Sugar Tech
https://doi.org/10.1007/s12355-024-01443-8

RESEARCH ARTICLE

Effects of Foliar Potassium Supplementation on Yield and Nutrient Uptake of Plant Sugarcane

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Received: 18 March 2024 / Accepted: 25 June 2024

Abstract

Sugarcane, a globally significant economic crop, depends on potassium (K) for critical processes such as photosynthesis and sugar translocation. This study explored the impacts of various foliar K supplements, including 2.5% w/v KCl, KNO_3, K_2SO_4, and K_2SiO_3, alongside diluted molasses and vinasse (5 × dilution). The field experiment was conducted on sugarcane grown in soil with sufficient soil K levels, applying foliar solutions at 120 days at 2667 L/ha. The results indicated that combining soil chemical fertilizers with foliar K_2SiO_3 and KNO_3 resulted in the highest yields of 155.19 and 154.81 tons/ha, respectively, significantly outperforming the foliar water combined with soil chemical fertilizers (132.81 tons/ha) and the control (no basal fertilizer with foliar water, at 130.67 tons/ha, $P \leq 0.05$). This enhancement is expected to result from the improvement in chlorophyll content and photosynthesis, enabled by timely K and nutrient acquisition, bypassing root transport. However, no significant differences were noted among the foliar K forms. Foliar K application also affected nutrient concentrations and uptake, with molasses showing the highest nutrient absorption in stalks: N (322 kg/ha), K (215 kg/ha), S (80.9 kg/ha), and Si (23.2 kg/ha) ($P \leq 0.05$). These findings provide valuable insights and recommendations for utilizing foliar application of K_2SiO_3 and KNO_3 to improve plant sugarcane yield, as well as employing molasses foliar application to enhance nutrient uptake in sugarcane cultivated in soils with adequate K.

Keywords Foliar fertilizer · Potassium silicate · Potassium nitrate · Molasses · Plant sugarcane

Introduction

Sugarcane (*Saccharum* spp.) is an essential agro-industrial crop cultivated in over 130 countries across tropical and subtropical regions, primarily for sugar, ethanol, electricity, and other derivatives production (de Souza Barbosa et al. 2020). As the leading primary crop, sugarcane represented 20 percent of global production in 2020, with 1.9 billion tonnes (FAO 2022). However, yields vary significantly, ranging from 6.27 to 120.74 tons/ha across 91 countries in 2023 (FAOSTAT 2024), influenced by factors such as the growing period length, crop type (plant or ratoon), management practices, and environmental conditions. This variation is in stark contrast to the theoretical yield potential of up to 381 tons/ha (Waclawovsky et al. 2010), indicating substantial room for production improvement. Enhancing sugarcane productivity hinges on selecting crop varieties, optimizing growth environments, and implementing effective management practices. Particularly, potassium (K) management is vital for improving yield and quality, given its significant roles in growth, photosynthesis, drought and cold resistance (Jaiswal et al. 2021; Johnson et al. 2022), and sugar transport, impacting sugarcane juice quality and parameters like commercial cane sugar (CCS), brix, and overall sugar yield (Watanabe et al. 2016; Johnson et al. 2022).

Potassium chloride (KCl) is the most widely used K fertilizer in crop nutrition, primarily due to its low cost and high K_2O content, which reduces handling, storage, transport, and application expenses (Mikkelsen and Roberts 2021).

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However, studies show that K^+ and Cl^- are abundant in sugarcane juice and negatively correlate with sucrose concentration. Cl^- can adversely affect sugarcane quality if K^+ is supplied in excess (Watanabe et al. 2016; Watanabe et al. 2017). Other K fertilizers, like KNO_3, K_2SO_4, and K_2SiO_3, provide essential nutrients including N, S, and Si. N is vital for growth and development (Zeng et al. 2020), S enhances yield and sweetness (Abdelrahman et al. 2014), and Si helps mitigate water stress, improving transpiration, photosynthesis, and nutrient use efficiency while reducing water deficit damage (Teixeira et al. 2022; Costa et al. 2023). Molasses and vinasse, by-products of the sugar industry, are rich in nutrients, particularly K, and their application in sugarcane cultivation can improve productivity and quality, offering a cost-effective nutrient source (Christofoletti 2013; Palmonari et al. 2020). Jiang et al. (2012) reported that continuous application of vinasse to sugarcane fields for 2–3 years resulted in enhanced soil physicochemical properties. Specifically, they observed a decrease in soil bulk density and an increase in total porosity, capillary porosity, and soil K content. Similarly, Wu et al. (2023) found that the combined application of chemical fertilizer with moderate molasses (160 mg C/kg soil) can increase sugarcane biomass grown in pot experiment and facilitate the utilization of stable organic phosphorus (Po) by altering bacterial community and soil properties.

Foliar fertilization involves applying nutrients directly to plant leaves, allowing for efficient nutrient absorption, particularly during growth spurts or when additional nutrition is required. While the increased use of foliar fertilizers in sugarcane cultivation has been explored, most studies focus on comparing or combining foliar with soil applications. Notably, foliar application of K in maize, even with sufficient soil K levels, has been shown to improve yield and sweetness by promoting chlorophyll synthesis (Suwannarit and Sestapukdee 1989). This finding has led to research on the effects of foliar K supplementation in sugarcane fields with adequate soil K, using various K fertilizer formulations to examine their impact on productivity and nutrient uptake. The research also considers the use of molasses and vinasse in foliar applications, aiming to provide a source of supplementary foliar K fertilizer.

