วารสารแก่นเกษตร
THAIJO

Content List Available at ThaiJo

Khon Kaen Agriculture Journal

Journal Home Page : https://li01.tci-thaijo.org/index.php/agkasetkaj

Effects of potassium thiosulfate foliar application on yield, nutrient uptake and potassium use efficiency of cassava planted in Satuk soil series

Nattapong Worapoje[1], Somchai Anusontpornperm[1]*, Suphicha Thanachit[1] and Mutchima Phun-iam[1]

[1] *Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900 Thailand*

ABSTRACT: Potassium fertilization is less effective in sandy soils, resulting in higher costs with unsatisfactory cassava fresh tuber yield return. This study was carried out to comparatively investigate the efficiency of potassium chloride (KCl) and potassium thiosulfate (KTS) foliar application, and KCl soil application and their impact on cassava yields. A single-year field experiment was conducted in a farmer field in Nakhon Ratchasima province with Satuk soil series as a representative soil of the experimental area. The experiment was arranged in a randomized complete block design with four replications. Seven treatments comprised no K fertilization, 50 and 100 kg K_2O/ha KCl soil application, 50 and 100 kg K_2O/ha KCl and KTS foliar application. The cassava, Huat Bong 80 variety was a tested plant and harvested at 10-month-old. The KCl and KTS foliar application at the rate of 50 kg K_2O/ha significantly increased fresh tuber yield by 73.0% and 68.8%, respectively, over the control (22.05 t/ha) but the higher rate (100 kg K_2O/ha) did not boost the yield over the lower rate. It was also the case for starch yield. Both rates of KCl soil application gave much inferior yields to the highest ones. The KCl and KTS foliar application at the rate of 50 kg K_2O/ha also significantly promoted the highest N and P uptake whilst the KTS foliar application at the rate of 100 kg K_2O/ha significantly induced the highest K and S uptake in cassava. The KCl and KTS foliar application at the rate of 50 kg K_2O/ha had the significantly highest agronomic efficiency and partial factor productivity with the latter significantly having the highest apparent recovery efficiency. The KCl and KTS foliar application at the rate of 50 kg K_2O/ha can be a better alternative K fertilization for increasing cassava yield in this soil due to their high K use efficiency.
Keywords: potassium thiosulfate; potassium chloride; foliar application; cassava; nutrient use efficiency

Introduction

Cassava (*Manihot esculenta* L. Crantz) is an important upland crop in Thailand and other tropical countries in the world. Nigeria is the leading producer followed by DR Congo and Thailand, respectively. However, Thailand is the leading exporter of cassava products, accounting for 7.1 million tonnes (Sowcharoensuk, 2023). In Asia, approximately 55% of cassava in the continent was grown in Ultisols, 18% in Alfisols, 9% in Entisols and only 7% in the other soils combined (Howeler, 1992). In Thailand, cassava is dominant in upland Ultisols followed by in Entisols; however, these soils, such as Yasothon, Warin, Satuk and Korat soil series, in the country have low fertility levels with some problems of soil physical properties such as plough pan and surface soil compaction (Anusontpornperm et al., 2009; Anusontpornperm et al., 2014; Boonrawd et al., 2021). In particular, Nakhon Ratchasima province has

* Corresponding author: somchai.a@ku.ac.th
Received: date; July 23, 2024 Revised: date; November 15, 2024

Accepted: date; November 15, 2024 Published: date

the largest cassava growing area in Thailand accounting for 237,109 ha (Office of Agricultural Economics, 2022). However, some recent studies showed that most soils used for cassava cultivation were poor, physically and chemically (Boonrawd et al., 2021). This should partly be responsible for the low level of average yield per planted area (19.55 t/ha) and per harvested area (21.94 t/ha) in the province (Office of Agricultural Economics, 2022).

Potassium (K) is a primary plant nutrient, essential for plant growth. In the case of cassava, K stimulates the net photosynthetic activity of a given leaf area and increases the translocation of photosynthates or carbohydrates to the tuberous roots (Blevins, 1994) with the quality of tuber such as character of starch much dependent on potash nutrition (Bhattacharyya et al. 2018). Potassium is most important for cassava tuberization (Biratu et al., 2018). Potassium deficiency in cassava is generally found in tropical soils with low activity clay such as in Oxisols, Ultisols and Inceptisols, as well as in Alfisols derived from sandstone (Howeler, 2012). As of the case, this nutrient content was naturally very low in Ultisols of the northeast, Thailand (Anusontpornperm et al., 2009; Boonrawd et al., 2021). Numerous studies showed significant improvement of cassava tuber yield by improving K nutrition in soils with low inherent soil fertility (Wilson and Ovid, 1994; Olaleye et al., 2006 Boateng and Boadi, 2010; Ukaoma and Ogbonnaya, 2013; Taufiq et al., 2013; Uwah et al., 2013; Sogbedji et al., 2015; Umeh et al., 2015). In a 2-year experiment, 150 kg K_2O/ha of K fertilization significantly increased K availability over the control and also increased fresh tuber yield and stem yield (Munyahali et al. 2017). A 2-year trial in a tropical sandy Typic Paleustult in northeast Thailand, cassava fresh tuber yield responded best to 125 kg/ha of K_2O in both years (Prombut et al., 2022). In the same region, the highest K concentration was observed in tubers when grown in an Oxyaquic Paleustult (Phun-iam et al. 2018) whilst in an Ustic Quartzipsamment, K fertilizer increased N, P and K uptake in almost all plant parts of cassava and K uptake was substantial in tuber (Chaem-Ngern et al., 2020). However, Sittibuasaya (1996) recommended a 100 kg/ha of K_2O fertilization for cassava planted in tropical upland coarse-textured soils in this region when the soil contained less than 30 mg/kg of available K.

Foliar applications are a great way to deliver mineral nutrition to growing plants, especially micro and trace minerals. It is also a direct way to apply nutrients for plants grown in soils with low ability to retain plant nutrients such as sandy soils. Comprehensive studies showed that spraying chelated fertilizer on leaves can reduce the total amounts of fertilizer applied and achieve high fertilizer efficiency (Liu et al., 2020). With no exceptions for K, this plant nutrient is very soluble and so can be leached to great depth or to surface water (Goulding et al., 2021), especially in sandy soils in the northeast with low clays and organic matters (Anusontpornperm et al., 2009; Boonrawd et al., 2021) as K is bound to clays and organic materials and adsorbed mostly in association with fine soil particles. However, Fernández and Brown (2013) remarked the diversity of plant response to foliar fertilizers. Improving the efficacy and utility of foliar fertilizers will require a sound understanding of the physical, chemical, biological, and environmental principles which influence the absorption, translocation, and utilization of foliar-applied nutrients by plants.

Potassium chloride (KCl) is by far the most widely used K fertilizer for crop nutrition due to its relatively low cost and highest percentage of K_2O, 60–63% (Mikkelsen and Roberts, 2021). Potassium thiosulfate (KTS), an inorganic compound with the formula $K_2S_2O_3$ and easily soluble in water, is less commonly used; however, it provides both K and sulfur (S) in forms that are readily soluble and available to plants. There were far fewer studies using KTS as a K source (Salim et al., 2014; Lo'ay et al., 2021) compared to KCl. In Thailand, Traithipchawalit et al.

