# Studies into Potassium Management for Sugarcane Production in Northeast Thailand Based on Factory Juice Analysis Combined with Cultivation Experiment

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**Abstract:** Potassium (K) is one of the essential nutrients for plants; nevertheless, it has been reported that overdoses of K fertilizer have resulted in impaired sugarcane juice quality and a reduction in the efficiency of sugar processing. Therefore, to maximize sugar production per unit area, K levels in sugarcane should be kept just adequate. The aim of this study was to propose a practical method of K fertilizer management based on the nutritional status of sugarcane juice. First, we conducted a pot experiment treating sugarcane with different K fertilizers (potassium chloride, KCl and potassium sulfate, $K_2SO_4$) and K rates (0, 2, 10, 30, and 50 g pot$^{-1}$). Raising KCl rates caused considerably negative impacts on not only the quality but the yield as juice K concentration exceeded 2000 mg L$^{-1}$, whereas the effects of the $K_2SO_4$ treatments were less severe. Second, we collected sugarcane juice at a raw sugar factory over 2 years. Because of its ease of measurement, electrical conductivity was used to deduce juice K concentration. The juice analysis revealed that more than 60% of the samples possessed K concentrations higher than 2000 mg L$^{-1}$, and the relationship between juice K and sugarcane quality was significantly negative. These results indicate that impairments of sugarcane quality have probably been occurring in the actual fields. Given that sugarcane is generally fertilized with KCl, reducing K fertilizer dose should contribute to improving sugarcane quality and accordingly sugar yield when juice K is considered high.

**Keywords:** Sugarcane, Potassium Management, Juice Quality, Sugar Yield, Electrical Conductivity

## 1. Introduction

In sugarcane production, it is necessary to improve juice quality as well as cane yield to maximize sugar production per unit area. Fertilizer management practice is one of the factors that affect sugarcane quality and thus appropriate practices based on the nutritional status of each field are imperative for quality improvement. Potassium (K) is one of the three essential macronutrients for plant growth, along with nitrogen and phosphorus, and plays numerous roles including enzyme activation, stomatal activity, photosynthesis, transport of sugar, water, and nutrient, and synthesis of protein and starch [1]. Bartholomew and Janssen have made an observation that plants absorb considerably more K than is necessary for the normal processes of growth,

known as luxury consumption [2]. Depending on the crop, the K requirement can be nearly as high as the nitrogen requirement. In fact, sugarcane may remove up to 800 kg of K ha$^{-1}$ [3].

Despite its importance, it has been reported that overdoses of K fertilizer beyond suitable levels rather lead to lower quality of cane juice [4, 5]. In addition, on the basis of a hypothesis that sugarcane quality is affected by the accessory components of K fertilizer as well as K itself, Watanabe et al. examined the effects of raising K levels using potassium chloride (KCl) and potassium sulfate ($K_2SO_4$) and observed significant sucrose reductions in sugarcane juice with increasing levels of KCl but not of $K_2SO_4$ [6]. This point was further studied and it was confirmed that the sucrose reduction was caused only when K was supplied in excess

amounts combined with chloride in the form of KCl [7]. These findings are considered noteworthy since the vast majority of crops are fertilized with KCl, actually accounting for more than 90% of world K consumption in agriculture [8]. Apart from its adverse impacts on the juice quality, K is also known to impair sucrose recovery in the process of sugar production, being the most abundant cation in cane juice to the extent that between 30 to 50% of ash [4]. In sugarcane juice or raw sugar, ash refers to the soluble inorganic salts and increases the solubility of sucrose; therefore, high levels of ash increase sucrose loss during both the milling and refining processes [9]. All these negative aspects suggest that K in sugarcane should be kept at just adequate levels to optimize juice quality during cultivation and recoverable sugar yield during processing, so that sugar production per unit area is maximized.

In order to perform suitable K fertilizer managements, the knowledge of the K status of each sugarcane field is necessary; however, the common nutrient diagnosis methods by analyzing leaf or soil samples can be quite complex because these exercises usually require considerable time and technical machines and skills. Nutrient diagnosis should be as easy as possible to meet the demands of anyone who requires it. Electrical conductivity (EC) denotes a material's ability to allow the transport of an electric charge and can be easily and quickly measured with simple devices. Because of its convenience, in the sugar and sugarcane industry, EC has been intensively used to manage ash content during the milling process [10, 11] and in breeding programs [9, 12, 13], as it is closely associated with ash in sugarcane juice [14-16]. Similarly, a highly positive correlation exists between EC and K in sugarcane juice [17]. Hence, the use of this parameter will surely facilitate the analysis of juice K concentration in a large number of samples.

