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Influence of foliar and soil potassium fertilizer on ratoon sugarcane performance: yield, quality, and nutrient uptake

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Potassium (K) is essential for optimizing sugarcane production, playing a critical role in various processes that influence yield and quality. However, the effectiveness of different K forms in enhancing sugarcane productivity through foliar application remains underexplored, leaving a significant knowledge gap. This study investigates the impact of various foliar K supplements under differing soil K conditions, hypothesizing that such supplementation will enhance yield and nutrient uptake in ratoon sugarcane. Field trials were conducted on first ratoon sugarcane in loamy soil, using a 2 × 7 factorial in a randomized complete block design. The first factor compared no soil-applied K with soil-applied K, while the second factor consisted of foliar K treatments: water (control), 2.5% weight by volume of KCl, K_2SO_4, K_2SiO_3, KNO_3, diluted molasses, and vinasse at a 5× dilution. Results indicated that foliar supplementation with KNO_3 and K_2SiO_3 (without soil-applied K) effectively maintained ratoon sugarcane yield and sugar yield, comparable to yields achieved with soil-applied K combined with foliar water. Foliar K supplementation also improved the uptake of N, P, K, and Si in cane stalks, matching or exceeding uptake levels observed in ratoon sugarcane with soil-applied K. Although no yield enhancement was observed with the combination of foliar K supplementation and soil-applied K, most foliar K treatments increased K uptake even with adequate soil K levels. In conclusion, foliar K supplementation, particularly with KNO_3 and K_2SiO_3, is an effective strategy for maintaining sugarcane productivity, and improving nutrient use efficiency, especially when K fertilizer is unavailable or costly.

KEYWORDS

foliar potassium, sugarcane juice, potassium nitrate, potassium silicate, potassium use efficiency

Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most economically important crops worldwide, playing a crucial role as the primary raw material in the sugar and ethanol industries. Its role extends beyond just sugar production because the crop also yields a variety of valuable by-products, such as filter cake, bagasse, molasses, and vinasse. These by-products contribute to various industrial processes, making sugarcane a versatile and indispensable crop in global agricultural and industrial systems (1, 2). Sugarcane is a tropical grass belonging to the family *Poaceae* and is known for its ability to tiller and produce ratoons (3). Ratooning is a common practice in sugarcane cultivation, where the crop is harvested, and the stubble is allowed to regrow for subsequent harvests. This ability to ratoon reduces the need for frequent replanting, saving both time and resources, makes sugarcane cultivation more sustainable and cost-effective (4, 5). However, a major challenge with ratoon sugarcane crops is the gradual decline in yield with each successive harvest, which is influenced by a variety of factors, including the sugarcane variety, soil conditions, and overall environmental factors (5–7). Nutrient management, particularly the management of potassium (K), has emerged as a key strategy to address the decline in ratoon crop yield (8). K is an essential element for plants and animals, playing a vital role in various physiological and metabolic processes. In sugarcane, K is particularly critical due to its involvement in processes such as photosynthesis, enzyme activation, water regulation, carbohydrate metabolism, and providing abiotic stress tolerance (9, 10). The high K requirement of sugarcane makes its management a focal point in efforts to sustain and enhance yield, especially in ratoon crops. The study by Radasai et al. (11) showed that foliar K supplementation, in addition to adequate soil K supply, significantly improved the yield and nutrient uptake of plant sugarcane in tropical regions. These findings have spurred further research into the potential benefits of K supplementation in ratoon sugarcane. The current study aimed to evaluate the effects of various foliar K supplementation strategies on the productivity of ratoon sugarcane grown under both sufficient and insufficient soil K conditions. We hypothesize that foliar K supplementation will enhance the yield and nutrient uptake of ratoon sugarcane, regardless of whether soil K is sufficient, by supporting physiological processes essential for growth. Additionally, we expect that different K forms will vary in effectiveness due to differences in their properties and composition. The findings could provide valuable insights for developing foliar fertilizer management strategies to enhance sugarcane production and nutrient use efficiency, while addressing the growing global demand for sugar and biofuels.

Materials and methods

Experimental plot area, soil sampling, and analysis

The experimental site was located in Kamphaeng Saen district of Nakhon Pathom province, central Thailand (Latitude: 14.036028, Longitude: 99.958806). It covered approximately 0.8 ha and was a part of the experimental plots of Kasetsart University on the Kamphaeng Saen campus. The plot soil belonged to the Kamphaeng Saen (Ks) soil series, being classified as Typic Haplustalfs with a loam-textured soil. The sugarcane plot used for the experiment was a first ratoon crop of the Khon Kaen 3 variety of a *Saccharum* spp. hybrid, continuing the study reported by Radasai et al. (11). Figure 1 presents the environmental data including the rainfall and air temperature during the growing season of planted sugarcane (Feb 2022–Feb 2023) and of first ratoon sugarcane (Feb 2023–Jan 2024). The annual rainfall

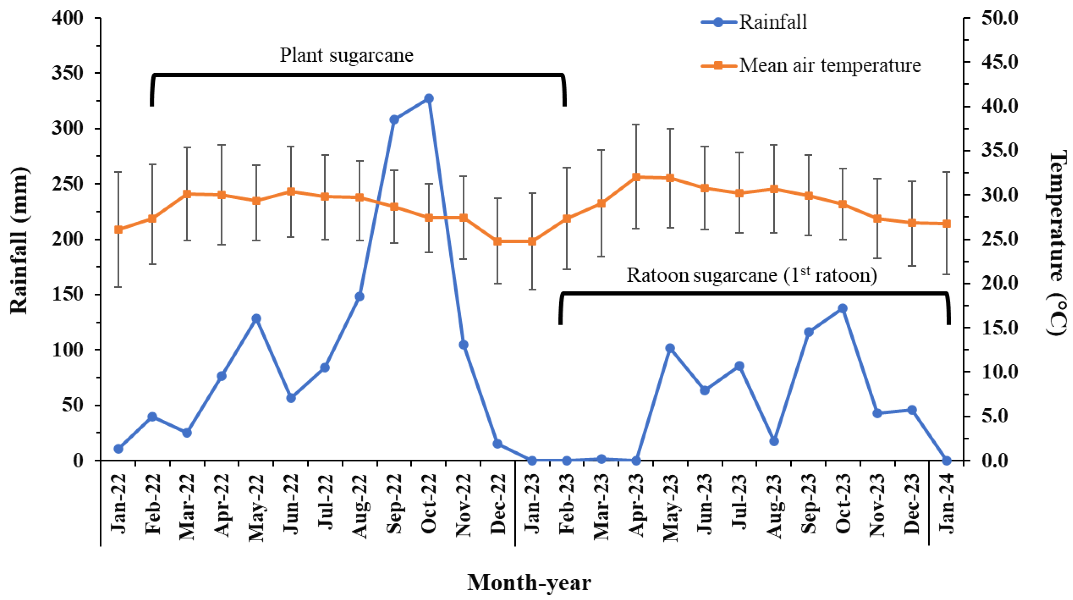

FIGURE 1
Average monthly rainfall and air temperature data in experimental area. Error bars represent the maximum and minimum air temperature for each month.

levels for the 2022–2023 and 2023–2024 growing seasons were 1,316 mm and 613 mm, respectively, and the mean temperatures were 28.3°C and 29.3°C, respectively.