(2018) reported that the foliar application of KTS at the rate of 46.9 kg/ha of K_2O significantly gave the highest fresh virgin cane yield and aboveground biomass when planted in Kamphaengsaen soil series, but none has been tested in cassava. Therefore, this study was conducted to objectively compare the effect of K from two sources, KTS and KCl, applied in the form of soil and foliar applications on cassava yield and nutrient uptake in Satuk soil series (Typic Paleustults). Potassium use efficiency was also investigated. Results will provide an alternative K management practice for cassava grown in inherently low K and/or K-depleted soils with low ability to retain this nutrient or in the other words, low K use efficiency.

Materials and Methods

Site description and soil properties prior to conducting the experiment

A field trial was conducted in a farmer field at Ban Supplu Noi, Huay Bong District, Nakhon Ratchasima province, Northeast Thailand (15°11'07.38"N 101°27'18.55"E). A soil representing the experimental area was Satuk soil series, classified as sandy, siliceous, isohyperthermic, Typic Paleustults. This soil was derived from wash over residuum of conglomeratic sandstone with 2% sloping surface. Properties of the soil (0-25 and 25-60 cm) prior to conducting the experiment are presented in **Table 1**. This soil had a loamy sand texture throughout 0-60 cm. Soil pH extracted with 1:1 water was strongly acid in both topsoil (pH 5.39) and the layer underneath (pH 5.29). Both layers contained very low amounts of total N, available P and K, and extractable Ca and Mg with also very low cation exchange capacity.

Experimental design

The experiment was arranged in a randomized complete block design with 4 replications. There were 7 treatments: 1) 0 kg/ha of K_2O (control), 2) 50 kg/ha of K_2O-KCl soil application using, 3) 100 kg/ha of K_2O-KCl soil application, 4) 50 kg/ha of K_2O-KCl foliar application, 5) 100 kg/ha of K_2O-KCl foliar application, 6) 50 kg/ha of K_2O-KTS foliar application, and 7) 100 kg/ha of K_2O-KTS foliar application. The KTS was composed of 25% K_2O and 17% S. Foliar application used 4% concentration (KCl or KTS mixed in 2,500 L/ha of tapping water) where the control and soil application treatments also received 2,500 L/ha of sprayed water. Soil application of 100:50 kg/ha of N:P_2O_5 in the form of respective urea and ammonium phosphate were similarly performed in all plots. The proportion and amount of NPK fertilizer was based on that recommended by Sittibusaya (1996) for upland coarse-textured Ultisols in northeast Thailand.

Land preparation began with the first plough using a 3-disc plough with 28-inch diameter disc which ploughed into 40-45 cm depth (deep tillage). The experimental area was left for two weeks, then loosened the topsoil by using a 7-disc plough before making ridges across the slope with a space of 1.2 m between ridges right afterword. Cassava, Huay Bong 80 variety was planted with an 80 cm spacing between plants. For soil application, chemical fertilizer was applied by placing fertilizer into a hole dug on the top of ridges in the middle between 2 plants and buried with the topsoil when the plant was 2 months of age. Foliar application was done at the same time as soil application. Weed control was performed as necessary by using hand hoes and herbicides. This field experiment was conducted under rainfed conditions.

Plant data and sample collection

Cassava was harvested at 10 months of age. Plant components such as fresh tuber yield and aboveground fresh weight (stem base, stem, and leaf plus branch) were recorded at the harvesting time. Starch content was measured using 5 kg of fresh tuberous roots which were then weighed in the air before weighing in water, and the content was read from a Riemann scale balance according to Bainbridge et al. (1996). This starch content together with fresh tuber yield was used for the calculation of starch yield. Four different plant parts (tuber, stem base, stem, and leaf plus branch) from each plot were sampled and weighed separately, and a known-amount of samples was collected from the field for dry weight measurements and the analysis of plant nutrient concentration in each plant part.

Plant analysis

Ground plant samples were digested using nitric-perchloric acid mixtures (HNO_3:$HClO_4$) (Johnson and Ulrich, 1959) with the exception of total N that was extracted by digestion mixture (H_2SO_4-Na_2SO_4-Se) and determined using Kjeldahl method (Jackson, 1965). Total P was determined colorimetrically using vanado-molybyellow method (Westerman, 1990), and then measured using spectrophotometry (Murphy and Riley, 1962). Total K was measured using atomic absorption spectrophotometry (Westerman, 1990). Total S was determined using turbidimetry with $BaSO_4$, and the amount was determined using spectrophotometry with a 450 nm wavelength (Bardsley and Lancaster, 1965).

Potassium use efficiency

Different methods (modified from Dobermann, 2007) were used for the evaluation of K use efficiency (KUE). They were calculated from the following equations:

1) Agronomic efficiency (AE, t/ha) = Y – Y_0/Quantity of K applied

where, Y = fresh tuber yield (t/ha) with K applied, Y_0 = fresh tuber yield (t/ha) with no K applied.

2) Physiological efficiency (PE, t/ha) = Y - Y_0/U-U_0

Where, Y = fresh tuber yield (t/ha) with K applied, Y_0 = fresh tuber yield (t/ha) with no K applied, U = K uptake in whole plant (kg/ha) with K applied; U_0 = K uptake in whole plant (kg/ha) with no K applied.

3) Apparent recovery efficiency (ARE, %) = (U - U_0/Quantity of K applied) x 100

where, U = K uptake in whole plant (kg/ha) with K applied; U_0 = K uptake in whole plant (kg/ha) with no K applied

4) Partial factor productivity (PFP, t/ha) = Fresh tuber yield (t/ha)/Quantity of K applied (kg/ha).

Statistical analysis

Statistical analysis of data collected was carried out using standard analysis of variance. The significance of the treatment was determined using the F-test appropriate to the general linear model as described by Gomez and Gomez (1984). To determine the significance of the difference between the means of the treatments, Duncan multiple range test was computed at the 0.05 probability level ($p \leq 0.05$). Coefficient of variability (CV) was used to analyze the data (SAS Institute 2004). The statistical software used in this study was SPSS program version 21.0 (SPSS Inc., Chicago, IL).

Table 1 Soil texture and soil chemical properties prior to conducting the experiment

Soil property	Topsoil (0-25 cm)	Subsoil (25-60 cm)
Texture[1]	Loamy sand	Loamy sand
pH_w[2] (1:1 H_2O)	5.39	5.29
Organic matter[3] (g/kg)	4.47	1.38
Cation exchange capacity, CEC[4] ($cmol_c$/kg)	1.25	1.25
Total N[5] (g/kg)	0.70	0.60
Available P[6] (mg/kg)	3.07	2.36
Available K[7] (mg/kg)	27.1	15.7
Extractable Ca[7] ($cmol_c$/kg)	0.97	0.62
Extractable Mg[7] ($cmol_c$/kg)	0.07	0.04

[1]Texture measured by pipette method (Gee and Bauder, 1986), [2]pH (1 : 1 H_2O) analyzed by pH meter (National Soil Survey Center, 1996), [3]organic matter estimated by Walkley and Black titration (Walkley and Black, 1934), [4]CEC measured by saturating the exchange site and displacing by 1 M NH_4OAc at pH 7.0 (Chapman, 1965); [5]total N measured by Kjeldahl method (Jackson, 1965), [6]available P analyzed by Bray II extraction (Bray and Kurtz, 1945), [7]available K, extractable Ca and Mg extracted with 1 M NH_4OAc at pH 7.0 and analyzed by atomic absorption spectrophotometry (AAS) (Thomas, 1982).