The present study, composed of two parts, was carried out in Northeast Thailand. First, sugarcane was grown using different rates of K supplied with either KCl or $K_2SO_4$ to investigate the treatment effects and determine an optimum K range in juice in terms of both yield and quality. Second, sugarcane juice was collected at a raw sugar factory to observe variations of juice K and its relationship with cane quality in the study area. The aim of the study was to propose a practical method of K fertilizer management based on the K status of sugarcane juice to improve sugarcane quality and eventually sugar production in this region.

## 2. Methodology

### 2.1. Sugarcane Cultivation Experiment with Various K Treatments

A pot experiment was conducted from May 23, 2017 to February 12, 2018 in a greenhouse at Mitr Phol Sugarcane Research Center Company Limited in Chaiyaphum, Thailand (16°46'N, 102°12'E; 223 m a.s.l.). Stalks of *Saccharum* spp cv. Khon Kaen 3 (KK3) were cut into single-bud setts and sown in a nursery. After the first fully expanded leaves were

confirmed, seedlings were transplanted into plastic pots (34 cm wide × 28 cm deep with a 24 cm base width, 18 L) filled with 15 kg of soil mixture composed of three materials: clay soil, sandy soil, and filter cake (1:1:1 on a volume basis; pH, 7.2; EC, 3.4 S m$^{-1}$; OM, 2.2%; exchangeable K, 232 mg kg$^{-1}$). During cultivation, tillers were immediately removed after emergence and irrigation was performed with tap water through daily soil moisture evaluation to prevent water stress. Due to unknown reasons, a few plants showed inhibited growth and accordingly were removed from the experiment.

The plants were fertilized four times at 14, 84, 134, and 196 days after transplanting (DAT). Following the recommended doses in the study area, 4 g N, 2 g P, 0.3 g Ca, 0.3 g S, 0.25 g Mg, 2.4 mg Fe, 1.4 mg Mn, 1.4 mg Zn, 1 mg Cu, 1 mg B, and 1 mg Mo pot$^{-1}$ in total were supplied to all the plants in the forms of urea, ammonium sulfate, ammonium phosphate, and multiple fertilizer. Along with a K-free group, eight treatments were set up using four rates of K (2, 10, 30, and 50 g pot$^{-1}$) supplied with either KCl or $K_2SO_4$. Four replicates were prepared for each group, except those given 50 g K pot$^{-1}$ which had one replicate. The group names are expressed as combinations of the supplied K type and rate; for example, KCl-2.

Plant height from the ground to the base of the top visible dewlap leaf, number of leaves, and soil-plant analysis development (SPAD) index of the top visible dewlap leaf using a chlorophyll meter (SPAD-502 Plus, Konica Minolta) were measured every 28 days from 13 DAT until the termination of the experiment. At 265 DAT, three to four plants for each group were cut at the ground. Stalk height, weight, and diameter were recorded after removal of parts unnecessary for sugar refining.

Clean stalks were crushed using a three-roll squeezer, and the obtained juices were roughly filtered for later measurements. Pol in juice (%) was derived from Brix in juice (%) measured with a refractmeter (Schmidt + Haensch, ATR-P) and polarimeter reading recoded on a Schmidt + Haensch instrument (Polartronic NIR W2) following the method of International Commission for Uniform Methods of Sugar Analysis with minor modification [18]. These parameters were used to calculate Brix in cane (%), Pol in cane (%), impurities in cane (%), and commercial cane sugar (CCS, %) as follows, using an assumed figure of 13 for fiber (%).

$$\text{Brix in cane} = \text{Brix in juice} \times [1 - (\text{fiber} + 3)/100] \quad (1)$$

$$\text{Pol in cane} = \text{Pol in juice} \times [1 - (\text{fiber} + 5)/100] \quad (2)$$

$$\text{Impurities in cane} = \text{Brix in cane} - \text{Pol in cane} \quad (3)$$

$$\text{CCS} = \text{Pol in cane} - \text{impurities in cane}/2 \quad (4)$$

Sugar yield (g stalk$^{-1}$) was simply calculated from stalk weight (g) and CCS (%):

$$\text{Sugar yield} = \text{stalk weight} \times \text{CCS}/100 \quad (5)$$

Thereafter, the juice samples were stored in a freezer at -

20°C until ion analysis. After thawing, the samples were diluted 100-fold with extra-pure water and passed through a 0.45 mm membrane filter. Juice K concentration was determined by ion chromatograph (ICS-1600, Thermo Fisher Scientific). The column and the mobile phase used were Ion Pac CS12 (Thermo Fisher Scientific) and 20 mM methane sulfonic acid solution.