Following the harvesting period of plant sugarcane (pre-experiment), composite topsoil samples were randomly collected from a depth of 0–15 cm to analyze various physical and chemical properties: particle size distribution, pH, electrical conductivity, cation exchange capacity, organic matter, total nitrogen (N), available phosphorus (P), extractable potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and silicon (Si) (12–15). Table 1 presents the properties of the soil prior to conducting the experiment. Additionally, soil samples were collected from each subplot after harvest to analyze the amount of extractable K in the soil post-experiment, using the same method as for the pre-experiment soil samples.

Experimental design and field experiment

The experiment was designed as a 2 × 7 factorial in a randomized complete block design with three replications, totaling 14 treatment combinations across 42 subplots. The first factor was the application of soil K fertilizer (basal fertilizer), with K0 representing no application and K1 representing application. The second factor was the type of foliar-supplemented K fertilizer, consisting of seven solutions: F0-water (control); F1-KCl; F2-K_2SO_4; F3-K_2SiO_3; F4-KNO_3; F5-molasses; and F6-vinasse. The foliar chemical fertilizers used were of commercial fertilizer grade and applied at a concentration of 2.5% weight by volume (w/v), while the molasses and vinasse were obtained from the sugarcane-sugar-ethanol industry and applied with 5× dilution. Each subplot was 7.5 × 10 m^2 and consisted of five rows sugarcane, along with other planting details according to Radasai et al. (11). Basal chemical fertilizer was applied approximately 2 months after harvesting the plant crop at rates of 93.75 kg N ha^{-1}, 18.75 kg P_2O_5 ha^{-1}, and 75 kg K_2O ha^{-1} for K1; however, no K fertilizer was applied for K0. These fertilizer rates were based on recommendations by Thai Department of Agriculture for ratoon sugarcane, using soil analysis data (16). N fertilizer was applied in two splits (at 2 and 4 months) and foliar fertilizer was sprayed when the ratoon sugarcane was aged about 5 months, during the grand or vegetative growth phase (120–240 days), according to Tayade et al. (17). The foliar fertilizer was sprayed uniformly over the subplots at a rate of 2,000 L ha^{-1} (15 L per plot). An anionic, straight-chain leaf binder was used at a rate of 1 mL per 2 L of fertilizer solution in all treatments to enhance absorption and reduce any loss from rain wash-off. Table 2 lists the properties of the foliar-applied fertilizer solution and the amounts of nutrients provided to each treatment through foliar supplementation. Irrigation was provided using a furrow system solely to prevent water deficiency, while pest control measures were applied uniformly across all subplots.

TABLE 1 Soil properties after plant sugarcane harvest and prior to conducting experiment.

Parameter	Value
Sand[a](g kg^{-1})	253
Silt[a](g kg^{-1})	494
Clay[a](g kg^{-1})	253
Texture[a]	Loam
pH (1:1 H_2O)[b]	6.51
Electrical conductivity[c](dS m^{-1})	0.71
Cation exchange capacity[d]($cmol_c$ kg^{-1})	15.0
Organic matter[e](g kg^{-1})	17.8
Total nitrogen[f](g kg^{-1})	0.10
Available phosphorus[g](mg kg^{-1})	68.8
Extractable potassium[h](mg kg^{-1})	72.4
Extractable cacium[h](mg kg^{-1})	1940
Extractable magnesium[h](mg kg^{-1})	229
Extractable sulfur[i](mg kg^{-1})	3.58
Extractable iron[j](mg kg^{-1})	68.7
Extractable manganese[j](mg kg^{-1})	72.6
Extractable zinc[j](mg kg^{-1})	1.57
Extractable copper[j](mg kg^{-1})	2.10
Extractable silicon[k](mg kg^{-1})	15.8

Method of measurement: [a]pipette method; [b]pH meter; [c]measured when soil saturated with water; [d]1N NH_4OAc pH 7.0 method; [e]Walkley and Black titration; [f]Kjeldahl method; [g]Bray II extraction; [h]1N NH_4OAc pH 7.0 extraction; [i]$Ca(H_2PO_4)_2$ extraction; [j]DTPA extraction; [k]KCl extraction.

Measurement of growth, yield, and juice quality of first ratoon sugarcane

The first ratoon sugarcane from 9 m^2 plots was harvested 11 months after the initial harvest, focusing on the three central rows, each 2 m in length. The evaluation included determining the fresh weight and the number of millable canes, with 10 representative millable canes being randomly selected from each plot to measure length and diameter. Sugarcane juice quality parameters—fiber (%), Brix (%), polarity (%) or sucrose concentration, commercial cane sugar (CCS, %), purity (%), sugar recovery (%), and sugar yield (Mg ha^{-1}), were analyzed and calculated as described by Radasai et al. (11).

Plant collection and analysis

Two representative millable canes were randomly collected from each plot and oven-dried at 70°C until a consistent dry weight was achieved. Then the dried samples were homogenized using grinding. The total N content was determined using the Kjeldahl method with wet oxidation (H_2SO_4-$NaSO_4$-Se), according to Bremner (18). The resulting solution was used to measure the total concentrations of P, K, and Si. Total S concentrations were measured using an acid digestion mixture (3:1 HNO_3:$HClO_4$),

TABLE 2 Some properties of foliar-applied fertilizer solutions and nutrient amounts.

Type of foliar fertilizer	Properties					
	pH[a]	Electrical conductivity[b] ($dS\ m^{-1}$)	Soluble potassium[c] (%, w/v)	Total nitrogen[d]	Soluble sulfur[e]	Soluble silicon[c]
Water	6.77	0.01	nd	na	na	na
2.5% w/v KCl	6.22	38.59	1.40 (28)	na	na	na
2.5% w/v K_2SO_4	2.87	27.52	1.07 (21)	na	0.43 (8.5)	na
2.5% w/v K_2SiO_3	4.81	13.25	0.21 (4.3)	na	na	0.003 (0.1)
2.5% w/v KNO_3	9.35	26.56	0.96 (19)	0.18 (3.6)	na	na
Molasses (5× dilution)	4.90	17.34	0.89 (18)	0.09 (1.8)	0.04 (0.8)	0.024 (0.5)
Vinasse (5× dilution)	4.37	16.88	0.49 (10)	0.01 (0.2)	0.04 (0.8)	0.004 (0.1)

Methods of measurement: [a]pH meter; [b]electrical conductivity meter; [c]atomic absorption spectroscopy; [d]element analyzer; [e]UV-visible spectroscopy. Values in parentheses indicate the nutrient applied through foliar supplementation ($kg\ ha^{-1}$). w/v , weight by volume; nd, not detected; na, no analysis.

according to Kongtawee et al. (19). The concentrations of P and S were determined via UV-visible spectrophotometry, while the K and Si concentrations were analyzed using atomic absorption spectroscopy. Then, these concentration data were used to calculate the nutrient uptake of sugarcane stalks per unit area.