Results

Effects of K applications on cassava yields

Potassium foliar application using KCl and KTS as a source of K both at the rate of 50 kg/ha of K_2O significantly promoted the highest fresh tuber yield of 37.23 and 38.14 t/ha, respectively (**Figure 1A**). The yield from both treatments was, however, not statistically different from that obtained from the KTS foliar application at the rate of 100 kg/ha of K_2O (35.60 t/ha). For soil application using KCl, there was only the rate of 100 kg/ha of K_2O that significantly induced greater fresh tuber yield (35.60 t/ha) than did the control treatment with no K application. Potassium fertilization in the form of soil or foliar application in both KCl and KTS forms had no clear impact on starch content with the range across all treatments of 25.73-27.55% (**Figure 1B**). The impact of K applications on starch yield showed the same trend as of fresh tuber yield of which the KCl foliar application at the rate of 50 kg/ha of K_2O and KTS foliar application at both rates significantly gave the highest starch yield in the range of 9.80-10.32 t/ha (**Figure 1C**) whereas the other treatments with K supplied showed no statistical difference to that of the control with no K fertilization.

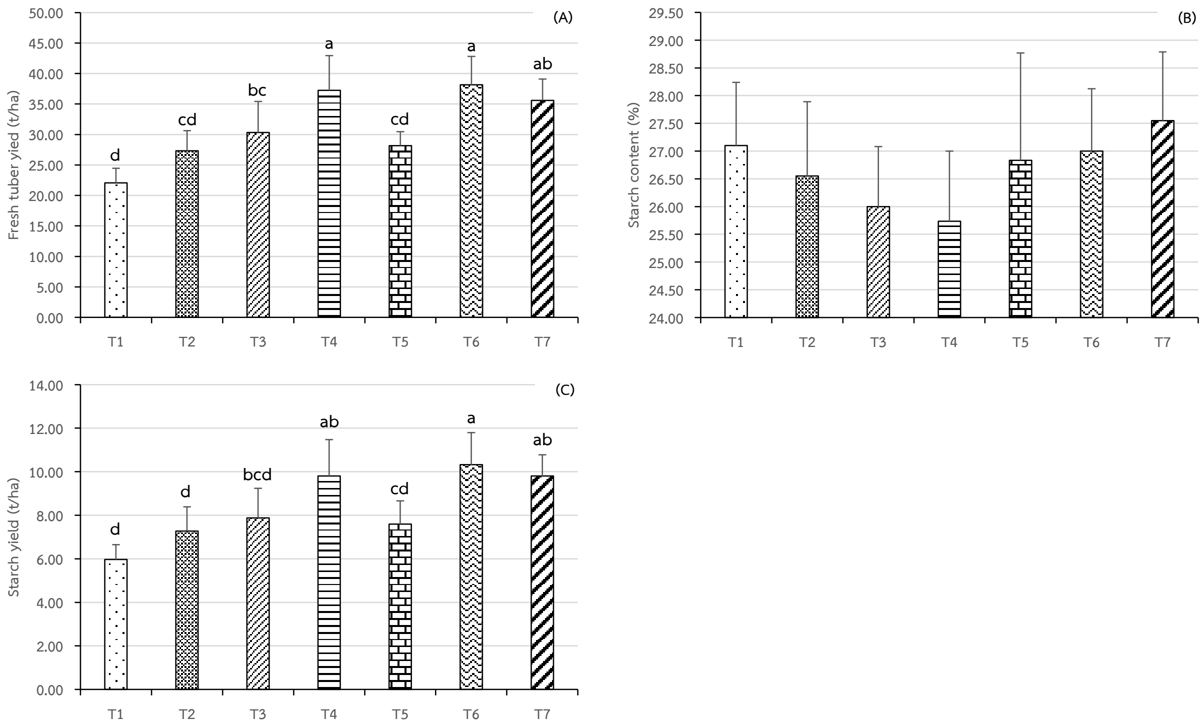

Figure 1 Cassava yields, fresh tuber yield (A), starch content (B) and starch yield (C), response to K applications, where different lowercase letters above bars are significantly (p ≤ 0.05) different and error bars represents +SD, T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; T7 = 100 kg/ha of K_2O-KTS foliar application.

Effects of K applications on top growth of cassava and other plant traits

Apart from 50 kg/ha of K_2O soil application using KCl, the other treatments significantly showed an increment of stem base fresh weight over the control with no K fertilization with the KTS foliar application at the rate of 50 and 100 kg/ha of K_2O significantly stimulating the highest stem base fresh weight of 4.43 and 4.83 t/ha, respectively but with no statistical difference to that received KCl foliar application at both rates (**Figure 2A**). Nonetheless, the K applications had no clear impact on stem fresh weight (**Figure 2B**). The KTS foliar application at the rate of 50 and 100 kg/ha of K_2O along with the KCl foliar application at the rate of 50 kg/ha of K_2O significantly gave the highest respective leaf plus branch fresh weight of 8.65, 6.78 and 6.61 t/ha whereas the other K-fertilized treatments showed no different impact from the control (**Figure 2C**).

It was clear that the KTS foliar application at the rate of 100 kg/ha of K_2O significantly induced the greatest aboveground biomass of 19.09 t/ha followed by the amount obtained from other K foliar applications (**Figure 2D**) but the KCl soil application at both rates did not improve the aboveground biomass (12.09-14.45 t/ha) over the control (9.94 t/ha). Nonetheless, all K fertilization treatments did not increase numbers of tuber per plant and stem per area, survival rate and HI (**Figure 3A, 3B and 3D**).