After harvest, pot soils were air-dried and a 500-g subsample was taken from each pot. The soil samples were sieved ($\leq$ 2 mm) and 10 g of each was shaken with 50 mL of 1 N ammonium acetate solution for 30 minutes. The filtrates passed through filter papers (Whatman, No. 5) were used to determine soil exchangeable K concentration by atomic absorption spectrometer (AA280FS, Agilent Technologies).

### 2.2. Analysis of Sugarcane Juice Obtained from Raw Sugar Factory

This analysis was conducted at Mitr Phol Phu Khiao Park in Chaiyaphum, Thailand (16°48'N, 102°12'E; 228 m a.s.l.). Its surrounding sugarcane farmland amounts to approximately 65,000 ha and KK3 is the most dominant variety, occupying more than 80% of the area [19]. The park contains two raw sugar factories with a total crushing capacity of 40,000 tons of cane day$^{-1}$. While Factory A is capable of milling both manually and mechanically harvested canes, Factory B only accepts mechanically harvested ones. Both factories have small laboratories connected to the juice pipe lines, and first expressed juice (FEJ) is sent to the laboratories to evaluate its quality for cane payment purposes. To exclude any possible effects of harvesting method, juice collection was performed in the laboratory of Factory B.

In December, 2016, 50 mL of FEJ was taken for each cane sample and 60 samples in total were obtained (Table 1). Along with EC measurements using a PC 700 benchtop meter (Eutech Instruments) equipped with a conductivity electrode, juice K concentration was determined for these samples by the ion chromatography method as described previously. The data sets were used for regression analysis using EC and K concentration as independent and dependent variables, respectively. The linear regression equation developed was later used for the conversion of EC to juice K concentration.

During the 2017/18 and 2018/19 seasons, 340 and 437 samples in total were, respectively, obtained weekly throughout the crushing periods. Approximately 500 mL of FEJ was taken for each cane sample to measure Brix in juice, Pol in juice, and CCS as the basic practice of the factory, following the above-described procedure [18]. Fiber was measured daily and the means of three representative

cane samples ranging from 12.31 to 13.76% were used for the calculation of CCS. The parameters were all analyzed and recorded in the laboratory so that data sets were easily retrieved thereafter. The rest of the juice samples after the lab measurements were further used to measure EC with a PC 700 meter (Eutech Instruments). EC readings were then converted into K concentrations using the equation developed by the regression analysis performed with the 2016/17 season samples. Afterward, estimated juice K concentration was used to perform correlation analysis with the qualitative parameters to see how juice K levels affected sugarcane qualities at the factory scale.

### 2.3. Statistical Analysis

All statistical analyses were performed using the software R [20]. For the cultivation experiment, the mean and standard error (SE) of each group were calculated and data was subjected to two-way analysis of variance (ANOVA) to test the main effects and interactions of K type and K rate, excluding the K-free, KCl-50 and $K_2SO_4$-50 groups. In the juice analysis, Pearson's correlation coefficients were calculated between estimated juice K concentration and Brix in juice, Pol in juice, and CCS. Significances were all accepted based on a P value < 0.05.

## 3. Results

### 3.1. Sugarcane Cultivation Experiment with Various K Treatments

#### 3.1.1. Sugarcane Growth

Plant height continued to increase throughout the experimental period (Figure 1). Treatment effects were observed from 69 DAT in the KCl groups and the differences became gradually clearer in later periods. Irrespective of the K fertilizer type, raising K rates negatively affected plant height; however, the extent of the reduction caused by the KCl treatments was much greater. Plant height at harvest markedly differed from 103 to 178 cm among the KCl groups, whereas the $K_2SO_4$ groups had a smaller variance. Leaf number was about 4 at the beginning and gradually increased to reach to maximum during 150 to 209 DAT. The increments of KCl tended to reduce leaf number, and that of KCl-50 stayed lower with its maximum of 9. SPAD index ranged between 25 and 50 during the experiment, being affected by the fertilizations. The maximum values were recorded at 41 DAT and SPAD index started declining afterward. All the groups showed similar tendencies, except for the drastic changes seen in KCl-50.