Data analysis

All collected data (cane length, cane diameter, fresh yields, juice quality, and nutrient uptake) were checked for normality using the Kurtosis and Skewness tests. All data were normally distributed, except for juice purity, which required data transformation using reflection and logarithmic methods prior to analysis. Analysis of variance with F-tests was conducted to statistically assess mean differences. *Post hoc* multiple comparisons were performed using Duncan's test at a significance level of 0.05 ($p < 0.05$) to identify significant differences among treatments, with the IBM SPSS Statistics 27.

K use efficiency (KUE), defined as the mass of harvested products relative to the mass of K applied to the sugarcane, and agronomic efficiency (AE) of applied K were adapted from the method for N use efficiency described by Thorburn et al. (20). KUE was calculated based on the yields for each treatment (K rate applied through basal and foliar applications, expressed as $K_2O\ ha^{-1}$), and AE was calculated as the increase in yield per kg of K_2O applied through basal and foliar applications, as follows:

$$\text{KUE (kg cane kg}^{-1}\text{ K}_2\text{O)} = \frac{\text{Sugarcane yield (kg cane ha}^{-1}\text{)}}{\text{K fertilizer applied (kg K}_2\text{O ha}^{-1}\text{)}} \quad (1)$$

$$\text{AE (kg cane kg}^{-1}\text{ K}_2\text{O)} = \frac{\text{Sugarcane yield}_t - \text{Sugarcane yield}_0\text{ (kg cane ha}^{-1}\text{)}}{\text{K fertilizer applied (kg K}_2\text{O ha}^{-1}\text{)}} \quad (2)$$

where *Sugarcane yield*$_t$ and *Sugarcane yield*$_0$ refer to the sugarcane yields for each treatment and the control, respectively.

Results

Growth and yield performance of first ratoon sugarcane

The growth of the first ratoon sugarcane variety Khon Kaen 3 in loamy soil, whether with or without soil-applied K combined with foliar K supplementation, did not significantly affect the growth parameters of the ratoon sugarcane (cane length, cane diameter, and the number of millable canes). Additionally, soil K application and foliar K supplementation did not significantly affect these growth parameters (Table 3). However, the sugarcane yield was affected by the interaction between soil K levels and foliar K supplementation at $p < 0.05$. The combination of no soil-applied K with foliar K_2SiO_3 (K0×F3) resulted in the highest cane yield, which was not significantly different from those achieved with no soil-applied K combined with foliar KNO_3 (K0×F4) and with soil-applied K combined with foliar water (K1×F0). Furthermore, the absence of soil-applied K combined with foliar K supplementation using KCl (K0×F1), vinasse (K0×F6), and K_2SO_4 (K0×F2) resulted in ratoon sugarcane yields, which were not significantly different from those with soil-applied K and foliar water (K1×F0). The significantly lowest ratoon sugarcane yield was in the treatment without soil-applied K and with foliar water application (K0×F0), likely due to insufficient K supply. In the case of soil with sufficient K application, foliar K supplementation with K_2SO_4 (K1×F2), KNO_3 (K1×F4), and KCl (K1×F1) did not significantly affect ratoon sugarcane yield compared to foliar water (K1×F0). Conversely, foliar K supplementation with K_2SiO_3 (K1×F3), molasses (K1×F5), and vinasse (K1×F6) significantly reduced the ratoon sugarcane yield compared to foliar water (K1×F0), as shown in Table 3.

TABLE 3 Effect of soil potassium application and foliar potassium supplementation on growth and fresh yield of first ratoon sugarcane.

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
Cane length (cm)								
K0	306	314	314	330	306	326	319	316
K1	315	309	302	310	306	309	306	308
Mean	311	311	308	318	306	317	313	
p value								
Soil K fertilizer	0.10							
Foliar fertilizer supplementation	0.76							
Soil K fertilizer × Foliar fertilizer supplementation	0.67							
CV (%)	4.72							
Cane diameter (cm)								
K0	30.5	29.0	29.9	29.8	29.4	29.4	30.3	29.6
K1	29.3	28.9	30.1	30.2	29.1	27.2	32.0	29.5
Mean	29.9	29.0	29.5	30.0	29.3	28.3	31.1	
p value								
Soil K fertilizer	0.88							
Foliar fertilizer supplementation	0.08							
Soil K fertilizer × Foliar fertilizer supplementation	0.19							
CV (%)	5.15							
Number of millable canes (stalks ha^{-1})								
K0	88,888	80,556	86,113	81,481	94,444	75,000	85,188	84,644
K1	101,850	85,188	94,444	94,444	81,481	75,925	70,369	85,831
Mean	95,369	83,331	91,113	86,669	86,669	75,556	77,775	
p value								
Soil K fertilizer	0.80							
Foliar fertilizer supplementation	0.20							
Soil K fertilizer × Foliar fertilizer supplementation	0.37							
CV (%)	15.85							
Cane yield (Mg ha^{-1})								
K0	101e	127bc	125bcd	149a	143ab	113cde	125bcd	126
K1	135ab	124bcd	130bc	112cde	129bc	111cde	105de	119
Mean	118	126	127	131	137	112	115	
p value								
Soil K fertilizer	0.17							
Foliar fertilizer supplementation	0.07							
Soil K fertilizer × Foliar fertilizer supplementation	<0.01							
CV (%)	7.64							

K0 and K1 refer to no soil-applied K and soil-applied K at 75 kg K_2O ha^{-1}, respectively. F0-F6 refer to the types of foliar fertilizer supplementation at a rate of 2,000 L ha^{-1}. Means with different capital letters indicate significant differences of main effect and different lowercase letters indicate significant differences of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

Juice quality and sugar output of first ratoon sugarcane

The study results indicated that the soil-applied K fertilizer and foliar K supplementation in various forms had no effect on juice quality parameters (fiber, Brix, polarity, and CCS), nor on sugar quantity, as measured by sugar recovery. Additionally, there were no interaction effects between these two factors for any of these juice quality parameters and sugar recovery. However, soil-applied K fertilizer did significantly increase the purity of the sugarcane juice compared to the treatment without soil-applied K (Table 4).

The interaction between soil K fertilization and foliar K supplementation impacted the sugar yield. Non-soil-applied K combined with foliar KNO_3 (K0×F4) produced the highest sugar yield. However, this was not significantly different from the combination treatments of non-soil-applied K with foliar K_2SiO_3 (K0×F3), soil-applied K with foliar water (K1×F0), and foliar KNO_3 (K1×F4), (Table 4). With the non-soil-applied K, foliar K supplementation helped to maintain sugar yield levels, preventing any decrease. Based on the study results, non-soil-applied K combined with foliar K supplementation resulted in sugar yields that were not significantly different from treatments with soil-applied K combined with foliar water (K1×F0), except when foliar molasses was applied (K0×F5). On the other hand, the ratoon sugarcane that was treated using soil-applied K, foliar K supplementation with K_2SiO_3 (K1×F3), molasses (K1×F5), and vinasse (K1×F6) resulted in a significant reduction in the sugar yield, similar to the reduction in overall sugarcane yield (Table 3).