Materials and Methods

Study Area and Soil Analysis

To investigate the effects of foliar K supplementation on sugarcane yield and nutrient uptake, a field experiment was conducted at the Kasetsart University Kamphaeng Saen campus, located in Nakhon Pathom province, central Thailand (coordinates: 14°02′09.6″ N, 99°57′33.4″ E, at an elevation of 9 m). The study site's soil is part of the Kamphaeng Saen (Ks) Series, classified as Typic Haplustalfs. A composite soil sample was collected from the topsoil (0–15 cm) before the experiment, air-dried, homogenized by grinding and sieving (0.5 mm and 2 mm), and analyzed using standard physicochemical methods (Soil Survey Staff 2014). The analysis included soil texture, pH1:1, electrical conductivity at saturated soil paste extracts (ECe), organic matter (OM), cation exchange capacity (CEC), total N, available P, K, Ca, and Mg. For extractable S and Si in soil, assessment was conducted using $Ca(H_2PO_4)_2$ and KCl extraction methods, respectively (Fox et al. 1964; Crusciol et al. 2018).

Analysis of Molasses and Vinasse, a By-Product from Sugarcane-Sugar Industry

In this study, molasses and vinasse were analyzed for pH and EC using a pH meter and an electrical conductivity meter, respectively. Total solids (TS) and suspended solids (SS) were determined through dry evaporation and Buchner's funnel methods, with dissolved solids (DS) calculated as DS = TS−SS. The total concentrations of elements such as P, K, Ca, Mg, S, Cu, Fe, Mn, Zn, Ni, Si, Na, Al, Cr, As, and Cd in molasses and vinasse were analyzed via aqua regia digestion (3:1 v/v, HCl: HNO_3) (Chen and Ma 2001), followed by quantification using an inductively coupled plasma-optical emission spectrometer (ICP-OES) (Optima 8300, PerkinElmer, Waltham, MA, USA). P and S concentrations were measured using a UV–Visible spectrophotometer (Lambda 265, PerkinElmer), while total N was determined through wet oxidation with the micro-Kjeldahl method (Soil Survey Staff 2014).

Field Experiment and Sugarcane Cultivation

The field experiment was set up as a randomized complete block design (RCBD) with four replications. The Khon Kaen 3 variety of *Saccharum* spp. hybrid, known for its drought tolerance, high yield, sugar content, stalk number, and favorable ratooning characteristics, was selected (Ponragdee et al. 2011). The experiment took place during the 2022/23 growing season, focusing on the plant cane. Eight treatments of foliar K applications were established: T1—Control (no basal fertilizer + foliar water); T2−BF + water (basal fertilizer + foliar water); T3−BF + KCl (basal fertilizer + 2.5% w/v foliar KCl); T4−BF + KNO_3 (basal fertilizer + 2.5% w/v foliar KNO_3); T5−BF + K_2SO_4 (basal fertilizer + 2.5% w/v foliar K_2SO_4); T6−BF + K_2SiO_3 (basal fertilizer + 2.5% w/v foliar K_2SiO_3); T7−BF + molasses (basal fertilizer + foliar diluted molasses at 5x); and T8−BF + vinasse (basal fertilizer + foliar diluted vinasse at 5×). Each experimental plot measured 7.5×10 m^2, consisting of five rows of sugarcane with a 1.5 m inter-row spacing and 2.0 m between plots.

Table 1 pH and electrical conductivity of foliar fertilizer solution used in this study

Foliar fertilizer solution	pH	EC (dS/m)	K (%, w/v)
Water	7.18	0.03	Not detected
2.5%w/v KCl	6.66	38.35	1.45
2.5%w/v KNO_3	9.02	26.50	1.00
2.5%w/v K_2SO_4	2.82	28.48	1.04
2.5%w/v K_2SiO_3	4.50	14.88	0.20
Diluted molasses (5 × dilution)	4.88	17.00	0.97
Diluted vinasse (5 × dilution)	4.50	17.21	0.53

Basal fertilizer application followed the Department of Agriculture Thailand's 2021 recommendations in accordance with the soil analysis values (OM, available P, and available K) (Department of Agriculture 2021): 75 kg N/ha, 18.75 kg P_2O_5/ha, and 112.5 kg K_2O/ha, applied 30 days post-planting for treatments T2–T8. However, N fertilizer was applied twice, at 30 and 90 days post-planting. Foliar K fertilizers were applied at 120 days post-planting, during the grand or vegetative growth phase (120–240 days) (Somard et al. 2021), using a battery sprayer at 2667 L/ha (20 L/plot). During this phase, sugarcane undergoes rapid growth in height and biomass developing a robust root system and a dense canopy of leaves. The solution was sprayed on the tops and stalks to ensure even coverage. Two control treatments (T1 and T2) involved foliar water application to assess the potential impact of water application. A leaf binder ($C_9H_{19}C_6H_4(OCH_2CH_2)_9OH$), which enhancing absorption and reducing loss from rain wash-off, was added to all fertilizer solutions at a ratio of 1 mL–2 L. Table 1 details the pH, EC, and K content of the foliar fertilizer solution, diluted molasses, and vinasse used in the experiment.