*Table 1. Sampling information about the factory juice analysis.*

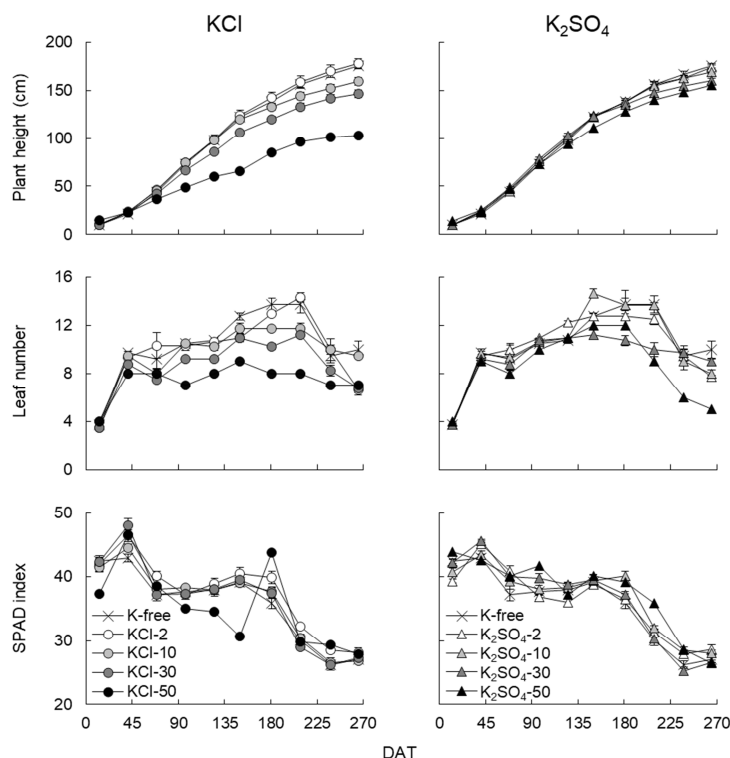| Season | Sampling date | Number of samples per day | Total number of samples |
|---|---|---|---|
| 2016/17 | Dec-22, Dec-24, Dec-26 (3 dates) | 17 – 23 | 60 |
| 2017/18 | Dec-22, Dec-28, Jan-5, Jan-12, Jan-19, Jan-29, Feb-2, Feb-9, Feb-16, Feb-26, Mar-12, Mar-16, Mar-28, Apr-2 (14 dates) | 23 – 25 | 340 |
| 2018/19 | Nov-28, Dec-4, Dec-13, Dec-21, Dec-28, Jan-4, Jan-11, Jan-17, Jan-25, Feb-1, Feb-7, Feb-15, Feb-22, Feb-28, Mar-8, Mar-15, Mar-22, Mar-29 (18 dates) | 23 – 25 | 437 |

***Figure 1.*** *Changes of plant height, leaf number, and SPAD index in the KCl (left) and K₂SO₄ (right) groups.*

Bars represent SE of the means (n = 3 – 4). Note that the graphs for both the KCl and K$_2$SO$_4$ groups contain the data sets of K-free.

### 3.1.2. Juice K and Soil Exchangeable K

Irrespective of the K fertilizer type, juice K concentration was significantly increased from 1425 to 7299 mg L$^{-1}$ in the KCl groups and from 2190 to 7930 mg L$^{-1}$ in the K$_2$SO$_4$ groups as K rates rose from 2 to 50 g pot$^{-1}$ (Figure 2). These results suggest that there were no apparent differences between KCl and K$_2$SO$_4$ in terms of the uptake of K by sugarcane. Likewise, soil exchangeable K concentration at harvest largely varied depending on K rate but not K fertilizer type. It is noted that large gaps were observed between the groups given 10 and 30 g K pot$^{-1}$, indicating that available K for sugarcane may have not been properly absorbed and remained in the soil when the K application rates were 30 g pot$^{-1}$ or more.
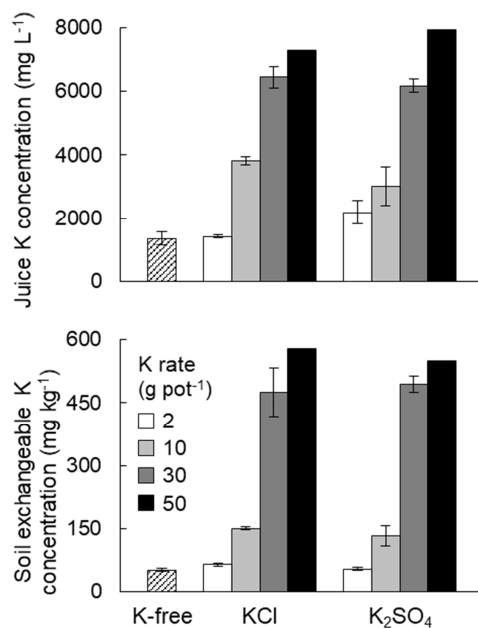


Bars represent SE of the means (n = 3 – 4).