Nutrient uptake patterns in first ratoon sugarcane

The interaction between soil K application and foliar K supplementation influenced the uptake of N, P, K, and Si, but had no effect on the uptake of S in the cane stalk of ratoon sugarcane. In addition, based on the results, foliar K supplementation induced ratoon sugarcane without soil-applied K to take up N at levels comparable to those with soil-applied K. Notably, the treatment without soil-applied K combined with foliar water (K0×F0) had the lowest N uptake, which was significantly different from the other treatments (Table 5). The combination of non-soil-applied K with foliar supplementation of KNO_3 (K0xF4) produced the significantly highest uptake of P in ratoon sugarcane. However, this value was not significantly different from those of the combinations of soil-applied K with foliar KNO_3 (K1×F4), non-soil-applied K with foliar supplementation of K_2SiO_3 (K0×F3), and K_2SO_4 (K0×F2) (Table 5).

The combination of non-soil-applied K with foliar supplementation of KNO_3 (K0×F4) produced the significantly highest K uptake in the ratoon sugarcane stalk. However, this was not significantly different from the treatments of soil-applied K combined with foliar K_2SiO_3 (K1×F3), KCl (K1×F1), and KNO_3 (K1×F4), and non-soil-applied K combined with K_2SiO_3 (K0×F3) (Table 5). The combination of soil-applied K with foliar supplementation of K_2SO_4 (K1×F2) produced in the significantly highest Si uptake in the cane stalk of ratoon sugarcane. This was higher than the treatments where molasses (F5) and water (F0) were sprayed, regardless of whether soil-applied K was used, as well as being higher than the treatment with soil-applied K combined with foliar KCl (K1×F1). There were no significant differences in S uptake across treatment combinations, although there was a trend toward higher S levels with the combination of soil-applied K and foliar supplementation of K_2SO_4 (K1×F2), likely due to the additional S supplied by the K_2SO_4 foliar application (Table 5).

Discussion

Ratoon sugarcane response to foliar K supplementation

Based on the results, KNO_3 and K_2SiO_3 foliar supplementations were more effective among the various types of K foliar fertilizers. Foliar supplementation with 2.5% w/v of KNO_3 and K_2SiO_3 in ratoon sugarcane grown in soil with an extractable K level of 72.4 mg kg^{-1} without additional soil-applied K, maintained ratoon sugarcane productivity—cane yield and sugar yield—at levels comparable to treatments with soil-applied K. When soil K levels are limited, foliar K supplementation can enhance K absorption and utilization within the plant, particularly during the grand growth period, which typically has higher nutrient demands. This effect was particularly notable in the uptake of nutrients such as N, P, and Si. Furthermore, foliar K application (whether or not soil-applied K was used) promoted K uptake in the cane stalk at levels equal to or higher than from soil-applied K alone. Foliar fertilization optimizes nutrient absorption, translocation, and assimilation within the plant, thereby increasing fertilization efficiency (21).

In soils where K fertilizer was applied, foliar K supplementation did not lead to further increases in cane yield and sugar yield compared to soil-applied K without foliar K supplementation (foliar water). In contrast, combining foliar K_2SiO_3, molasses, and vinasse with soil-applied K had a negative impact, resulting in lower cane and sugar yields than for soil-applied K without foliar supplementation. It was likely that these foliar K applications created some unfavorable conditions for the ratoon sugarcane, leading to a decrease in cane and sugar yields. The exact cause is still unknown; even considering the properties of the fertilizer solutions applied, as shown in Table 2, there was no evidence that the pH and EC of these fertilizers affected sugarcane growth. The pH of these three fertilizer solutions was low (pH 4.37–4.81) but still higher than that of the K_2SO_4 solution (pH 2.87), while their EC range (13.25–17.34 dS m^{-1}) was lower than that of the other fertilizer solutions (26.56–38.59 dS m^{-1}). Additionally, they had a lower concentration of K than the other solutions but contained Si, which has been shown to have positive effects on sugarcane growth and yield (22–24).

The response of ratoon sugarcane that had received sufficient K through soil application differed from that of plant sugarcane, despite foliar application reducing the translocation distance of K from roots to leaves. These findings contrasted with Radasai et al. (11), who reported no negative effects of foliar K supplementation

TABLE 4 Effect of soil potassium application and foliar potassium supplementation on juice quality of first ratoon sugarcane.

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
Fiber (%)								
K0	11.3	11.1	12.5	12.1	12.1	12.3	11.6	11.9
K1	12.3	12.2	11.9	12.0	12.0	11.7	11.2	11.9
Mean	11.8	11.7	12.2	12.0	12.1	12.0	11.4	
p value								
Soil K fertilizer					0.89			
Foliar fertilizer supplementation					0.71			
Soil K fertilizer × Foliar fertilizer supplementation					0.70			
CV (%)					7.46			
Brix (%)								
K0	20.5	20.8	20.6	20.1	20.7	20.3	20.3	20.5
K1	20.6	21.0	20.3	21.4	21.1	20.7	20.8	20.8
Mean	20.6	20.9	20.4	20.7	20.9	20.5	20.5	
p value								
Soil K fertilizer					0.07			
Foliar fertilizer supplementation					0.87			
Soil K fertilizer × Foliar fertilizer supplementation					0.65			
CV (%)					3.19			
Polarity (%)								
K0	18.4	19.0	18.7	17.7	18.7	18.2	18.2	18.4
K1	18.7	19.3	18.4	19.6	19.2	18.6	18.9	19.0
Mean	18.5	19.1	18.5	18.7	19.0	18.4	18.5	
p value								
Soil K fertilizer					0.05			
Foliar fertilizer supplementation					0.84			
Soil K fertilizer × Foliar fertilizer supplementation					0.61			
CV (%)					4.42			
Commercial cane sugar; CCS (%)								
K0	14.4	14.9	14.4	13.5	14.5	14.0	14.1	14.2
K1	14.4	15.1	14.3	15.3	15.0	14.4	14.9	14.8
Mean	14.4	15.0	14.3	14.4	14.7	14.2	14.5	
p value								
Soil K fertilizer					0.05			
Foliar fertilizer supplementation					0.77			
Soil K fertilizer × Foliar fertilizer supplementation					0.51			
CV (%)					5.56			

(Continued)

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TABLE 4 Continued

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
Purity (%)								
K0	89.9	91.2	90.5	88.0	90.6	89.6	89.4	89.9B
K1	90.5	92.0	90.7	91.8	91.3	89.8	91.0	91.0A
Mean	90.2	91.6	90.6	89.9	90.9	89.7	90.2	
p value								
Soil K fertilizer	0.04							
Foliar fertilizer supplementation	0.64							
Soil K fertilizer × Foliar fertilizer supplementation	0.46							
CV (%)	1.75							
Sugar recovery (%)								
K0	12.9	13.3	13.0	12.2	13.1	12.7	12.6	12.8
K1	13.0	13.6	12.9	13.8	13.5	13.0	13.3	13.3
Mean	12.9	13.4	12.9	13.0	13.3	12.8	12.9	
p value								
Soil K fertilizer	0.05							
Foliar fertilizer supplementation	0.82							
Soil K fertilizer × Foliar fertilizer supplementation	0.59							
CV (%)	4.97							
Sugar yield (Mg ha^{-1})								
K0	13.0g	16.9bcd	16.3cd	18.2ab	18.7a	14.3efg	15.8cde	16.2
K1	17.6abc	16.9bcd	16.7bcd	15.4def	17.4abc	14.4efg	13.9fg	16.0
Mean	15.3BCD	16.9AB	16.5ABC	16.8AB	18.0A	14.4D	14.9CD	
p value								
Soil K fertilizer	0.79							
Foliar fertilizer supplementation	<0.01							
Soil K fertilizer × Foliar fertilizer supplementation	<0.01							
CV (%)	5.96							