Sugarcane Growth Parameters and Productive Yields

Sugarcane was harvested 12 months after planting from plots of 9 m^2, focusing on three central rows, each two meters long, to determine fresh weight and stalk count. Ten representative stalks were randomly selected from each plot to measure stalk length, diameter, and sugarcane juice quality. Juice quality assessments included Fiber (%) obtained by spinning and drying, Brix (%) measured with a refractometer, and Polarity (%) evaluated using a polarimeter. Subsequently, Thailand's commercial cane sugar (CCS), originally known as Pure Obtainable Cane Sugar or POCS, was calculated as follows (Kirasak et al. 2015; Kulasekara et al. 2024):

$$\text{CCS (\%)} = \frac{3(\%\text{Polarity})}{2}\left(1 - \frac{(\%\text{Fiber})+5}{100}\right) - \frac{\%\text{Brix}}{2}\left(1 - \frac{(\%\text{Fiber})+3}{100}\right) \quad (1)$$

Purity, sugar recovery, and sugar yield also were calculated as follows (Mehareb and Abazied 2017; Divakar et al. 2023):

$$\text{Purity (\%)} = \left(\frac{\%\text{Polarity}}{\%\text{Brix}}\right) \times 100 \quad (2)$$

$$\text{Sugar recovery (\%)} = \left[\%\ \text{Polarity} - 0.4(\%\ \text{Brix} - \%\ \text{Polarity})\right] \times 0.73 \quad (3)$$

$$\text{Sugar yield (tons/ha)} = \frac{\text{Yield (tons/ha)} \times\ \%\text{Sugar recovery}}{100} \quad (4)$$

Furthermore, cane stalks and tops, including leaves and upper parts, were randomly collected from each plot and oven-dried at 70 °C to achieve a consistent dry weight. These samples were homogenized by grinding. The total N content in the cane stalk and tops was determined using the micro-Kjeldahl method for wet oxidation (H_2SO_4-$NaSO_4$-Se), the resulting solution was then used to measure the total concentrations of P, K, and Si. To measure the total concentrations of S, an acid digestion mixture (3:1 HNO_3:$HClO_4$) was used. The concentrations of P and S were determined through UV–Visible spectrophotometry, whereas K and Si concentrations were analyzed using atomic absorption spectroscopy (AAS). These concentration data were then used to calculate the nutrient uptake of sugarcane per unit area.

Statistical Analysis

All data collected in this study, encompassing growth parameters, productive yields, nutrient concentrations, and nutrient uptakes, were analyzed using analysis of variance (ANOVA) with F-tests to statistically evaluate mean differences. Post hoc multiple comparisons were conducted to identify significant differences among treatments, using Duncan's test at the 0.05 probability level ($P \leq 0.05$).

Results and Discussion

General Soil Characteristics

The soil properties (Table 2) show that the soil had a loamy texture, a natural pH of 6.96, and was non-saline, with an ECe of 1.24 dS/m. The soil had a low CEC of 12.49 $cmol_c$/kg and a moderate OM content of 17.30 g/kg. The total N, available P, and K in the soil were measured at 0.74 g/kg, 86.89 mg/kg, and 50.23 mg/kg, respectively. Additionally, the soil contained 3,407 mg/kg of available Ca and 168.71 mg/kg of Mg, while extractable S and Si were 39.25 mg/kg and 16.12 mg/kg, respectively.

Table 2 Physicochemical properties of the studied soil before sugarcane cultivation

Parameters	Unit	Value
Sand	g/kg	332
Silt	g/kg	255
Clay	g/kg	413
Soil texture	–	Loam
pH (1:1 H_2O)	–	6.96
ECe	dS/m	1.24
Cation exchange capacity; CEC	$cmol_c$/kg	12.49
Organic matter; OM	g/kg	17.30
Total N	g/kg	0.74
Available P	mg/kg	86.89
Available K	mg/kg	50.23
Available Ca	mg/kg	3,407
Available Mg	mg/kg	168.71
Extractable S	mg/kg	39.25
Extractable Si	mg/kg	16.12

Table 3 Chemical properties and composition of molasses and vinasse used in this study

Parameter	Unit	Molasses	Vinasse
pH	–	4.93*	4.31
Electrical conductivity (EC)	dS/m	26.45*	38.80
Total solids	mg/L	98.32	38.54
Suspended solids	mg/L	0.12	0.16
Dissolved solids	mg/L	98.20	38.38
Total N	g/L	16.76	10.86
Total P	g/L	1.73	1.45
Total K	g/L	47.69	32.41
Total Ca	g/L	13.30	7.11
Total Mg	g/L	3.26	2.64
Total S	g/L	7.35	2.24
Total Cu	mg/L	2.41	0.12
Total Fe	mg/L	93.80	88.55
Total Mn	mg/L	87.03	99.91
Total Zn	mg/L	7.83	6.06
Total Ni	mg/L	1.96	2.37
Total Si	mg/L	286.56	62.69
Total Na	mg/L	791.96	1,397.22
Total Al	mg/L	21.31	9.68
Total Cr	mg/L	0.34	0.25
Total As	mg/L	ND	ND
Total Cd	mg/L	ND	ND
Total Pb	mg/L	ND	ND