***Figure 2.*** *Effects of type and rate of K fertilizer on juice K (top) and soil exchangeable K (bottom) concentrations at harvest.*

**Table 2.** *Effects of type and rate of K fertilizer on yield and quality traits at harvest.*

| K type | K rate | Stalk length (cm) | Stalk diameter (mm) | Stalk weight (g) | Pol in juice (%) | CCS (%) | Sugar yield (g stalk$^{-1}$) |
|---|---|---|---|---|---|---|---|
| K-free | 0 | 148±6 | 32.3±0.7 | 1420±34 | 20.9±0.3 | 16.4±0.3 | 232±3 |
| | 2 | 150±10 | 33.2±0.8 | 1534±153 | 21.2±0.1 | 16.6±0.1 | 255±27 |
| KCl | 10 | 134±6 | 33.1±0.2 | 1290±73 | 20.8±0.1 | 16.2±0.2 | 209±13 |
| | 30 | 123±8 | 32.1±0.4 | 1148±86 | 19.4±0.2 | 14.9±0.2 | 171±15 |
| | 50 | 78 | 29.0 | 654 | 18.5 | 14.1 | 92 |
| | 2 | 146±4 | 33.4±0.5 | 1427±72 | 20.9±0.3 | 16.4±0.2 | 233±11 |
| K$_2$SO$_4$ | 10 | 144±5 | 33.3±0.3 | 1455±71 | 21.2±0.3 | 16.5±0.2 | 241±13 |
| | 30 | 137±6 | 33.1±0.8 | 1303±88 | 21.0±0.2 | 16.2±0.2 | 212±16 |
| | 50 | 133 | 34.5 | 1278 | 20.4 | 15.8 | 202 |
| K type | | | | | ** | ** | |
| K rate | | | | * | ** | *** | * |
| K type × K rate | | | | | ** | ** | |

Values are means ± SE (n = 3 – 4), except for KCl-50 and K$_2$SO$_4$-50 (n = 1). *, **, and *** denote significances at the 5%, 1%, and 0.1% levels, respectively (two-way ANOVA). Note that K-free, KCl-50, and K$_2$SO$_4$-50 were excluded from the statistical analysis.

### 3.1.3. Sugarcane Yield and Quality

Although the main effect was insignificant, increasing K rates caused certain reductions of stalk height, especially in the KCl groups (Table 2). Similar results were acquired in stalk weight with a significant main effect of K rate, whereas stalk diameter was likely to be less affected. The highest stalk height and weight were obtained in KCl-2, followed by K-free, K$_2$SO$_4$-2, and K$_2$SO$_4$-10. Surprisingly, KCl-10, KCl-30, and K$_2$SO$_4$-30 showed lower values in these parameters than K-free. Quality traits, as well as the yield components, were markedly affected by the K treatments. Increasing KCl rates caused negative impacts, reducing Pol in juice from 21.2 to 18.5% and CCS from 16.6 to 14.1%. On the other hand, raising K$_2$SO$_4$ rates hardly impaired the quality traits. As a result of the two-way ANOVA, the K type × K rate interactions for Pol in juice and CCS were significant at the 1% and 0.1% levels, respectively. Sugar yield was calculated from stalk weight and CCS. KCl-2 which recorded the highest stalk weight and CCS accordingly gained maximum sugar yield of 255 g stalk$^{-1}$ across all. Along with increasing K rates, substantial reductions of sugar yield were observed in the KCl groups since CCS was also remarkably reduced. Meanwhile, among the K$_2$SO$_4$ groups, K$_2$SO$_4$-10 showed the greatest sugar yield. Still, the main effect of K rate was revealed to be significant, implying that higher K rates led to lower sugar yields. Not statistically analyzed due to the small numbers of replicates, however, KCl-50 exhibited far smaller values for all parameters as compared to the other groups, whereas K$_2$SO$_4$-50 resulted in lesser degrees of reduction and showed greater values than KCl-30. Large gaps between the 50 g K groups again demonstrated the disadvantages of excessive use of KCl over K$_2$SO$_4$.

### 3.1.4. Relationships Between Juice K and Sugarcane Yield and Quality Traits

Figure 3 comprises of scatter diagrams to illustrate the three relationships between juice K concentration and stalk weight, CCS, and sugar yield. For all of these, maximum values were obtained in KCl-2 with a juice K concentration of 1500 mg L$^{-1}$. The second-order polynomial trendlines for