K0 and K1 refer to no soil-applied K and soil-applied K at 75 kg K_2O ha^{-1}, respectively. F0-F6 refer to the types of foliar fertilizer supplementation at a rate of 2,000 L ha^{-1}. Means with different capital letters indicate significant differences of main effect and different lowercase letters indicate significant differences of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

TABLE 5 Effect of soil potassium application and foliar potassium supplementation on nutrient uptake in cane stalks of first ratoon sugarcane.

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
N uptake (kg ha^{-1})								
K0	67.6b	96.0a	98.3a	105a	112a	86.5ab	95.7a	94.0
K1	102a	101a	111a	93.0a	109a	91.1ab	87.5ab	99.5
Mean	81.3	98.4ABC	105AB	99.2ABC	110A	88.8BC	91.6ABC	

(Continued)

TABLE 5 Continued

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
p value								
Soil K fertilizer					0.28			
Foliar fertilizer supplementation					0.04			
Soil K fertilizer × Foliar fertilizer supplementation					0.03			
CV (%)					13.02			
P uptake (kg ha^{-1})								
K0	14.1fg	17.6def	22.7abcd	23.5abc	26.5a	10.6g	17.0ef	19.4
K1	20.3bcde	19.6cde	15.2efg	20.5bcde	25.2ab	19.0cdef	18.4cdef	19.7
Mean	17.2BC	18.4BC	18.9BC	22.0AB	25.8A	15.6C	17.8BC	
p value								
Soil K fertilizer					0.84			
Foliar fertilizer supplementation					<0.01			
Soil K fertilizer × Foliar fertilizer supplementation					<0.01			
CV (%)					13.63			
K uptake (kg ha^{-1})								
K0	29.4e	47.0cd	37.1de	67.5ab	80.0a	35.6de	62.4bc	52.0
K1	39.0de	66.9ab	56.4bc	70.7ab	64.1abc	48.4cd	49.8cd	56.5
Mean	31.8C	56.9AB	46.6BC	68.8A	72.0A	40.7C	57.4AB	
p value								
Soil K fertilizer					0.44			
Foliar fertilizer supplementation					<0.01			
Soil K fertilizer × Foliar fertilizer supplementation					<0.01			
CV (%)					14.11			
S uptake (kg ha^{-1})								
K0	27.1	45.7	40.3	38.5	42.7	34.1	35.5	37.9
K1	39.1	42.9	49.4	38.3	34.9	39.9	38.7	40.2
Mean	33.1	43.9	44.9	38.4	38.3	37.0	37.1	
p value								
Soil K fertilizer					0.34			
Foliar fertilizer supplementation					0.10			
Soil K fertilizer × Foliar fertilizer supplementation					0.07			
CV (%)					17.03			
Si uptake (kg ha^{-1})								
K0	3.01c	4.80ab	4.60abc	5.12ab	4.47abc	4.29bc	5.41ab	4.52
K1	4.10bc	3.98bc	6.04a	4.61abc	4.72ab	3.82bc	4.86ab	4.57
Mean	3.44C	4.39ABC	5.32A	4.87AB	4.59AB	4.01BC	5.14AB	

(Continued)

TABLE 5 Continued

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
p value								
Soil K fertilizer	0.97							
Foliar fertilizer supplementation	0.02							
Soil K fertilizer × Foliar fertilizer supplementation	0.05							
CV (%)	17.32							

K0 and K1 refer to no soil-applied K and soil-applied K at 75 kg K_2O ha^{-1}, respectively. F0-F6 refer to the types of foliar fertilizer supplementation at a rate of 2,000 L ha^{-1}. Means with different capital letters indicate significant differences of main effect and different lowercase letters indicate significant differences of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

on sugarcane yield and sugar yield. In their study, foliar supplementation with K_2SiO_3 and KNO_3 significantly increased plant sugarcane yields. Additionally, in plant sugarcane, foliar K supplementation, especially with molasses, enhanced nutrient uptake. It was possible that foliar K supplementation had a more pronounced effect on plant sugarcane compared to ratoon sugarcane that had already received adequate soil-applied K. Alternatively, environmental factors may have influenced the results. For example, during the 2023–2024 growing season in the study, the rainfall was one-half of that recorded in the 2022–2023 season, while the average temperature was slightly higher (Figure 1). This was consistent with a general decrease in the average sugarcane yield in Nakhon Pathom province, Thailand, which fell from 53.8 Mg ha^{-1} in the 2022–2023 season to 50.6 Mg ha^{-1} in the 2023–2024 season (25, 26). Robertson et al. (27) observed that water deficits during the tillering phase significantly impacted leaf area, tillering, and biomass accumulation, but had minimal effect on final yield. In contrast, they reported that water deficits during the canopy establishment phase had a much greater negative effect on final yield, including total biomass, stalk biomass, and stalk sucrose.

Potassium use efficiency of first ratoon sugarcane

The KUE of first ratoon sugarcane revealed that withholding soil-applied K while applying foliar K supplementation resulted in a KUE range of 2,493–19,149 kg cane kg^{-1} K_2O, significantly higher than soil-applied K alone (K1F0), which measured at 1,798 kg cane kg^{-1} K_2O. Similarly, soil-applied K combined with foliar K supplementation produced a lower KUE (987–1,349 kg cane kg^{-1} K_2O) than foliar K alone (Figure 2). Among foliar K sources, K_2SiO_3