Remark *measuring at 1:2 H_2O, and *ND* Not detected

Property of Molasses and Vinasse

The molasses and vinasse used in this study were highly acidic, with pH values of 4.93 and 4.31, respectively, vinasse being the more acidic. This higher acidity in vinasse could be due to the fermentation process. Both substances had high EC values, 26.45 dS/m for molasses and 38.80 dS/m for vinasse. Molasses had higher levels of dissolved and total solids, as well as viscosity, than vinasse. Both were rich in plant nutrients like K, N, Ca, S, Mg, P, and various micronutrients, with molasses generally containing higher concentrations of these elements. No toxic elements, such as As, Cd, and Pb, were detected in either substance (Table 3).

Effect of Foliar K Supplementation on Growth Parameters and Yields of Plant Sugarcane

K is an essential nutrient crucial for the growth, yield, and sugar content of sugarcane crops. This study investigated the effects of foliar supplementation with various K sources, including KCl, KNO_3, K_2SO_4, K_2SiO_3, diluted molasses, and diluted vinasse, on sugarcane growth parameters. The results showed that no significant differences were observed among different foliar supplementation treatments; however, foliar K_2SiO_3 (T6) supplementation tended to increase cane length (337.49 cm) and diameter (28.61 mm) (Table 4). Similarly, foliar supplementation with diluted vinasse (T8) appeared to raise the number of millable cane (86,667 stalk/ha), although no significant differences were observed among the treatments for these growth parameters. In contrast, foliar supplementation with K_2SiO_3 (T6) and KNO_3 (T4) significantly enhanced cane yield, producing 155.19 and 154.81 tons/ha, respectively ($P \leq 0.05$). These yields were significantly greater than those of the foliar water (T2) and control (T1) treatments, which were 132.81 and 130.67 tons/ha, respectively, as shown in Table 4. Even though the changes in yield attributes were not statistically significant, the combined effect of slight improvements across several parameters could collectively impact the total cane yield significantly. This aligns with several studies that have shown that yield attributes, regardless of statistical significance, can still contribute to differences in yield, or in some cases, may not affect yield at all (Raposo Junior et al. 2013; Desalegn et al. 2023; Kumar et al. 2023). Nevertheless, among the different forms of foliar K supplementation (T3-8), no significant differences in cane yield were found. Furthermore, no significant differences in sugar yield among the treatments were observed, possibly because the increase in cane yield was not substantial enough to significantly boost sugar yield. However, there was a noticeable trend towards increased sugar yield with foliar supplementation of KNO_3 and K_2SiO_3 (19.96 and 19.70 tons/ha, respectively), which correlates with the increase in cane yield (Table 4).

K primarily acts as an enzyme activator in plant metabolism, photosynthesis, starch formation, and the translocation

Table 4 Effects of foliar K supplementation on length, diameter, number of millable cane, cane yield, and sugar yield of sugarcane

Treatments	Length (cm)	Diameter (mm)	Millable cane (stalk/ha)	Cane yield (tons/ha)	Sugar yield (tons/ha)
T1-Control	328.43	26.28	77,778	130.67b	16.88
T2-BF + Water	335.88	27.59	74,815	132.81b	17.34
T3-BF + KCl	331.28	27.53	77,778	141.93ab	18.48
T4-BF + KNO_3	324.02	26.94	81,481	154.81a	19.96
T5-BF + K_2SO_4	330.84	28.05	71,389	137.86ab	18.09
T6-BF + K_2SiO_3	337.49	28.61	75,926	155.19a	19.70
T7-BF + Molasses	331.94	27.98	80,741	146.33ab	19.27
T8-BF + Vinasse	318.64	27.87	86,667	139.22ab	18.54
F-test	ns	ns	ns	*	ns
C.V (%)	5.44	3.80	7.10	6.88	7.84

of proteins and sugars in sugarcane (Cui and Tcherkez 2021). For high yields and optimal juice quality, sugarcane requires K in quantities at least equal to or greater than those of N and P (Kwong 2002). Foliar supplementation with K_2SiO_3 not only enhanced K availability but also supplied additional silicon (Si) to the sugarcane, tending to increased cane length and diameter, and consequently, higher crop weight, as shown in Table 4. Si played a role in reducing carbon (C) concentration while enhancing N and P absorption, suggesting that Si benefits physiological processes, thereby increasing biomass production (Frazão et al. 2020). Additionally, Si reduced transpiration rates and increased chlorophyll concentration in the leaves (Teixeira et al. 2022; Costa et al. 2023), potentially influencing sugarcane yield in this study. The foliar application of K and N, particularly in the form of KNO_3, at 120 days after planting supported the sugarcane during its tillering and grand growth phases, facilitating improved plant growth and development. Nutrient scarcity in the soil can hinder plant growth, but foliar nutrient application mitigates soil nutrient fixation and ensures timely nutrient availability to plants. Consistent with Bamrungrai et al. (2022), it was found that combining soil NPK application with foliar N and K applications during the dry season at 90 days after planting (DAP) and the rainy season at 210 DAP, especially under flooding stress conditions, positively affected yield components, ultimately enhancing sugarcane yield.