the KCl groups elucidate that these parameters tended to decline as juice K concentrations became higher than 2000 mg L$^{-1}$. By contrast, the plants treated with K$_2$SO$_4$ showed lesser degrees of reduction as K rates rose; as a result, sugar yield was maximized in K$_2$SO$_4$-10 with a K concentration around 3000 mg L$^{-1}$ among the K$_2$SO$_4$ groups.
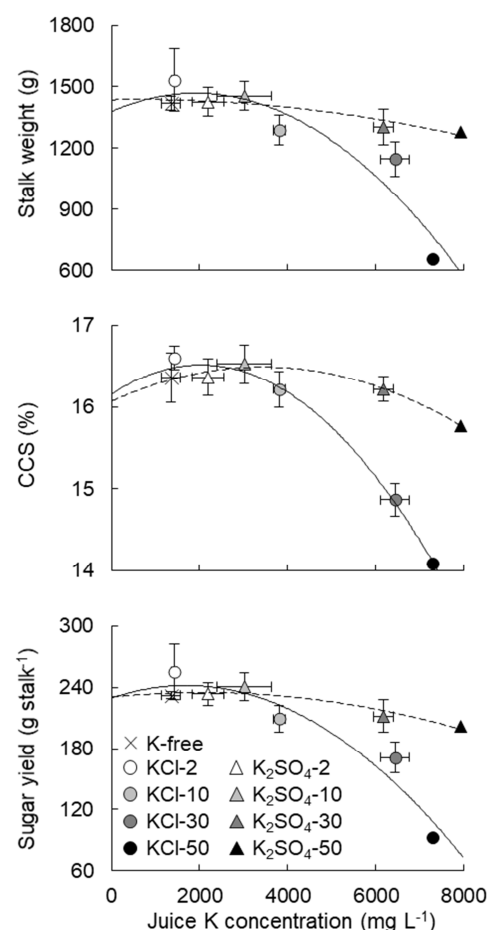


**Figure 3.** *Relationships between juice K concentration and stalk weight (top), CCS (middle), and sugar yield (bottom).*

Bars represent SE of the means (n = 3 – 4). The second-order polynomial trendlines for the KCl (solid) and K$_2$SO$_4$ (broken) groups including K-free are shown in the graphs.

### 3.2. Analysis of Sugarcane Juice Obtained from Raw Sugar Factory

### 3.2.1. Regression Analysis Between Juice K and EC

The 60 FEJ samples collected in December, 2016 possessed wide ranges of EC values from 603 to 1748 mS m$^{-1}$ and K concentrations from 1083 to 3353 mg L$^{-1}$, meaning that the sample collection was successfully performed to be used for regression analysis. The data sets of EC measured with a benchtop meter and K concentration determined by ion chromatograph were then plotted in a scatter diagram (Figure 4). It is clear that EC was highly associated with juice K concentration. According to the regression analysis applied between juice K concentration (mg L$^{-1}$) and EC (mS m$^{-1}$), a linear equation was yielded as follows:

K concentration = 1.9007 × EC - 88.677 (6)

The coefficient of determination ($R^2$), which indicates the quality of its fit to the data, was calculated to be 0.9209, implying that EC can explain 92% of the variation in juice K concentration of the obtained samples. The SE of the analysis was 182.5, which corresponds to as much as 8.08% of the average K concentration of 2259 mg L$^{-1}$. The equation was also highly significant with an F ratio of 998.7 at the 0.1% level.

### 3.2.2. Variability in Juice K

Juice K concentration was then estimated from EC for all the 2017/18 and 2018/19 season samples by applying the equation developed in the previous section. The means ± standard deviations of the estimated juice K concentrations were calculated to be 2143 ± 497 and 2279 ± 523 mg L$^{-1}$ in the 2017/18 and 2018/19 seasons, respectively. The histogram tells that the estimated juice K concentration were distributed within 4000 mg L$^{-1}$, with a peak range of 2000 ≤ K < 2500 mg L$^{-1}$ and that similar distribution patterns were observed in both years (Figure 5). The percentages of the samples with estimated juice K concentrations above 2000 mg L$^{-1}$ were 60.3 and 65.9% in the 2017/18 and 2018/19 seasons, respectively.
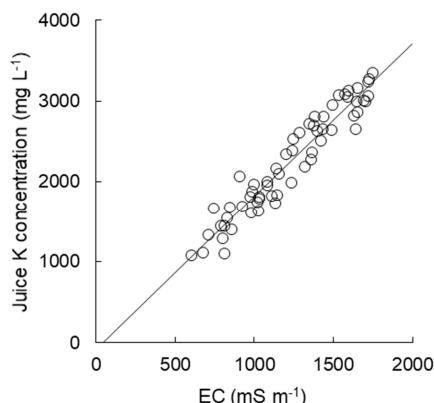