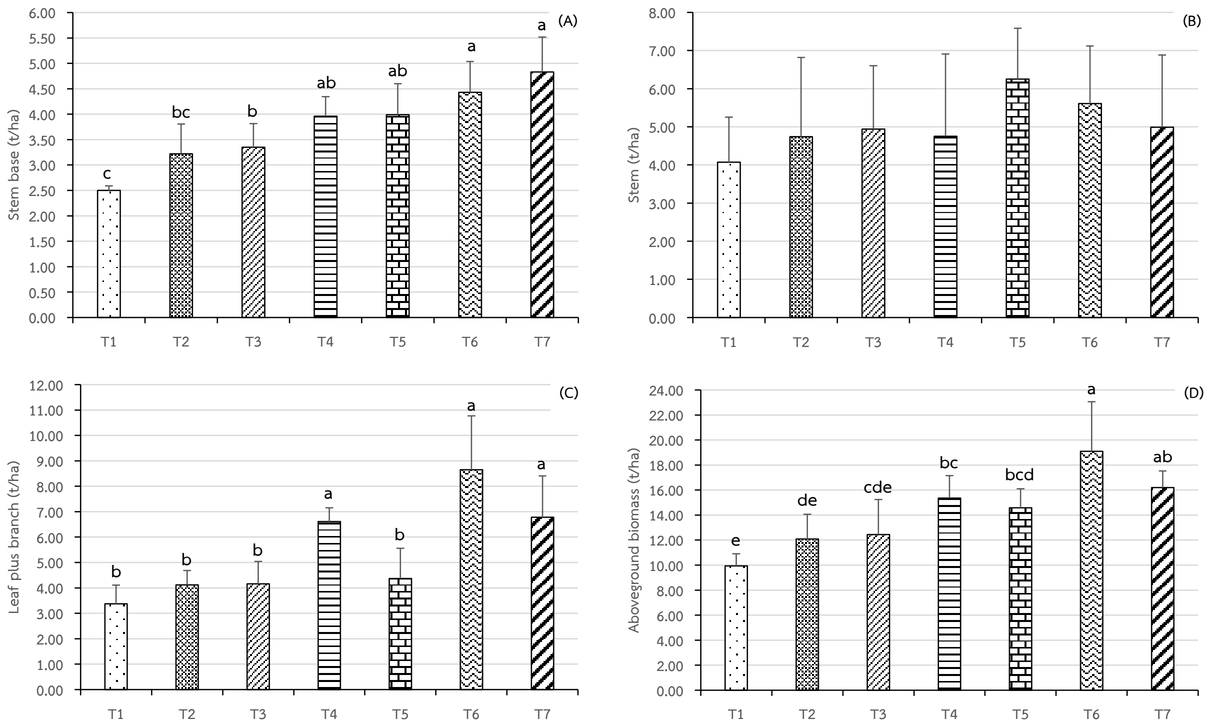

Figure 2 Effect of K applications on aboveground pant parts: stem base (A), stem (B), leaf plus branch (C) and aboveground biomass (D), where different lowercase letters above bars are significantly ($p \leq 0.05$) different and error bars represents +SD, T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; T7 = 100 kg/ha of K_2O-KTS foliar application.

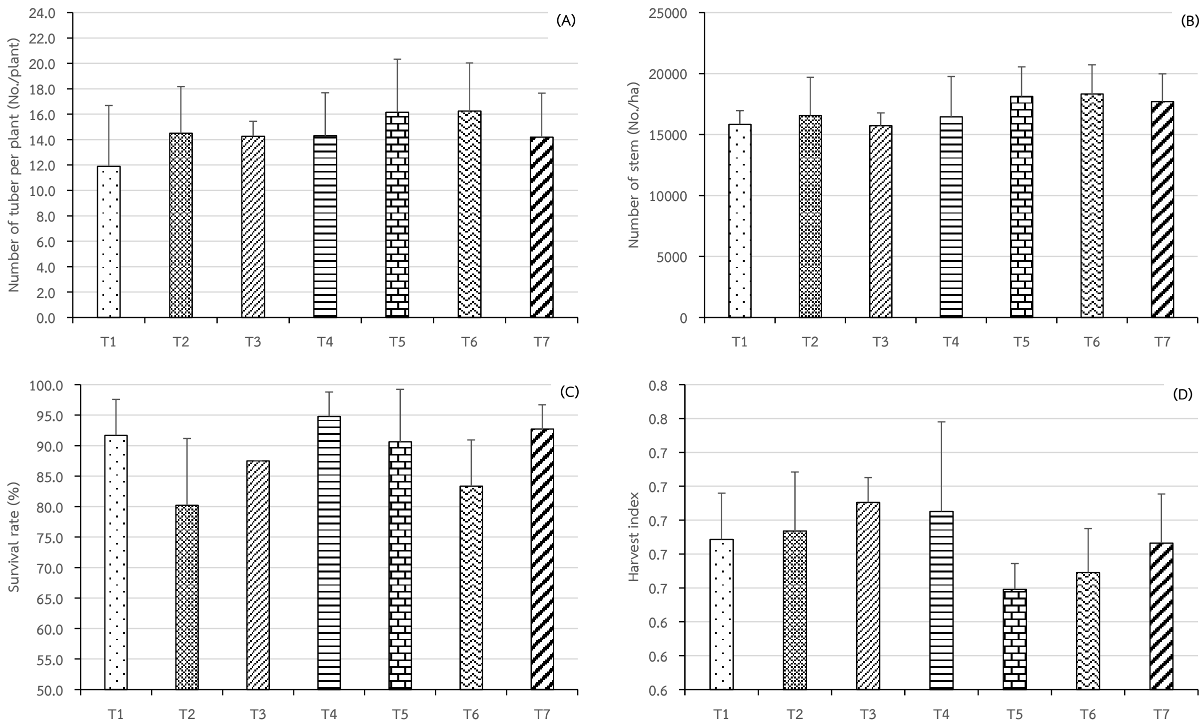

Figure 3 Effect of K applications on other plant parameters: number of tuber per plant (A), number of stem per (B) and survival rate (C), different and error bars represents +SD, T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; 100 kg/ha of K_2O-KTS foliar application.

Effect of K fertilizer on primary plant nutrient and sulfur uptake

Potassium applications had a clear impact on N, P, K and S uptake in almost all plant parts (**Table 2**). Across all treatments, cassava took up K in the highest amount with N taken up slightly lower whereas P was taken up in much smaller amount compared to N and K while S as a secondary plant nutrient was taken up slightly lower than P. Nitrogen was stored mainly in leaf plus branch which was slightly greater than in tuber with the proportion in stem base and stem being much lower (**Table 2**). Cassava took up P in tuber in the highest amount whereas this nutrient in the other parts of cassava was far lower. Potassium was mainly accumulated in tuber while that in leaf plus branch was slightly greater than that in stem base and stem, but the amounts were much lower than that in the tuber. The trend of S uptake was similar to that of N uptake of which cassava took up this nutrient greater in tuber and leaf plus branch than in stem base and stem.

The foliar application of KCl and KTS, except the rate of 100 kg K_2O/ha of KCl, significantly induced the highest N uptake in all plant parts with the highest amount of 101.61 kg/ha in the whole plant observed from the plot sprayed with 50 kg K_2O/ha KTS (**Table 2**). The K foliar applications still performed better in the context of P uptake but the highest P uptake in different plant parts statistically varied among K-foliar treatments with the KTS foliar application at the rate of 50 kg K_2O/ha inducing the highest P uptake of 10.73 kg/ha in the whole plant. Both soil and foliar application of K evidently had a positive impact on K uptake in all plant parts of cassava. The KTS foliar application at both rates significantly stimulated the highest K uptake in all plant parts except for the rate of

50 kg K_2O/ha in tuber with the significantly highest P uptake of 77.90-86.47 kg/ha in the whole plant being obtained from the KTS applications at both rates. The KTS foliar application, especially at the rate of 100 kg K_2O/ha significantly induced the highest S uptake in all plant parts of cassava and in the whole plant with the latter having 9.99 kg/ha of S uptake.