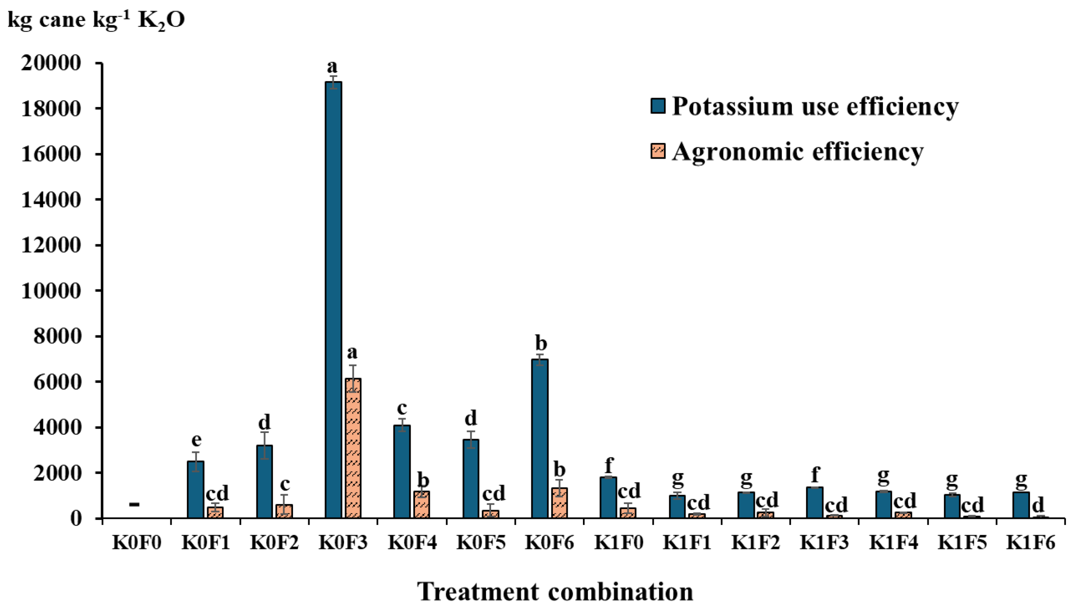

FIGURE 2
Potassium (K) use efficiency and agronomic efficiency of first ratoon sugarcane of the Khon Kaen 3 variety. K0 and K1 refer to no soil-applied K and soil-applied K (75 kg K_2O ha^{-1}), respectively. F0–F6 represent foliar K supplementation with water (control), KCl, K_2SO_4, K_2SiO_3, KNO_3, diluted molasses, and diluted vinasse, respectively, at a rate of 2,000 L ha^{-1}. Bars on the columns represent ± standard deviation. Lowercase letters indicate significant differences between treatment combinations at $p < 0.05$. K0F0 is not shown as there was no K applied either through soil or foliar methods.

TABLE 6 Extractable potassium in soil after experiment.

Soil K fertilizer	Foliar fertilizer supplementation							Mean
	F0-Water	F1-KCl	F2-K_2SO_4	F3-K_2SiO_3	F4-KNO_3	F5-Molasses	F6-Vinasse	
Extractable K in soil (mg kg^{-1})								
K0	75.1	72.4	65.7	66.0	72.1	69.8	65.4	69.5
K1	79.1	76.4	71.6	78.4	76.5	69.6	71.5	73.6
Mean	74.4	74.0	69.2	72.2	74.8	69.7	68.4	
p value								
Soil K fertilizer				0.29				
Foliar fertilizer supplementation				0.96				
Soil K fertilizer × Foliar fertilizer supplementation				>0.99				
CV (%)				19.40				

K0 and K1 refer to no soil-applied K and soil-applied K at 75 kg K_2O ha^{-1}, respectively. F0-F6 refer to the types of foliar fertilizer supplementation at a rate of 2,000 L ha^{-1}.

exhibited the highest KUE despite its low K content (Table 2), as it generated substantial ratoon cane yields, followed by foliar vinasse and KNO_3. This suggests that K_2SiO_3 may enhance K efficiency by delivering Si, which could synergistically promote plant growth under limited K conditions. Likewise, AE values confirmed that foliar K application without soil-applied K produced consistently higher results than soil-applied K alone, with AE values ranging from 351 to 6,129 kg cane kg^{-1} K_2O, compared to 446 kg cane kg^{-1} K_2O for soil-applied K alone (K1F0). When soil-applied K was combined with foliar K, AE values dropped further to between 36 and 249 kg cane kg^{-1} K_2O (Figure 2). These findings suggest that, when soil K levels are limited, foliar K supplementation, especially with K_2SiO_3, can effectively enhance KUE and AE in first ratoon sugarcane. Traditional soil-applied K may be less effective in ratoon cane, possibly due to soil fixation or leaching losses that limit K availability. Foliar applications may bypass these issues by delivering K directly where it is needed for growth.

While foliar K application incurs additional costs due to increased labor requirements and the need for specialized spraying equipment, the same equipment used for pesticide application can be utilized if thoroughly cleaned beforehand. Foliar K application offers higher KUE by requiring less K fertilizer, which can lead to cost savings by reducing K inputs while maintaining yields. However, scaling up foliar K application presents practical limitations, including the need for appropriate equipment, favorable weather conditions to ensure effective application, and sufficient farmer training. Educating farmers is essential, as foliar application requires precise timing and technique to maximize its benefits.

Sustainability of soil potassium levels with foliar K supplementation

Maintaining adequate plant nutrient levels in the soil is crucial for sustainable crop production. Although foliar supplementation effectively maintains productivity—both cane and sugar yields—without soil-applied K, relying solely on foliar K supplementation over the long term could potentially affect soil nutrient status. Analysis of soil available K after the experiments (Table 6) shows that, although there were no significant differences between treatment combinations, treatments without soil K application generally exhibited lower available K levels compared to those with soil K application. This indicated a need for further research, particularly into continuous cropping systems relying solely on foliar K without soil K application. Continuous cropping can deplete soil nutrients, alter microbial communities, and change soil properties (28). Despite these concerns, using foliar KNO_3 and K_2SiO_3 in soils with insufficient available K can be a valuable strategy for farmers, especially when fertilizer prices are high. Foliar fertilizer application can reduce the total amounts of fertilizer applied while achieving high fertilizer efficiency (29). This approach offers a way to reduce K fertilizer usage or to manage soils with high K accumulation from long-term use, where foliar application provides an efficient means of nutrient delivery without further increasing soil K saturation. Foliar application of 2.5% w/v KNO_3 and K_2SiO_3 can serve as a practical and effective alternative to soil K fertilizers, providing a viable option for maintaining productivity and managing nutrient levels.

Variation in plant and first ratoon sugarcane productivity

Comparing the productivity of plant sugarcane (from 11) with first ratoon sugarcane (from the current study) of the same variety and at the same site, it was observed that the fresh yield of first ratoon sugarcane decreased by 7.7–23.5%, with an average reduction of 14.0%. This reduction was consistent with the general trend of decreasing yields in ratoon sugarcane due to factors such as variety, nutrient management, and environmental conditions (5–7). Historical data from 35 experimental plots of the Khon Kaen 3 variety in Northeastern Thailand (1995–2007) showed average yields of 113.13 Mg ha^{-1} for plant sugarcane and

103.13 Mg ha^{-1} for ratoon sugarcane, an 8.8% reduction (30). Global comparisons show similar reductions: Indonesia with 3.5–24.8% (31); India with 27.4% for first ratoon and 31.4% for second ratoon (32) and 7.0–9.6% in calcareous soils (33); South Africa with 12.3–24.4% for the first-to-fifth ratoons (5); and Brazil with 0.9–11.1% (34).

The sugar yield of first ratoon sugarcane, with various foliar K supplementation treatments, decreased by 8.7% to 25.5%, averaging a 14.1% reduction compared to plant sugarcane. Typically, this decrease was due to the reduced fresh yield as the number of ratoon crops increased. Environmental factors may also play a role. For example, rainfall is crucial during the growth stage for higher-quality yields, and sucrose accumulation occurs post-primary growth (17). Historical data for the Khon Kaen 3 variety shows that sugar yield was 16.94 Mg CCS ha^{-1} for plant sugarcane and 15.38 Mg CCS ha^{-1} for ratoon sugarcane, indicating a 9.23% decrease (30). In the current study, based on the CCS calculations, the sugar yield decreased by 5.2% to 24.9%, averaging a 12.2% reduction. These reductions aligned with findings from other regions: India (6.7–9.2%, 33) and Indonesia (1.3–38.7%, 31). The variation in sugar yield reduction may also have been due to differences in sugar yield calculation, as some studies base their calculations on sugar recovery, CCS, or sucrose content.