***Figure 4.*** *Juice K concentration plotted against EC for the 2016/17 season samples.*

The linear trendline is shown in the graph. The $R^2$ value and SE of the analysis were 0.9209 and 182.5, respectively. The equation was statistically significant (n = 60, F = 998.7, P < 0.001).
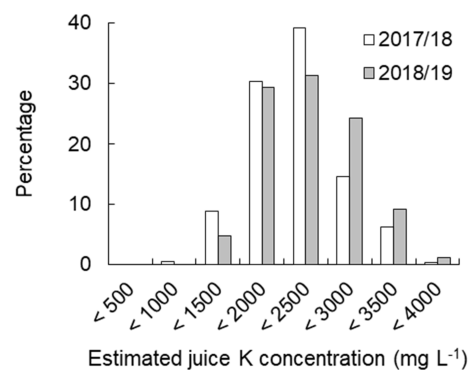


***Figure 5.*** *Distributions of juice K concentration estimated from EC for the 2017/18 (n = 340) and 2018/19 (n = 437) season samples.*

### 3.2.3. Relationships Between Juice K and Sugarcane Quality Traits

The correlation analyses revealed that Brix in juice (correlation coefficient (r) = -0.4106), Pol in juice (r = -0.4470) and CCS (r = -0.4645) were all significantly negatively correlated with estimated juice K concentration at the 0.1% levels. Among these, CCS was plotted against estimated juice K concentration to visually grasp the relationship at the factory scale (Figure 6). The means ± standard deviations of CCS were 13.94 ± 1.04 and 13.78 ± 1.30% in the 2017/18 and 2018/19 seasons, respectively. Although the trend was not sufficiently clear, it is seen that CCS linearly declined as juice K concentration increased. Extremely low CCS values below 11% were observed particularly in the 2018/19 season, accompanied with high K concentrations above 2000 mg L$^{-1}$. The average CCS value of the overall samples with estimated juice K concentrations below 2000 mg L$^{-1}$ was 14.40%, while that with juice K above 2000 mg L$^{-1}$, 13.54%, was significantly lower.
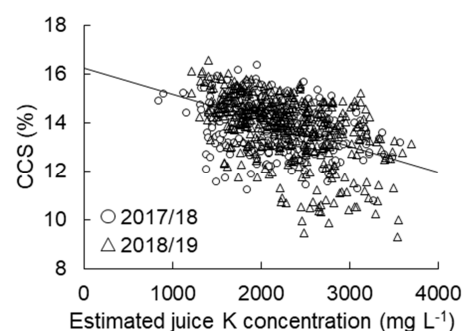


***Figure 6.*** *Relationship between estimated juice K concentration and CCS for the 2017/18 (n = 340) and 2018/19 (n = 437) season samples.*

The linear trendline for the overall samples is shown in the graph. The relationship was statistically significant (n = 777, r = -0.4645, P < 0.001).

## 4. Discussion

From the cultivation experiment using a commercial Thai variety, KK3, we found that raising KCl rates gave considerably negative impacts on Pol in juice and CCS, whereas the effects of the K$_2$SO$_4$ treatments were comparatively negligible. The output of the two-way ANOVA

also revealed the K type × K rate interactions for these parameters to be statistically significant, meaning that KCl and $K_2SO_4$ caused different effects on sugarcane quality. These results concur with the previous study that significant reductions of sucrose concentration in juice were caused by higher doses of KCl but not of $K_2SO_4$ [6]. In our present study, besides juice quality, sugarcane growth and yield traits such as stalk height and weight were also substantially decreased by the KCl applications. This is partially contrary to their finding that clear treatment effects on yield components were not confirmed. This was probably attributed to varietal difference in responses to raising KCl rates since the uptake of K is also affected by genetic background [21, 22]. Watanabe et al. subjected several sugarcane varieties to a KCl-abundant condition and reported that its effects on the yield and quality as well as juice K concentration significantly varied across the varieties [23]. These imply that KK3, the variety used for the present study, was more sensitive to changes of KCl dose in point of quantitative traits.

Other findings from the cultivation experiment are that the plants treated with 2 g K with KCl exhibited the best results in terms of both quantitative and qualitative traits and that stalk weight, CCS, and sugar yield all tended to decline with juice K concentrations exceeding 2000 mg $L^{-1}$ in the KCl groups. Therefore, this level is considered the threshold of juice K to impair the yield and quality when KK3 is fertilized with KCl. Given that KCl is the major source of K fertilizer used in agriculture, juice K concentration should be kept lower than this level in order to prevent any losses in sugar yield. Nevertheless, it was found that, based on the results of the factory juice analysis, 60.3% and 65.9% of the analyzed juice samples possessed K concentrations above 2000 mg $L^{-1}$ in the 2017/18 and 2018/19 crushing seasons, respectively. Assuming that the study area were covered with KK3 only, it would be deduced that more than 60% of sugarcane crops have been receiving more K than they need. Meanwhile, this estimation would be false if $K_2SO_4$ were supplied in the actual fields instead of KCl. In the cultivation experiment, $K_2SO_4$-10 gained the highest sugar yield among the $K_2SO_4$ groups with a K concentration of 3000 mg $L^{-1}$, which spanned the majority of the juice K concentrations observed in the factory juice analysis. Although $K_2SO_4$ is not as prevalent as KCl and normally is not applied for sugarcane production today, our study could prove the use of this K fertilizer worth considering.