Table 2 Effect of K applications on N, P, K and S uptake (kg/ha) in different plant parts of cassava

Treatment	Tuber	Stem base	Stem	Leaf plus branch	Whole plant
Nitrogen uptake					
T1	18.98±2.06^{c}	5.5±0.20^{e}	3.75±0.09^{d}	20.27±1.80^{c}	48.55±3.53^{c}
T2	19.91±0.88^{c}	6.83±0.86^{cde}	5.56±1.37^{c}	24.42±0.19^{bc}	56.72±1.63^{c}
T3	28.18±4.76^{b}	6.37±0.88^{de}	4.61±1.05^{cd}	31.76±1.04^{b}	10.92±6.07^{b}
T4	34.40±5.29^{a}	7.93±0.16^{abc}	8.29±2.35^{b}	43.50±3.58^{a}	94.11±7.22^{a}
T5	29.06±0.62^{b}	7.20±0.70^{bcd}	10.09±1.12^{a}	32.39±1.72^{b}	78.73±2.55^{b}
T6	35.01±1.70^{a}	8.81±1.11^{a}	11.15±1.14^{a}	46.64±11.44^{a}	101.61±12.90^{a}
T7	38.26±3.74^{a}	8.48±1.32^{ab}	8.5±1.80^{b}	43.44±10.43^{a}	98.69±12.70^{a}
F-test	**	**	**	**	**
Mean±SD	29.11±7.59	7.31±1.33	7.42±2.94	34.64±11.05	78.48±20.88
CV (%)	10.61	11.25	13.43	18.64	10.52
Phosphorus uptake					
T1	1.91±0.21^{d}	0.34±0.01^{c}	0.51±0.01^{d}	0.25±0.02^{c}	3.01±0.23^{e}
T2	5.66±0.55^{c}	0.41±0.05^{bc}	0.75±0.19^{c}	0.28±0.04^{c}	7.10±0.52^{d}
T3	7.65±0.70^{b}	0.36±0.05^{bc}	0.63±0.14^{cd}	0.31±0.04^{c}	8.94±0.89^{bc}
T4	9.01±1.39^{a}	0.35±0.03^{c}	0.89±0.02^{b}	0.48±0.04^{b}	10.73±1.44^{a}
T5	6.52±0.53^{bc}	0.37±0.06^{bc}	1.10±0.12^{a}	0.33±0.02^{c}	8.31±0.61^{cd}
T6	6.79±0.83^{bc}	0.50±0.06^{a}	1.16±0.00^{a}	0.65±0.05^{a}	9.10±0.91^{bc}
T7	7.75±0.76^{b}	0.43±0.07^{b}	1.06±0.13^{a}	0.63±0.15^{a}	9.88±0.90^{ab}
F-test	**	**	**	**	**
Mean±SD	6.47±2.25	0.39±0.07	0.87±0.25	0.42±0.17	8.15±2.5
CV (%)	12.39	13.90	10.28	15.11	10.88

CV = coefficient of variation; T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; T7 = 100 kg/ha of K_2O-KTS foliar application.

*, ** significantly different at 0.05 and 0.01 probability levels, respectively; mean±SD superscripted with different lowercase letters grouped within the same plant part indicate significant difference of treatments, according to Duncan's multiple range test at $p \leq 0.05$.

Table 2 Effect of K applications on N, P, K and S uptake (kg/ha) in different plant parts of cassava (continue)

Treatment	Tuber	Stem base	Stem	Leaf plus branch	Whole plant
Potassium uptake					
T1	15.47±1.68^{e}	1.95±0.07^{d}	1.77±0.04^{d}	3.34±0.73d	22.52±2.17^{e}
T2	35.55±1.57^{d}	2.67±0.33^{c}	3.30±0.81^{b}	3.99±0.54d	45.53±2.44^{d}
T3	50.80±8.58^{bc}	2.63±0.27^{c}	3.24±0.74^{b}	5.00±0.65c	61.67±9.55^{bc}
T4	54.37±1.76^{bc}	3.57±0.07^{b}	2.57±0.73^{c}	7.10±0.58b	67.62±2.32^{b}
T5	47.35±1.01^{c}	3.34±0.31^{b}	2.46±0.27^{c}	5.16±0.85c	58.31±2.06^{c}
T6	56.03±6.87^{b}	4.97±0.62^{a}	5.68±0.58^{a}	11.21±0.81a	77.90±7.67^{a}
T7	66.45±6.50^{a}	4.75±0.74^{a}	5.22±0.66^{a}	10.05±1.34a	86.47±8.27^{a}
F-test	**	**	**	**	**
Mean±SD	46.58±16.25	3.41±1.12	3.46±1.48	6.55±2.96	60±20.65
CV (%)	10.57	11.97	12.29	12.09	9.91
Sulfur uptake					
T1	1.29±0.09^{e}	0.18±0.01^{c}	0.24±0.07^{c}	1.03±0.22^{c}	2.73±0.30^{e}
T2	1.73±0.08^{d}	0.35±0.06^{b}	0.35±0.12^{c}	1.50±0.20^{c}	3.93±0.22^{d}
T3	2.47±0.16^{bc}	0.37±0.05^{b}	0.40±0.07^{c}	1.54±0.33^{c}	4.78±0.50^{d}
T4	2.46±0.38^{bc}	0.47±0.05^{a}	0.38±0.16^{c}	2.39±0.20^{b}	5.71±0.43^{c}
T5	2.09±0.04^{cd}	0.40±0.04^{b}	0.65±0.07^{b}	1.41±0.23^{c}	4.54±0.32^{d}
T6	2.75±0.34^{b}	0.47±0.02^{a}	1.06±0.22^{a}	3.57±0.26^{a}	7.85±0.69^{b}
T7	4.49±0.44^{a}	0.50±0.03^{a}	1.01±0.24^{a}	4.00±0.96^{a}	9.99±1.17^{a}
F-test	**	**	**	*	**
Mean±SD	2.47±0.99	0.39±0.11	0.58±0.34	2.20±1.16	5.65±2.40
CV (%)	10.64	11.44	68.42	18.76	10.86

CV = coefficient of variation; T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; T7 = 100 kg/ha of K_2O-KTS foliar application.

*, ** significantly different at 0.05 and 0.01 probability levels, respectively; mean±SD superscripted with different lowercase letters grouped within the same plant part indicate significant difference of treatments, according to Duncan's multiple range test at $p \leq 0.05$.

Potassium use efficiency

Results of agronomic indices for the short-term assessment of K use efficiency are presented in **Table 3**. The foliar application of KCl and KTS at the rate of 50 K_2O/ha of K_2O significantly had the highest AE of 0.30 and 0.32 t/kg of K_2O, respectively, whereas the higher rate of foliar application of both K sources and KCl soil application at both rates showed much lower AE values. There was no clear impact of K applications on PE. The KTS foliar application at the rate of 50 K_2O/ha of K_2O significantly showed the highest RE of 110.75% followed by 90.18%

observed from the plot treated with the KCl foliar application at the rate of 50 K_2O/ha of K_2O. The K soil application including the higher rate of K foliar application using both KCl and KTS had much lower RE, nonetheless. The almost identical PFP values of 0.74 and 0.76 t/kg were obtained when respective KCl and KTS foliar applications both at the rate of 50 K_2O/ha of K_2O were performed. These PFP values were significantly higher than that of the other K applications.