A comparison of nutrient uptake between planted sugarcane (11) and the ratoon (current study) variety Khon Kaen 3 revealed significant reductions in N, P, K, S, and Si in the ratoon crop, averaging 57.0%, 53.6%, 60.7%, 37.1%, and 72.8%, respectively. These reductions were primarily due to the lower cane yield and reduced nutrient concentrations in the ratoon stalks, leading to a notable decrease in nutrient uptake per unit area. Singh et al. (35) suggested that ratooning induces rhizospheric changes, including pH alterations, soil enzymatic activities, and phenolic contents during the ratoon growth stage, which impact ratoon root properties. These changes result in significant impediment to nutrient acquisition and uptake, ultimately limiting growth and biomass production. Furthermore, field management practices such as irrigation, nutrient management, burning, and trashing, along with diseases, pests, increased competition between tillers, and subsequent tiller mortality, are associated with reduced ratoon cane yields (6). Additionally, nutrient uptake in the first ratoon cane in the current study was similar to that of planted sugarcane of the Khon Kaen 3 variety, as reported by Amonpon et al. (36) and Whangrattanacharoen et al. (37), grown in sandy soil and loamy sand soil, respectively. However, the nutrient uptake was lower than reported by Juntahum et al. (38), likely due to differences in environmental conditions, soil properties, and management practices. Compared to other regions, N and K uptake in the current study was typically lower, while P uptake was similar (33, 39, 40). These variations were likely influenced by differences in sugarcane varieties and environmental factors.

Conclusions

Based on the results of the current study, foliar K supplementation did not enhance the yield of first ratoon sugarcane (cane and sugar yield) when the soil K levels were already sufficient. However, foliar K supplementation with 2.5% w/v of K_2SiO_3, KCl, KNO_3, and K_2SO_4 increased K uptake in cane stalks, even when the soil K was adequate. Notably, foliar K supplementation with KNO_3 and K_2SiO_3 effectively maintained both cane and sugar yields at levels comparable to those achieved with soil-applied K, particularly in loamy soil with available K around 72.4 mg kg^{-1}. For ratoon sugarcane with insufficient soil-applied K, foliar K supplementation improved nutrient uptake of N, P, K, and Si to levels equal to or exceeding those in ratoon sugarcane with sufficient soil K. The KUE and AE of foliar K supplementation was higher than that of soil-applied K, highlighting its potential to improve nutrient uptake while reducing fertilizer inputs. Maintaining soil nutrient levels is crucial, as prolonged reliance on foliar K supplementation without concurrent soil K application may lead to rapid K depletion. Based on the findings of this study, it can be concluded that foliar K supplementation, especially with KNO_3 and K_2SiO_3, was an effective strategy for maintaining sugarcane productivity and soil K sustainability. This approach is particularly useful when K fertilizer cannot be applied during periods of high fertilizer costs or when residual soil K levels are high, helping to preserve soil K levels and improve nutrient use efficiency.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KK: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. DK: Conceptualization, Data curation, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. ST: Conceptualization, Supervision, Writing – review & editing. CW: Conceptualization, Supervision, Writing – review & editing. TI: Conceptualization, Supervision, Writing – review & editing. AW: Conceptualization, Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

1. Raza Q-U-A, Bashir MA, Rehim A, Sial MU, Raza HMA, Atif HM, et al. Sugarcane industrial byproducts as challenges to environmental safety and their remedies: a review. *Water*. (2021) 13:3495. doi: 10.3390/w13243495

2. Lima IM, Beacorn JA. Targeting a sustainable sugar crops processing industry: a review (Part I)—by-product applications. *Sugar Tech*. (2022) 24:970–91. doi: 10.1007/s12355-022-01169-5

3. Kumar Gaur R. *Omics Approaches for Sugarcane Crop Improvement*. Boca Raton: CRC Press (2022). doi: 10.1201/9781003292425

4. Xu F, Wang Z, Lu G, Zeng R, Que Y. Sugarcane ratooning ability: research status, shortcomings, and prospects. *Biology*. (2021) 10:1052. doi: 10.3390/biology10101052

5. Dlamini NE, Franke AC, Zhou M. Indices for measuring ratooning ability of sugarcane varieties. *Crop Sci*. (2024) 64:667–77. doi: 10.1002/csc2.21191

6. Ramburan S, Wettergreen T, Berry SD, Shongwe B. Genetic, environmental and management contributions to ratoon decline in sugarcane. *Field Crops Res*. (2013) 146:105–12. doi: 10.1016/j.fcr.2013.03.011

7. Dlamini NE, Zhou M. Soils and seasons effect on sugarcane ratoon yield. *Field Crops Res*. (2022) 248:108588. doi: 10.1016/j.fcr.2022.108588

8. Bhatt R, Singh P, Ali OM, Latef AAHA, Laing AM, Hossain A. Yield and quality of ratoon sugarcane are improved by applying potassium under irrigation to potassium deficient soils. *Agronomy*. (2021) 11:1381. doi: 10.3390/agronomy11071381

9. Uchida R. Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In: Silva JA, Uchida R, editors. *Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture*. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu (2000). p. 31–55.

10. Hasanuzzaman M, Bhuyan MHMB, Nahar K, Hossain MS, Mahmud JA, Hossen MS, et al. Potassium: a vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy*. (2018) 8:31. doi: 10.3390/agronomy8030031

11. Radasai N, Ketrot D, Tawornpruek S, Inboonchuay T, Wongsuksri A. Effects of foliar potassium supplementation on yield and nutrient uptake of plant sugarcane. *Sugar Tech*. (2024) 26:1665–75. doi: 10.1007/s12355-024-01443-8

12. Fox RL, Olson RA, Rhoades HF. Evaluating the sulfur status of soils by plant and soil tests. *Soil Sci Soc America J*. (1964) 28:243–6. doi: 10.2136/sssaj1964.03615995002800020034x

13. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci Soc America J*. (1978) 42:421–8. doi: 10.2136/sssaj1978.03615995004200030009x

14. Soil Survey Staff. *Kellogg soil Survey laboratory methods manual. Soil survey investigations report No.42, Version 5.0*. R. B, editor. U.S. Department of Agriculture, Natural Resources Conservation Service (2014).

15. Crusciol CAC, de Arruda DP, Fernandes AM, Antonangelo JA, Alleoni LRF, do Nascimento CAC, et al. Methods and extractants to evaluate silicon availability for sugarcane. *Sci Rep*. (2018) 8:916. doi: 10.1038/s41598-018-19240-1

16. Department of Agriculture. *The Recommendation for Fertilizer Application Based on Soil Analysis for Economic Crops*. Thailand: Department of Agriculture, Ministry of Agriculture and Cooperatives (2021).