It would be of great interest to associate juice K concentration with quantitative parameters such as cane yield at the factory scale. Unfortunately, we were unable to retrieve detailed sample information from the factory; hence, correlation analysis was performed only for qualitative parameters. The relationship between estimated juice K concentration and CCS would certainly be clearer if minor varieties other than KK3 were eliminated and/or if data sets were assigned to categories of plant and ratoon canes. Still, the relationship was significantly negative with an r value of -0.4645, and the sample group with juice K higher than 2000

mg $L^{-1}$ showed a 0.86% decrease in CCS on average, which could advocate the results of the KCl treatments in the cultivation experiment. Similar relationships between inorganic salts in juice and sugarcane quality have also been reported by other researchers. In Australia, the concentrations of $K^+$, $Cl^-$, and ash in juice were negatively correlated with Pol, purity, and CCS in juice [24]. In addition, the relationships between ash and CCS were all significantly negative for several varieties [11]. Watanabe et al. conducted sugarcane juice analysis in Japan over 3 years and demonstrated that $K^+$ and $Cl^-$ concentrations as well as EC were always negatively correlated with sucrose concentration in juice and the relationships were mostly significant regardless of variety and crop age [17]. Taking these together with the results of our cultivation experiment, it could be indicated that impairments of sugarcane quality have probably been occurring in the actual fields of the study area. Therefore, appropriate practices for K fertilizer management should contribute to achieving better cane quality and consequently greater sugar production.

In Thailand, a number of fertilizer products are currently available at markets and fertilizer applications for sugarcane production vary from farm to farm. For instance, according to the recommendations by Thai Central Chemical Public Company Limited, 15 to 47 kg K $ha^{-1}$ and 45 to 66 kg K $ha^{-1}$ are to be applied at planting and at 2 to 3 months thereafter, respectively, using compound fertilizers containing 6 to 21% of K in the form of KCl [25]. As our study suggested, information on juice K concentration obtained from juice analysis will be of great help in selection of K fertilizer for the next cultivation season: those with lower percentages of K should be selected in a year following one when the K concentration in juice is found to be higher than 2000 mg $L^{-1}$. These practices would not only improve sugarcane quality but also alleviate the environmental burden and save fertilizer cost caused by excessively given K. Alternatively, the use of $K_2SO_4$ might be a solution for the high K problems; yet, the practice of this method awaits further study until it has been proven economically effective, considering that KCl is the cheapest K source [26]. Another important K source for sugarcane cultivation is vinasse, which is a liquid waste from the distillation process of ethanol production and is rich in macro- and micro-nutrients, mainly K [27]. In the study area, it is estimated that approximately 25% of the sugarcane growers apply vinasse to their fields [28]. Containing large quantities of K and Cl, vinasse is likely to have similar functions to KCl and thus could be a factor that reduces sugarcane quality as our study demonstrated. Nevertheless, the growers conventionally apply the same dose of K with chemical fertilizers, not knowing its possible risks. Consideration should be given to K application especially when associated with vinasse fertigation.

In the present study, we analyzed a limited number of juice samples which covered only a few percentages of the total cane samples processed at the factory. Even though the EC measurement method described in this paper is useful and readily applicable, it will not be practical to manually

analyze FEJ at all times during milling operation. Kingston and Kirby and Kingston have installed industrial conductivity meters to juice pipe lines in order to observe continuous changes of juice conductivity [10, 11]. By applying this idea, it will be possible to automatically obtain an EC reading for every juice sample, and thereby we are currently working on the installation of a conductivity monitor in the factory. To efficiently utilize the results obtained from the present study, systems to provide growers with feedback on the juice K status and actual recommended dose of each sugarcane field are desirable and should be developed in the future.

# 5. Conclusion

From the present study, it was revealed that sugarcane growth, yield, and quality were reduced by excessive uses of KCl particularly as juice K concentration became higher than 2000 mg $L^{-1}$. Number of growers in the study area potentially need improvements in K management and the suggested diagnosis method through juice analysis at factory scale could greatly facilitate the selection of K fertilizer for next season. Whether the fertilizer management practices based on this method certainly give positive impacts on sugarcane should be examined so that growers and millers will realize its importance and usefulness.

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# Conflict of Interest

The authors declare that there is no conflict of interest.

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