Effect of Foliar K Supplementation on Quality of Sugarcane Juice

The impact of foliar K supplementation on sugarcane juice components was examined, revealing no significant changes in fiber content (12.80–14.30%), brix (21.11–21.51%), polarity (18.49–19.20%), purity (87.52–89.83%), CCS (13.78–14.53%), and sugar recovery (12.68–13.31%) in sugarcane grown in K-sufficient soils (Table 5). This observation is consistent with prior studies, indicating that while K fertilizer could increase cane yield, it did not alter the sucrose concentration (polarity) in the cane (Kwong 2002). However, concerning sugarcane yield (Table 4), foliar supplementation with K_2SiO_3 (T6) and KNO_3 (T4) achieved the highest sugarcane yield. Despite showing a tendency to reduce CCS, the difference was not statistically significant

Table 5 Effects of foliar K supplementation on fiber, brix, polarity, purity, commercial cane sugar (CCS), and sugar recovery in sugarcane juice

Treatments	Fiber (%)	Brix (%)	Polarity (%)	Purity (%)	CCS (%)	Sugar recovery (%)
T1-Control	13.73	21.18	18.63	89.04	14.20	12.93
T2-BF + Water	13.88	21.39	18.82	89.25	14.23	13.06
T3-BF + KCl	13.53	21.33	18.82	87.99	14.53	13.02
T4-BF + KNO_3	13.45	21.11	18.64	88.37	13.78	12.90
T5-BF + K_2SO_4	13.10	21.51	18.92	89.02	14.29	13.13
T6-BF + K_2SiO_3	12.80	21.23	18.49	87.52	13.98	12.68
T7-BF + Molasses	14.30	21.25	18.98	89.83	14.48	13.18
T8-BF + Vinasse	14.18	21.15	19.20	88.53	14.23	13.31
F-test	ns	ns	ns	ns	ns	ns
C.V (%)	1.86	1.86	3.64	1.28	2.71	4.33

(Table 5). Furthermore, a noticeable trend towards improved juice quality was observed with foliar application of diluted molasses (T7) and vinasse (T8) compared to other treatments (Table 5). Bamrungrai et al. (2022) also noted that the combined application of soil NPK and foliar N and K during both the dry and rainy seasons did not significantly affect the sugar quality components. Conversely, Ali et al. (1997) reported that split applications of N fertilizer, both solid and foliar, could enhance the polarity and CCS of sugarcane. However, these effects were not observed in our study's N-containing treatments, including KNO_3 (T4), diluted molasses (T7), and vinasse (T8).

Effect of Foliar K Supplementation on Nutrient Concentration of Sugarcane

The findings revealed that nutrient concentrations, including N, P, K, and S, were higher in the tops of the sugarcane than in the cane stalks, with foliar K supplementation significantly affecting these concentrations at $P \leq 0.05$ (Table 6). Foliar application of diluted molasses (T7) significantly increased the total K concentration in both the tops and cane stalks, reaching 25.14 and 2.80 g/kg, respectively. In addition, foliar application with K_2SO_4 (T5), diluted vinasse (T8), and KNO_3 (T4) raised the total K concentration in the cane stalks to 2.70, 2.56, and 2.43 g/kg, respectively, compared to 2.11 g/kg for foliar water (T2) and 1.33 g/kg for the control (T1). Moreover, foliar application of diluted vinasse (T8) significantly increased total N and Si concentrations in the cane stalks, reaching 4.99 and 0.34 g/kg, respectively. Likewise, foliar applications with K_2SiO_3 (T6), diluted molasses (T7), and K_2SO_4 (T5) resulted in higher total Si concentrations in the cane stalks compared to 0.25 g/kg for foliar water (T2) and 0.24 g/kg for the control (T1) (Table 6). Foliar K supplementation with different K sources results in sugarcane obtaining other plant nutrients besides K, the availability of which varies depending on the form of the fertilizer. Foliar applications of molasses and vinasse are advantageous over others due to their rich nutrient content. This is consistent with the findings of Gaafar et al. (2019), who reported that foliar application of molasses and vinasse increased the concentrations of N, P, and K in fruit of sweet pepper.

Conversely, foliar applications with KNO_3 (T4) and K_2SiO_3 (T6) significantly reduced total P and N concentrations in the tops of the sugarcane, with values of 1.73 and 6.86 g/kg, respectively. Similarly, the application of diluted molasses and vinasse decreased total P and S concentrations in the cane stalks, with values of 0.53 and 0.96 g/kg, respectively, compared to foliar water (T2) and the control (T1). Additionally, foliar supplementation with K_2SiO_3 (T6) notably reduced the total S concentration in the tops (1.88 g/kg) and the total K concentration in the cane stalks (1.89 g/kg), akin to the effect of diluted molasses (T7), which also significantly reduced the total S concentration in the tops (1.90 g/kg). Furthermore, foliar K supplementation did not impact the total Si concentration in the tops of the sugarcane (Table 6). However, solely considering the concentration of plant nutrients in sugarcane may not be sufficient due to the dilution effect. Therefore, it is advisable to also consider data on the uptake of plant nutrients in sugarcane alongside (Jarrell and Beverly 1981), as discussed in the next section.