Table 3 Potassium use efficiency of cassava as influenced by K applications

Treatment	Agronomic efficiency (t/kg)	Physiological efficiency (t/kg)	Apparent recovery efficiency (%)	Partial factor productivity (t/kg)
T1	-	-	-	-
T2	0.11^{b}±0.11	0.21±0.22	46.01^{d}±7.65	0.55^{b}±0.07
T3	0.08^{b}±0.05	0.20±0.10	39.15^{d}±9.62	0.30^{c}±0.05
T4	0.30^{a}±0.08	0.22±0.19	90.18^{b}±6.74	0.74^{a}±0.11
T5	0.06^{b}±0.04	0.17±0.12	35.78^{d}±2.05	0.28^{c}±0.02
T6	0.32^{a}±0.12	0.28±0.06	110.75^{a}±17.89	0.76^{a}±0.09
T7	0.14^{b}±0.02	0.21±0.02	63.95^{c}±6.19	0.36^{c}±0.03
F-test	**	ns	**	**
CV (%)	46.4	64.2	15.0	14.3

CV = coefficient of variation; T1 = 0 kg/ha of K_2O; T2 = 50 kg/ha of K_2O-KCl soil application; T3 = 100 kg/ha of K_2O-KCl soil application; T4 = 50 kg/ha of K_2O-KCl foliar application; T5 = 100 kg/ha of K_2O-KCl foliar application; T6 = 50 kg/ha of K_2O-KTS foliar application; T7 = 100 kg/ha of K_2O-KCl foliar application.

ns = not significant, ** significantly different at 0.01 probability; mean±SD superscripted with different lowercase letters grouped within the same plant part indicate significant difference of treatments, according to Duncan's multiple range test at $p \leq 0.05$.

Discussion

Effect of K applications on cassava yields

Available K in Satuk soil series that represented the experimental area was only 27.1 and 15.7 mg/kg in the respective topsoil and subsoil underneath (**Table 1**). The amount, especially in the 0-25 cm layer, should be conformed with the recommended K fertilization at the rate of 100 K_2O/ha of K_2O (Sittibuasay, 1996). However, soil application using KCl at this recommended rate gave the fresh tuber yield of 30.31 t/ha which still accounted for 37.5% greater than that of the control with zero K fertilization (22.05 t/ha). The KCl soil application at a half quantity of this rate did not give any significantly higher fresh tuber yield than that of the control. This result was quite consistent with a two-year trial in a Typic Paleustult (Prombut et al., 2022) that fresh tuber yield of cassava responded best to the application of 125 K_2O/ha of K_2O in a Typic Paleustult in both growing seasons, also with a single-year experiment in an Ustic Quartzipsamment (Cahm-ngern et al., 2020) that 100 K_2O/ha of K_2O fertilization gave the highest fresh tuber yield, and with even higher rate of 150 K_2O/ha of K_2O in two-year trial (Munyahali et al., 2017).

Foliar applications are a great way to deliver mineral nutrition to growing plants, especially micro and trace minerals. It is also a direct way to apply nutrients for plants grown in soils with low ability to retain plant nutrients such as sandy soils which was the case in this study. It was clear that in this current study the K foliar application significantly performed better than the K soil application in terms of the impact on yield of cassava. With no statistical difference, the KTS foliar application at the rate of 50 K_2O/ha of K_2O resulted in slightly higher fresh tuber yield than did the KCl foliar application at the same rate. Both K sources applied at the same rate augmented the fresh tuber yield by 73.0% and 68.8%, respectively over the control with no K fertilization. In addition, these two foliar applications increased this yield by 39.6% and 36.2%, respectively over the soil application of KCl when cassava received the same 50 K_2O/ha of K_2O (**Figure 1A**). Furthermore, the 50 K_2O/ha of K_2O foliar application using KCl or KTS still significantly gave greater fresh tuber yield than the 100 K_2O/ha of K_2O soil application of KCl. It was also the case for starch yield (**Figure 1B**). This finding demonstrates that growing cassava in sandy soils, the foliar application of K is more effective than the K soil application because this plant nutrient is very soluble and so can be leached to greater depth or to surface waters (Goulding et al., 2021) as K is bound to clays and organic materials and adsorbed mostly in association with fine soil particles, even though Fernández and Brown (2013) remarked the diversity of plant response to foliar fertilizers. Another study in Thailand also showed that the foliar application of KTS at the rate of 46.9 kg/ha of K_2O significantly gave the highest fresh virgin cane yield and aboveground biomass when planted in Kamphaengsaen soil series (Traithipchawalit et al., 2018). Regarding the result obtained in this study, it is very likely that K fertilizer can be reduced to half of the recommended rate for this type of soil. However, additional labour cost and water availability required for the foliar application should be considered.

In contrast to a superiority of the foliar KTS to foliar KCl revealed in the study of Traithipchawalit et al. (2018), cassava yields did not respond rather differently to these two sources of K, despite the KTS providing extra SO_4^{2-} and the KCl giving more Cl^-. This should be coincided with a report showing that S fertilization can hardly increase yields of cassava in a sandy soil of the northeast (Hirunburana et al., 2018) whereas Cl is required by cassava in a very small amount and soil Cl is generally sufficient for the plant (Howeler, 2014). However, in this current study the KCl and KTS foliar application at the rate of 100 kg/ha of K_2O did not give any higher yields of cassava than did the rate of 50 kg/ha of K_2O and apparently the higher rate gave inferior yields to the lower rate. This might be because the concentration used, which was 4% and as reported that KCl and KTS have respective salt index per equal weights of materials of 120.1 and 68.0 (A & L Canada Laboratories, 2013), was too high and subsequently lead to fertilizer burn, causing damage to plant leaves.

Effect of K applications on nutrient uptake

The uptake of N, P and K in the whole plant across all treatments varied in the ranges of 48.55-101.61 kg/ha, 3.01-10.73 kg/ha and 22.52-86.47 kg/ha, respectively (**Table 2**). These demonstrates the approximate proportion of 11:1:8 which was in agreement with Leitch et al. (2023) who conducted a field experiment in Warin soil series where P was taken up in a very low amount even when cassava received 100 kg/ha of P_2O_5. However, other studies (Imas and John, 2013; Chaem-ngern et al., 2020; Prombut et al., 2022) reported greater P uptake proportional to N to K. Regarding the NPK ratio in tuber which was reported to be 5:1:10 (Vanlauwe et al., 2008; Chaem-Ngern et al., 2020), in this study the highest fresh tuber yield (38.14 t/ha) obtained from the plot received the foliar application of KTS at the rate of 50 kg/ha of K_2O had the NPK ratio in tuber of 4:1:8 which is close to the one reported. However, taking fresh tuber yield from the control plot that received no K fertilizer into account, the NPK uptake ratio in tuber was evidently different, demonstrating more N uptake than K uptake proportionally. This is indicative of requiring more K to increase the yield and either KCl or KTS foliar application is, to some extent, a solution to solving this matter. Moreover, IFA (1992) reported that to attain a fresh tuber yield of 45 t/ha cassava needed to take up 62 kg/ha of N, 23 kg/ha of P_2O_5 and 197 kg/ha of K_2O in tuber and 202 kg/ha of N, 73 kg/ha of P_2O_5 and 343 kg/ha of K_2O in whole plant whilst for the highest fresh tuber (38.14 t/ha) obtained in this study cassava took up 35.01 kg/ha of N, 6.79 kg/ha of P_2O_5 and 56.03 kg/ha of K_2O in tuber and 101.61 kg/ha of N, 9.10 kg/ha of P_2O_5 and 77.90 kg/ha of K_2O in the whole plant. This is far lower than that reported, indicating that with a yield difference at only 7 t/ha lower than the reported yield the cassava, Huay Bong 80 variety used in this study may have been better in terms of converting these primary plant nutrients taken up into producing fresh tuber yield.

