K^+ content shown in Fig. 2 suggests that a connection may exist among ion mobility, rainfall events, and clay mineral type. These findings corroborate the ideas of Fontes and Alleoni (2006) and Amoakwah and Frimpong (2013), who stated that kaolinite tends to interact with potassium.

Since the K^+ ion is exchangeable and formed by negatively charged clay particles, potassium does not move promptly in most soils (Freitas et al. 2018). Potassium is considered an immobile nutrient (Hillel 2008). The results demonstrate that this is not necessarily true because the K^+ ion behaves differently according to K_2O dose variation, as noted by applying 150 kg ha^{-1} (Figs. 2 and 3).

It is important to highlight that as potassium is removed from exchangeable or solution phases, a shift of potassium from slowly available forms to readily available forms occurs (Afari-Sefa et al. 2004). On the other hand, if the K^+ ion concentration in the soil solution and exchange complex increases by adding potassium fertilizer, as in our experimental design (Figs. 2 and 3), the reverse is true (El-Tilib et al. 2004; Ferreira et al. 2011). It is important to note that this evidence relies on a different electrochemical behavior of the K^+ ion (Table 1), such as outer-sphere complexes on highly weathered soils, as demonstrated by Fontes and Alleoni (2006). The zero point of charge of kaolinite is around 4.6 (Schroth and Sposito 1997; Bleam and Bleam 2017); it is the point at which the total concentration of anionic surface sites is equal to the total concentration of cationic surface sites (Bleam 2012). Table 1 shows pH soil solutions and provides evidence that K^+ tends to be more fixed in the surface than the undersurface (Figs. 2 and 3) because it has a more negative charge on the clay mineral surface.

One of the most important limitations of the experimental soil is the high compaction levels on the undersurface (Fig. 4). It is fundamental to note that compaction may alter mechanisms of nutrient behaviors in the soil and affect the availability of nutrient amounts (Costa et al. 2009). For example, soil compaction can decrease the uptake of potassium in corn (Aina 1980). Furthermore, the same author has observed the dependence of potassium availability on humidity (optimal point: around 17%). The reaction and intensity of the chemical process of soil nutrient dynamics are affected by the presence of water and the environmental pressure of crop production (Velayutham 2017). As mentioned in the literature, many studies demonstrate nutrient dynamics according to quantity, frequency, and intensity of climate, especially rainfall events and soil characteristics (Bleam 2012; Velayutham 2017; Andrade et al. 2018).

Together, these findings suggest a different behavior of sugarcane physiology and K^+ ion mobility under the application of high doses of K_2O. Watanabe et al. (2016) reported a great K^+ uptake (luxury consumption) by sugarcane when KCl was used as fertilizer, the same as used in this study (Fig. 5c) and in line with the previous study (Jat et al. 2014). These results help us understand how K^+ availability and clay mineral behavior, water content, and compaction are connected and may affect how sugarcane explores this nutrient in its metabolism.

Straw Decomposition and Potassium Release Time

Concerning potassium availability from straw decomposition, there was a slow behavior. Nevertheless, potassium from straw is important to the soil–plant system but is not expressive to K balance (Fig. 5 a and b). Several authors have stated that sugarcane straw may be affected by its chemical composition (Almeida et al. 2015; Souza Junior et al. 2015; Yamaguchi et al. 2017; Pimentel et al. 2019). In the present study, the response delay of straw decomposition is probably due to high fiber levels on sugarcane. The same result was observed by Tan et al. (2005), and they affirmed that very high levels of potassium could increase fiber levels.

The K^+ ion absorbed by the plant provides the fertilizer input. Normally, potassium accumulates in leaf vacuoles (Okorokov et al. 1980; Gierth and Mäser 2007; Ragel et al. 2019); however, this study demonstrated a different dynamic, with high levels of potassium. Despite that, it was observed that stalk K content has a strong relation to K_2O doses (Fig. 5c). High potassium levels in sugarcane stalks suggest improvement in sucrose production; otherwise, the opposite happens. These results are likely because sucrose is the precursor of cell wall constituents (Patrick et al. 2013).

Considerable attention must be given when the analysis is on the K use by plants. As a phloem-mobile nutrient, plants absorb it in excess amounts concerning their requirements if it is readily available. Despite this, K does not improve technological crop production since this represents a kind of "luxury consumption" by the high doses applied, as demonstrated in this present study. These findings support the notion that sucrose production is not influenced by high potassium levels (SM 1). Otherwise, metabolic impacts may occur by high K_2O applications, as reported by other authors for other different crop productions (Gierth and Mäser 2007; Jat et al. 2014; Ragel et al. 2019; Velayutham 2017; Watanabe et al. 2016).

There are several possible explanations for such results. Considerable attention must be given when K associates with photosynthesis rates and CO_2 plant regulation, which is related to the opening and closing of stomata (Peoples and Koch 1979).

Jin et al. (2011) reported a relation between K concentration and metabolic parameters in *Carya cathayensis* leaves. The authors proved that K^+ ion concentration decreases intercellular CO_2 concentration and increases stomatal conductance and mesophyll conductance at 60 days of incubation.

K Balance

Nutrient balances are frequently used to evaluate the efficacy of products within the agroecosystems scale. In the case of this paper, that analysis can estimate the potential of nutrient turnover in crop productions by the mass balance of inputs, storage, and outputs. The results confirm the tendencies of K behavior at high doses, directly impacting yield. In the case of soil potassium, which has a positive charge, the flow of the ion responds not only to the osmotic gradient but also to the electrical gradient (Ragel et al. 2019).

Conversely, some studies have shown how K fertilizer application may increase yield (Almeida et al. 2015; Pancelli et al. 2015). Otherwise, K balance in the soil is demonstrated as a negative estimative that suggests losses in the system or attached in the clay mineral. The sugarcane stalk is the part that most absorbs the K^+ ion of the system. That dynamic was explained before, and it has a relation with K charge in the soil and the metabolic function of K^+ ion in the plant, as cell wall components, especially fiber (Reddy and Zhao 2005; Dong et al. 2018). On the other hand, 100 kg K_2O ha^{-1} has demonstrated a positive behavior in the system, and the authors believe that K application can stimulate a critical physiological point.

Finally, the negative results demonstrate a singular effect of soil type with K_2O applications and how K^+ was absorbed by sugarcane. The results finally reinforce that the buffering behavior of soil can directly impact the availability of K to plants. Higher doses of K fertilizer in clayey soils are not necessary (Otto et al. 2010). In summary, sugarcane does not improve its yield and technological parameters when K_2O is applied to the soil with a high absorption capacity but may upgrade the resistance capacity of plants due to a higher fiber production.

Conclusions

Around 60% of K ion leached to the deepest soil profile (0.8 m) at the highest K dose.

An annual application of 150 kg K_2O ha^{-1} increased potassium reserves in the soil, and the main reason was K balance variation in the soil caused by stalk uptake.

K doses did not change sugarcane stalk yield; conversely, it improves K reserves in the soil, which represents advantages to increase the longevity of sugarcane crop produced in the field because K is the most required nutrient by that plant.

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Declarations

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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