Effect of Foliar K Supplementation on Nutrient Uptake of Sugarcane

Nutrient accumulation in sugarcane primarily occurs in the cane stalks, aligning the plant's overall nutrient uptake with that of the stalks. Foliar K supplementation resulted in significant variations in nutrient uptake in sugarcane at $P \leq 0.05$, except for the leaves, as shown in Figs. 1 and 2. Sugarcane responded positively to soil fertilization (T2-8),

Table 6 Effects of foliar K supplementation on nutrient concentration in the tops and stalks of sugarcane (dry weight basis)

Treatments	Element concentration in top (g/kg)					Element concentration in cane (g/kg)				
	Total N	Total P	Total K	Total S	Total Si	Total N	Total P	Total K	Total S	Total Si
T1-Control	8.55ab	1.94a	21.23c	2.07bc	0.27	1.85d	0.74abc	1.33f	1.04bcd	0.24e
T2-BF + Water	7.88abc	1.89a	22.11bc	2.25ab	0.27	3.78bc	0.75abc	2.11d	1.08abc	0.25de
T3-BF + KCl	8.53ab	1.93a	23.09abc	2.16bc	0.27	3.36c	0.65bcd	2.23d	1.07abc	0.26 cd
T4-BF + KNO_3	8.68a	1.73b	22.68abc	1.99bc	0.27	3.77bc	0.81a	2.43c	1.14ab	0.27 cd
T5-BF + K_2SO_4	7.89abc	1.82ab	24.20ab	2.49a	0.26	3.48c	0.87a	2.70ab	1.16a	0.28c
T6-BF + K_2SiO_3	6.86d	1.85ab	23.86abc	1.88c	0.27	4.14b	0.62 cd	1.89e	0.97 cd	0.31b
T7-BF + Molasses	7.27 cd	1.92a	25.14a	1.90c	0.27	4.28b	0.53d	2.80a	1.11ab	0.31b
T8-BF + Vinasse	7.67bcd	1.86a	22.31bc	2.10bc	0.28	4.99a	0.80ab	2.56bc	0.96d	0.34a
F-test	*	*	*	*	ns	*	*	*	*	*
C.V (%)	9.61	5.61	10.37	11.70	11.88	11.88	16.68	6.73	8.93	0.00