17. Tayade AS, Geetha P, Anusha S, Arunkumar R, Vasantha S. Agro-technologies to sustain sugarcane productivity under abiotic stresses. In: Verma KK, Song XP, Rajput VD, Solomon S, Li YR, Rao GP, editors. *Agro-industrial Perspectives on Sugarcane Production under Environmental Stress*. Springer, Singapore (2022). p. 231–66. doi: 10.1007/978-981-19-3955-6_13

18. Bremner JM. *Nitrogen-Total," in Methods of Soil Analysis, Part 3: Chemical Methods*. Sparks DL, editor. Wisconsin: Soil Science Society of America: Madison (1996) p. 1085–121. doi: 10.2136/sssabookser5.3.c37

19. Kongtawee K, Ketrot D, Wisawapipat W, Tawornpruek S. Assessing critical level of lead in soils for leafy vegetables. *Water Air Soil pollut*. (2022) 233:459. doi: 10.1007/s11270-022-05937-7

20. Thorburn PJ, Biggs JS, Palmer J, Meier EA, Verburg K, Skocaj DM. Prioritizing crop management to increase nitrogen use efficiency in Australian sugarcane crops. *Front Plant Sci*. (2017) 8:1504. doi: 10.3389/fpls.2017.01504

21. Andrade J, Oliveira E, Lima A, Amorim GPS, Oliveira ES, Freire FJ, et al. Foliar Fertilization improves the nitrogen nutrition of sugarcane. *Agriculture*. (2024) 14:1984. doi: 10.3390/agriculture14111984

22. Savant NK, Korndörfer GH, Datnoff LE, Snyder GH. Silicon nutrition and sugarcane production: a review. *J Plant Nutr*. (1999) 22:1853–903. doi: 10.1080/01904169909365761

23. Verma KK, Liu XH, Wu KC, Singh RK, Song QQ, Malviya ML, et al. The impact of silicon on photosynthetic and biochemical responses of sugarcane under different soil moisture levels. *Silicon*. (2020) 12:1355–67. doi: 10.1007/s12633-019-00228-z

24. Costa MG, dos Santos Sarah MM, de Mello Prado R, Palaretti LF, de Cássia Piccolo M, de Souza Júnior JP. Impact of Si on C, N, and P stoichiometric homeostasis favors nutrition and stem dry mass accumulation in sugarcane cultivated in tropical soils with different water regimes. *Original Res Articles*. (2022) 13:949909. doi: 10.3389/fpls.2022.949909

25. Office of The Cane Sugar Board. *Annual Report on the Sugarcane Planting Situation for the 2022/23 Growing Season*. Thailand: Information and Communication Technology Group, Strategy and Planning Division, Ministry of Industry (2023).

26. Office of The Cane Sugar Board. *Annual Report on the Sugarcane Planting Situation for the 2023/24 Growing Season*. Thailand: Information and Communication Technology Group, Strategy and Planning Division, Ministry of Industry (2024).

27. Robertson MJ, Inman-Bamber NG, Muchow RC, Wood AW. Physiology and productivity of sugarcane with early and mid-season water deficit. *Field Crops Res*. (1999) 64:211–27. doi: 10.1016/S0378-4290(99)00042-8

28. Pang Z, Tayyab M, Kong C, Liu Q, Liu Y, Hu C, et al. Continuous sugarcane planting negatively impacts soil microbial community structure, soil fertility, and sugarcane agronomic parameters. *Microorganisms*. (2021) 9:2008. doi: 10.3390/microorganisms9102008

29. Niu J, Liu C, Huang M, Liu K, Yan D. Effects of foliar fertilization: a review of current status and future perspectives. *J Soil Sci Plant Nutr*. (2021) 21:104–18. doi: 10.1007/s42729-020-00346-3

30. Ponragdee W, Sansayawichi T, Sarawat P, Moulanon T, Kapetch P, Leabwon U. Khon Kaen 3: a sugarcane variety for the northeast. *Thai Agric Res J*. (2011) 29:283–301. doi: 10.14456/thaidoa-agres.2011.16

31. Riajaya PD, Hariyono B, Cholid M, Kadarwati FT, Santoso B, Djumali, et al. Growth and yield potential of new sugarcane varieties during plant and first ratoon crops. *Sustainability*. (2022) 14:14396. doi: 10.3390/su142114396

32. Gomathi R, Rao PNG, Rakkiyappan P, Sundara BP, Shiyamala S. Physiological studies on ratoon ability of sugarcane varieties under tropical Indian condition. *Am J Plant Sci*. (2013) 4:274–81. doi: 10.4236/ajps.2013.42036

33. Kumar N, Rana L, Singh AK, Pramanick B, Gaber A, Alsuhaibani AM, et al. Precise macronutrient application can improve cane yield and nutrient uptake in widely spaced plant-ratoon cycles in the Indo-gangetic plains of India. *Original Res Articles*. (2023) 7:1223881. doi: 10.3389/fsufs.2023.1223881

34. Farhate CVV, Souza ZM, Cherubin MR, Lovera LH, Oliveira IN, Guimarães Júnnyor WS, et al. Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage. *Rev Bras Ciec do Solo*. (2022) 46:e0210123. doi: 10.36783/18069657rbcs20210123

35. Singh P, Rai RK, Suman A, Srivastava TK, Singh KP, Yadav RL. Ratooning induced rhizospheric changes impede nutrient acquisition and growth in sugarcane ratoon crop during grand growth stage in sub-tropics. *Sugar Tech*. (2013) 15:52–64. doi: 10.1007/s12355-012-0189-2

36. Amonpon W, Kalayasilapin P, Luanmanee S, Thippayarugs S, Paisancharoen K. Optimal crop nutrient management for sugarcane production on sandy soil in the eastern of Thailand. *Khon Kaen Agric J 40(supplement*. (2012) 3):141–8.

37. Whangrattanacharoen T, Ketrot D, Anusontpornperm S, Thanachit S. Effect of vinasse from ethanol plant and chemical fertilizer on yield and nutrients uptake of sugarcane, and some soil properties. *Khon Kaen Agric J*. (2020) 48:1276–91. doi: 10.14456/kaj.2020.113

38. Juntahum S, Jongrungklang N, Kaewpradit W, Lumyong S, Boonlue S. Impact of arbuscular mycorrhizal fungi on growth and productivity of sugarcane under field conditions. *Sugar Tech*. (2020) 22:451–9. doi: 10.1007/s12355-019-00784-z

39. Shukla SK, Yadav RL, Singh PN, Singh I. Potassium nutrition for improving stubble bud sprouting, dry matter partitioning, nutrient uptake and winter initiated sugarcane (*Saccharum* spp. Hybrid Complex) ratoon yield. *Eur J Agron*. (2009) 30:27–33. doi: 10.1016/j.eja.2008.06.005

40. Ghube NB, Kadlag AD, Kamble BM. Soil test crop response based integrated plant nutrition system for desired yield target of preseasonal sugarcane ratoon on Inceptisols. *J Appl Natural Sci*. (2017) 9:799–804. doi: 10.31018/jans.v9i2.1279