Potassium use efficiency as affected by K applications

The AE of applied K (ton of fresh tuber yield increase per kg K applied) depends on management practices that affect RE and PE. The results showed that the KCl and KTS foliar application both at the rate of 50 kg/ha of K_2O had the best conversion. In area of 1 ha, they increased the fresh tuber yield of 0.30 and 0.32 t when 1 kg of K_2O was applied.

The PE of applied K (ton of fresh tuber yield per kg increase in K uptake from K fertilization) depends on genotype, environment and management. The low PE suggests sub-optimal growth of plants due possibly to nutrient deficiencies, drought stress, heat stress, mineral toxicities, pests etc. In this study, there was no clear impact of inputs on the PE values which indicated that, taking K applications into account, soil K was possibly sufficient to supply K to cassava as of in the control with the fresh tuber yield obtained (22.05 t/ha). This amount of yield was literally still higher than the average yield per harvested area (21.94 t/ha) of Nakhon Ratchasima province (Office of Agricultural Economics, 2022). Nevertheless, it cannot be implied that growing cassava in this soil can be sustained without K fertilization as K depletion can seriously occur, particularly in sandy soils, after repeated cultivations for a few years, resulting in a drastic decrease in cassava yield (Howeler, 2014).

The RE of applied K (kg increase in K uptake per kg K applied) depends on the congruence between plant demand and nutrient release from fertilizer. The RE can be affected by the application method (amount, timing, placement, N form) and factors that determine the size of the crop nutrient sink (genotype, climate, plant density, abiotic/biotic stresses). In this study, the maximum RE was achieved under the KTS foliar application at the rate of 50 kg/ha of K_2O, indicating that this treatment had the highest effectiveness in terms of K form the KTS foliar application being taken up by cassava. Soil K also additionally played a part in increasing the RE in this treatment. It should be noted that the KCl soil application at both rates had a very low RE, signaling that cassava could take up K form the fertilizer less than half of the K fertilizer applied. Leaching, which is pronounced in sandy soils, should be responsible for the ineffectiveness of the soil K fertilization.

The PFP of applied K (ton of fresh tuber yield per kg K applied) is most important for farmers because it integrates the use efficiency of both soil K and applied K. This is very useful in the case of this study as the result showed that the higher dose of K applied as of 100 kg/ha of K_2O both in the form of foliar and soil applications adversely had much lower PFP, indicating the efficiency of cassava to produce greater fresh tuber yield under lower input of K. Conclusively, the KTS foliar application at the rate of 50 kg/ha of K_2O enhanced the K use efficiency in

AE, RE and PFP due to the optimum dose of K applied and the proper method of application. This result was rather consistent with, to some instance, P use efficiency in rice, RD61 variety of which P soil application combined with P foliar application showed the highest P use efficiency (Sukyankij et al., 2022). However, it can be noticed that increasing rate of K fertilizer, both in the case of soil and foliar application, decreased K use efficiency which was in agreement with a study on Mg fertilizer response of maize grown in growing media (Poonpakdee and Onthong, 2021). Therefore, this nutrient use efficiency assessment can be a very useful tool for fertilizer management in order to improve crop production, especially cassava when planted in low fertility soils.

Conclusions

The KCl and KTS foliar application at the rate of 50 kg/ha of K_2O almost identically promoted the highest fresh tuber yield and starch yield. The K foliar application using both K sources at the rate of 100 kg/ha of K_2O gave inferior yields while the K soil application at both rates was far less effective in this context. The KCl and KTS foliar application at the rate of 50 kg/ha of K_2O induced the highest N and P uptake in almost all plant parts of cassava and the whole plant while the KTS foliar application at the rate of 100 kg/ha of K_2O gave the greatest K and S uptake in all plant parts. The KCl and KTS foliar application also had the highest AE and PFP with the latter having the best RE. Potassium foliar application can be a better alternative for K fertilization in cassava cultivation, particularly in sandy soils, depending upon the availability of water with additional labour cost being taken into consideration. A selection of either KCl or KTS for the foliar application will depend on the price of these K fertilizers. The lower concentration of K foliar application at the recommended rate for this soil (100 kg/ha of K_2O), or in the other word more water used to mix with this K quantity, should be investigated once more whether it can give a higher satisfactory yield.

Acknowledgements

This research was funded by the grant FF(KU5.65) from the Kasetsart University Research and Development Institute (KURDI). The Aditya Birla Chemicals (THAILAND) and the Thai Central Chemical Public Company Limited provided respective the KTS (NUTRATO) and the NPK chemical fertilizers.

References

A & L Canada Laboratories. 2013. Fertilizer Salt Index. Fact Sheet No. 141. A & L Canada Laboratories, Inc., London, UK.

Anusontpornperm, S., S. Nortcliff, and I. Kheoruenromne. 2009. Interpretability comparison between Soil Taxonomic and Fertility Capability Classification units: A case of some major cassava soils in northeast, Thailand. Kasetsart Journal (Natural Science). 43: 9–18.

Anusontpornperm, S., S. Thanachit, A. Suddhiprakarn, and I. Kheoruenromne. 2014. Is Rippering the Effective Solution to Alleviating Plough Pan Problem? In: Proceeding of the International Conference on Agricultural Engineering. Zurich, Switzerland.

Bainbridge, Z., K. Tomlins, K. Wellings, and A. Westby. 1996. Methods for Assessing Quality Characteristics of Non-grain Starch Staples. (Part 2. Field Methods.). Natural Resources Institute, Chatham, UK.

Bardsley, C. E., and J. D. Lancaster. 1965. Sulfur, pp. 1102–1116. In: C.A. Black (ed.). Methods of Soil Analysis, Part II: Chemical and Microbiological Properties. Agronomy Series No.9. American Society of Agronomy. Inc. Madison, WI, USA.

Biratu, G. K., E. Elias, P. Ntawuruhunga, and G. W. Sileshi. 2018. Cassava response to the integrated use of manure and NPK fertilizer in Zambia. Heliyon. 4: article ID e00759.

Blevins, D. G. 1994. Uptake, translocation, and function of essential mineral elements in crop plants, pp. 259-275. In: K.J. Boote, J.M. Bennett, T.R. Sinclair and G.M. Paulsen (eds.), Physiology determination of crop yield. John Wiley & Sons, Inc., New Jersey, USA.

Boonrawd, S., S. Anusontpornperm, S. Thanachit, I. Kheoruenromne, and N. Janjirawuttikul. 2021. Characteristics and fertility capability of cassava growing soils under different annual rainfall conditions in Northeast Thailand. Khon Kaen Agriculture Journal. 49: 1034–1046.