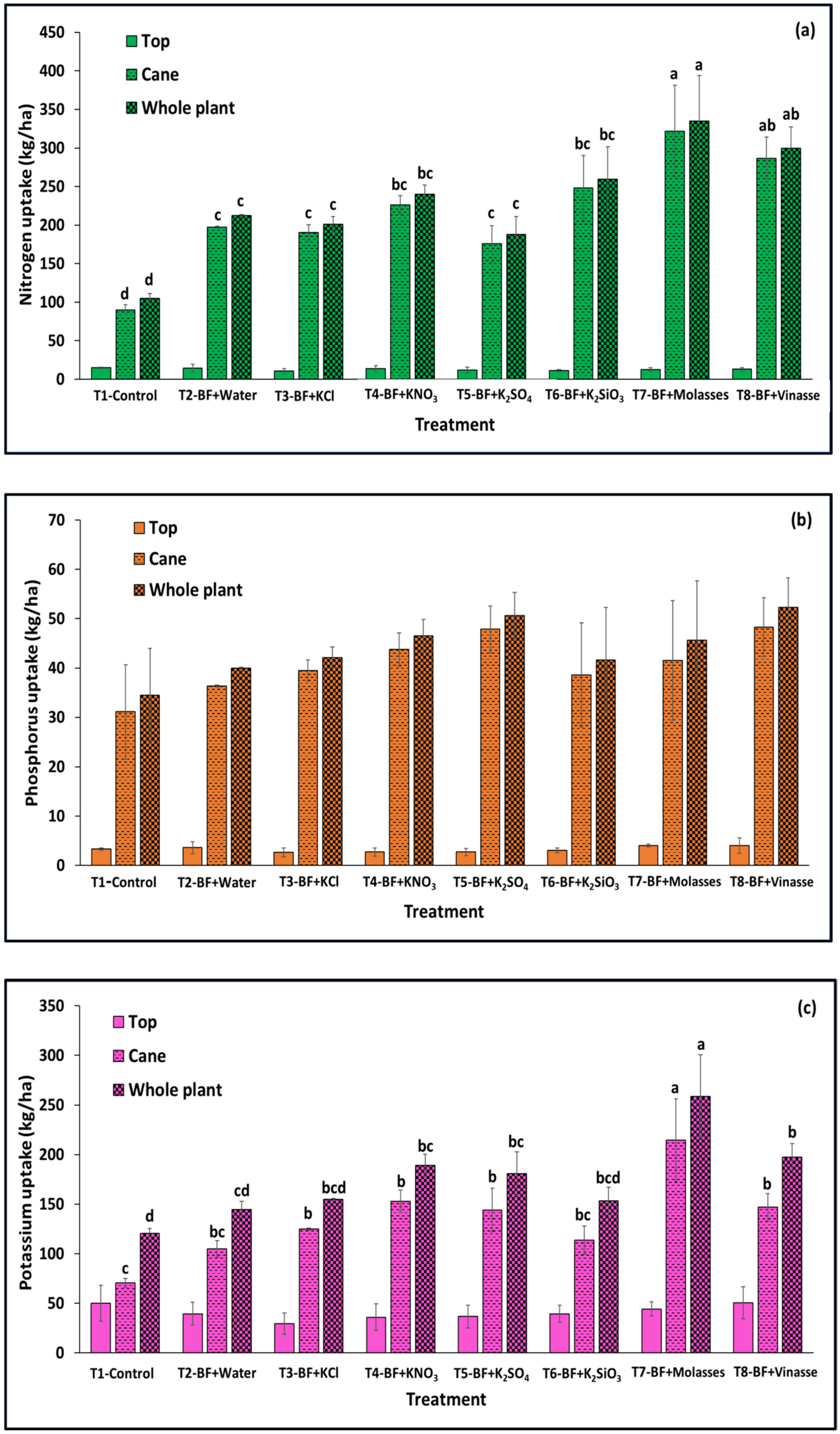

Fig. 1 Effects of foliar K supplementation on N (**a**), P (**b**), and K (**c**) uptake in the tops, stalks, and whole plant of sugarcane. The bars on the columns represent mean values ± standard deviation. Lowercase letters indicate significant differences at $P \leq 0.05$ between treatments

showing increased N uptake compared to the unfertilized control (T1) in both the cane stalks and the entire plant, as illustrated in Fig. 1a. Foliar application with diluted molasses (T7) led to the highest uptakes of N, K, S, and Si in the cane stalks, at 322, 215, 80.9, and 23.2 kg/ha, respectively, and in the entire plant, at 335, 259, 84.3, and 23.6 kg/ha, respectively, which were significantly higher than those from foliar water (T2) and the control (T1) (Figs. 1 and 2). Diluted vinasse application also enhanced N and Si uptake in both the cane stalks (287 and 20.0 kg/ha, respectively) and the entire plant (300 and 20.6 kg/ha, respectively), as indicated in Figs. 1a and 2b. Foliar application with K_2SiO_3 (T6) increased Si uptake in the cane stalks (18.1 kg/ha) and the entire plant (18.6 kg/ha) (Fig. 2b). Moreover, foliar application with diluted vinasse (T8) raised K uptake in the entire plant to 198 kg/ha (Fig. 1c).

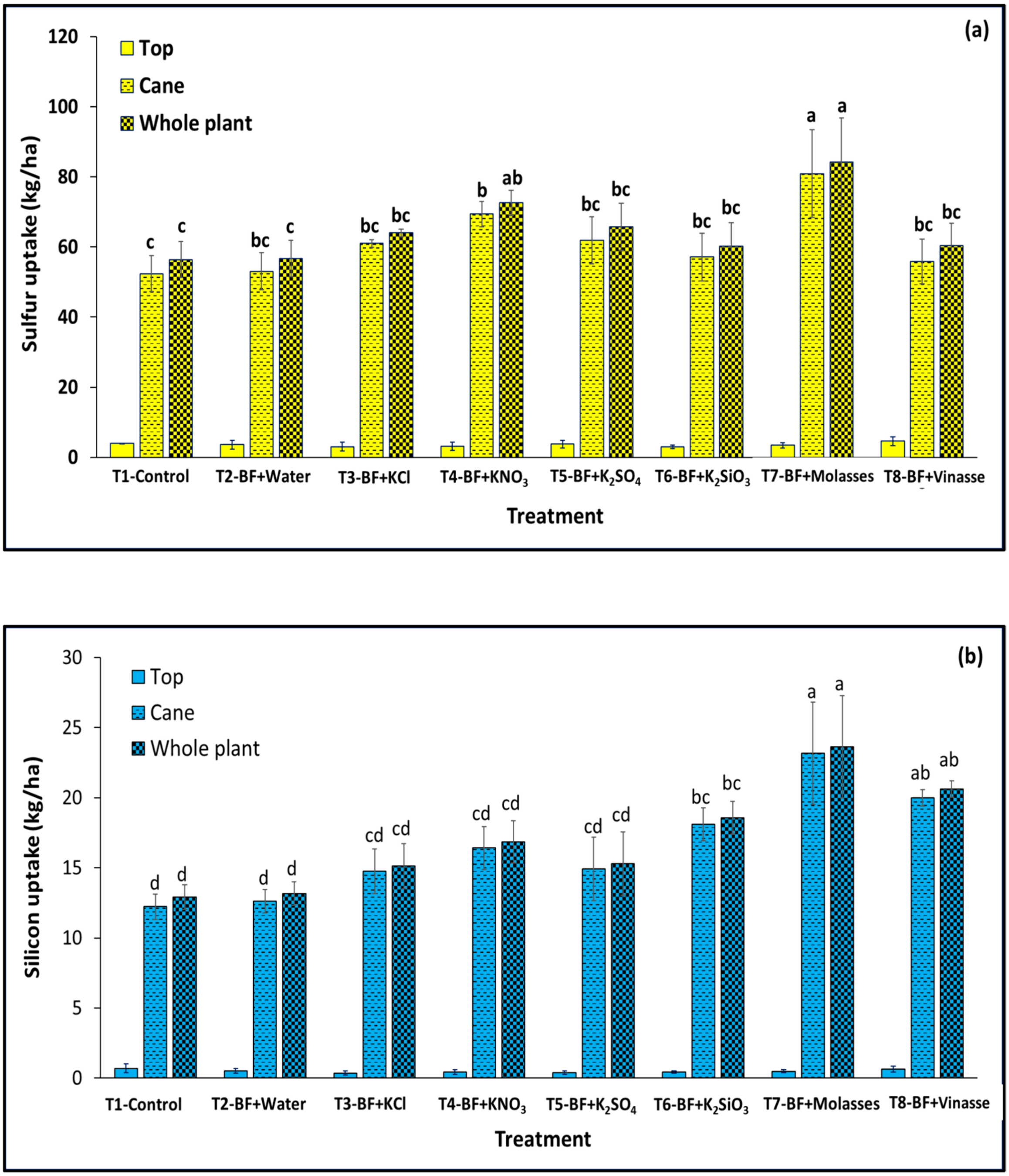

Fig. 2 Effects of foliar K supplementation on S (**a**) and Si (**b**) uptake in the tops, stalks, and whole plant of sugarcane. The bars on the columns represent ± standard deviation. Lowercase letters indicate significant differences at $P \leq 0.05$ between treatments

Molasses, rich in plant nutrients like N and K and containing S and Si (Table 3), facilitated the accumulation of these elements in the sugarcane (Figs. 1 and 2). N promotes growth and canopy expansion, improving light absorption efficiency, essential for increased cane stalk production (Milford et al. 2000; Shah et al. 2024), as observed with foliar supplementation with diluted vinasse (T8), molasses (T7), and KNO_3 (T4), all containing N. K, acting as an osmotic solute, is vital for sustaining cell turgor that drives N-stimulated growth, highlighting the need for adequate K to support the utilization of unassimilated N in the cane, thus aiding the transition of reducing sugars into sucrose during maturity (Kwong 2002). Despite its lower K content, K_2SiO_3 led to the highest yield (Tables 1 and 4), correlating with the lower total K concentration in the cane stalks (Table 6), possibly due to a dilution effect. However, foliar K supplementation did not influence P uptake in the sugarcane in this study (Fig. 1b), even though P was indirectly supplied through foliar application with diluted molasses and vinasse. This absence of effect could be due to the high P availability in the soil (Table 2) and soil fertilization.

This study, conducted on sugarcane grown in soil with sufficient K levels, revealed that foliar K supplementation, particularly K_2SiO_3 and KNO_3, significantly influenced cane yield and internal nutrient dynamics, including nutrient concentration and uptake, and exhibited a trend towards enhancing specific growth parameters. Other factors, such as environmental conditions (temperature, moisture, soil drainage), may contribute to the lack of statistically significant changes in growth parameters (Zhao and Li 2015).

Conclusion

Foliar K supplementation with 2.5% w/v of K_2SiO_3 and KNO_3 at 120 days post-planting significantly increased cane yields, surpassing those from foliar water and the unfertilized control. Despite the lack of statistical significance, foliar K supplementation has shown a trend towards enhancing certain yield attributes. The presence of Si from K_2SiO_3 likely bolstered physiological processes, leading to increased biomass production. Moreover, the supplementation of K and N, especially through KNO_3, proved advantageous during critical growth stages, thereby fostering overall plant growth and development. Despite the observed yield improvements, it's worth noting that foliar K supplementation did not exert significant impacts on sugarcane juice quality. Furthermore, our study revealed substantial variations in nutrient concentration and uptake in plant sugarcane due to foliar K supplementation, with diluted molasses leading to the highest uptakes of N, K, S, and Si in cane stalks. Molasses, being rich in N and K as well as S and Si, promoted the accumulation of these nutrients in sugarcane. This underscores the potential of foliar application in preventing soil nutrient fixation and ensuring timely nutrient availability, enhancing the viability of this approach. In conclusion, our study highlights the effectiveness of foliar K supplementation in increasing cane yield and nutrient uptake in sugarcane. Further research into foliar K supplementation, particularly in ratoon sugarcane, focusing on concentration, rate, and duration, is essential to optimize sugarcane yield under various soil fertility conditions.

Acknowledgements This research is funded by the Graduate School Fellowship Program in agriculture and agro-industry from the Agricultural Research Development Agency (Public Organization) as of fiscal year 2022. The authors are grateful to MITR PHOL GROUP for molasses and vinasse used in this study.

Author contributions All authors contributed to the study conception and design. Material preparation, and data collection were performed by Nattawat Radasai, Daojarus Ketrot, and Tawatchai Inboonchuay. Sample and data analysis were performed by Nattawat Radasai, Daojarus Ketrot, Saowanuch Tawornpruek and Acharaporn Wongsuksri. The first draft of the manuscript was written by Nattawat Radasai, and Daojarus Ketrot. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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