Boateng, S., and S. Boadi. 2010. Cassava yield response to sources and rates of potassium in the forest-savanna transition zone of Ghana. African Journal of Root and Tuber Crops. 8: 1-5.

Bray, R. A., and L. T. Kurtz. 1945. Determination of total organic and available forms of phosphorus in soil. Soil Science. 59: 39–45.

Chaem-Ngern, C., S. Anusontpornperm, S. Thanachit, and I. Kheoruenromne. 2020. Response of cassava, Huay Bong 80 variety, grown in an Ustic Quartzipsamment, to chicken manure and potassium fertilizer. Communication in Soil Science and Plant Analysis. 51: 2765-2777.

Chapman, H. D. 1965. Cation exchange capacity, pp. 891-901. In: C.A. Black, (ed.). Method of Soil Analysis, Part 2: Chemical and Microbiological Properties. Agronomy Series No. 9. American Society of Agronomy. Madison, WI, USA.

Dobermann, A. 2007. Nutrient use efficiency—measurement and management, pp. 1-28. In: A. Krauss, K. Isherwood, K., and P. Heffer (eds.), Fertilizer Best Management Practices: General Principles, Strategy for Their Adoption and Voluntary Initiatives Versus Regulations. International Fertilizer Industry Association, Paris, France.

Fernández, V., and P. H. Brown. 2013. From plant surface to plant metabolism: the uncertain fate of foliar applied nutrients. Frontier in Plant Science. 4: article ID 289.

Gee, G. W., and J. W. Bauder. 1986. Particle-size Analysis, pp. 383-411. In: A.L. Page (Ed.). Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods (2nd ed.). American Society of Agronomy, Inc. Soil Science Society of America, Inc., Madison, WI, USA.

Goulding, K., T. S. Murrell, R. L. Mikkelsen, C. Rosolem, J. Johnston, H. Wang, and M. A. Alfaro. 2021. Outputs: Potassium Losses from Agricultural Systems, pp. 75-98. In: T.S. Murrell, R.L. Mikkelsen, G. Sulewski, R. Norton and M. L. (eds), Improving Potassium Recommendations for Agricultural Crops. Springer, Cham, Switzerland.

Hirunburana, N., S. Thanachit, S. Anusontpornperm, and I. Kheoruenromne. 2018. Sulfur availability in a Typic Paleustult amended with different sulfur rich soil conditioners, pp. 54-59. In: Proceeding of the 44th Congress on Science and Technology of Thailand (STT 44). Bangkok, Thailand.

Howeler, R. H. 1992. Agronomic research in the Asian Cassava Network – An overview, 1987–1990, pp. 260–285 In: R.H. Howeler, R. (ed.). Proceedings of the 3rd Regional Workshop on Cassava Breeding, Agronomy and Utilization Research in Asia. Malang, Indonesia.

Howeler, R. H. 2012. Short- and long-term N, P, and K requirements of cassava, pp 429-454. In: R.H. Howeler (ed.), The Cassava Handbook. A Reference Manual Based on the Asian Regional Cassava Training Course, Thailand. Centro Internacional de Agricultura Tropical (CIAT), Bangkok, Thailand.

Howele, R. H. 2014. Sustainable Soil and Crop Management of Cassava in Asia. CIAT Publication No. 389. Centro Internacional de Agricultura Tropical (CIAT), Cali, Columbia.

IFA. 1992. IFA World Fertilizer Use Manual. International Fertilizer Industry Association. Paris, France.

Imas, P., and K. S. John. 2013. Potassium nutrition of cassava, pp. 13-18. In: Magen, H. (Ed.), Research Findings. E-ifc No.34. International Potash Institute. Basel, Switzerland.

Jackson, M. L. 1965. Soil Chemical Analysis-advanced Course. Department of Soils, University of Wisconsin. Madison, WI, USA.

Johnson, C. M., and A. Ulrich. 1959. Analytical methods for use in plant analysis. California Agric. Exp. Stat. Bull. 767: 25–78.

Leitch, A., S. Anusontpornperm, S. Thanachit, W. Jindaluang, and M. Phun-Iam. 2023. Cassava response to phosphorus fertilizer in Warin soil series amended with cassava tails and stalk-bentonite mixture. Trends in Science. 20: article ID 4885.

Liu, C., M. Huang, M. Huang, K. Liu, and D. Yan. 2020. Effects of foliar fertilization: a review of current Status and future perspectives. Journal of Soil Science and Plant Nutrition. 21: 1-15.

Mikkelsen, R. L., and T. L. Roberts. 2021. Inputs: potassium sources for agricultural systems, pp. 47-73. In: T.S. Murrell, R.L. Mikkelsen, G. Sulewski, R. Norton and M.L. (eds), Improving Potassium Recommendations for Agricultural Crops. Springer, Cham, Switzerland.

Munyahali, W., P. Pypers, R. Swennen, J. Walangululu, B. Vanlauwe, and R. Merckx. 2017. Responses of cassava growth and yield to leaf harvesting frequency and NPK fertilizer in South Kivu, Democratic Republic of Congo. Field Crops Research. 214: 194–201.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Analytica Chimica Acta. 27: 31–36.

National Soil Survey Center. 1996. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 3.0. Natural Conservation Service, United State Department of Agriculture. Washington DC, USA.

Office of Agricultural Economics. 2022. Cassava for Industry. Available: http://www.oae.go.th/assets/portals/1/fileups/prcaidata/files/cacava%2065.pdf. Accessed Jul.16, 2024.

Olaleye, A. O., S. O. S. Akinyemi, H. Tijani-Eniola, J. O. Akinyemi, E. Fapojuwo, M. A. Oladoja, and A. S. Onsanaya. 2006. Influence of potassium fertilizer on yield of plantain intercropped with cassava on an oxic paleustalf in Southwestern Nigeria. Communications in Soil Science and Plant Analysis. 37: 925-938.

Phun-iam, M., S. Anusontpornperm, S. Thanachit, and I. Kheoruenromnea. 2018. Yield response of cassava Huay Bong 80 variety grown in an Oxyaquic Paleustult to cassava starch waste and nitrogen fertilizer. Agriculture and Natural Resources. 52: 573–80.

Poonpakdee, C., and J. Onthong. 2021. Magnesium fertilizer response of maize grown in growing media. Journal of Agricultural Research and Extension. 38: 1-14.

Prombut, N., S. Anusontpornperm, S. Thanachit, I. Kheoruenromne, and M. Phun-Iam. 2022. Response of cassava to potassium fertilization in a tropical sandy Typic Paleustult amended with burnt rice husk for two-consecutive years. Communication in Soil Science and Plant Analysis. 53: 1823-1840.

Salim, B. B. M., H. G. Abd El-Gawad, and A. A. El-Yazied. 2014. Effect of foliar spray of different potassium sources on growth, yield and mineral composition of potato (*Solanum tuberosum* L.). Middle East Journal of Applied Science. 4: 1197–1204.

SAS Institute. 2004. SAS/STAT 9.1 User's Guide. SAS Institute Inc., North Carolina, USA.

Sittibusaya, C. 1996. Strategies for Developing Fertilizer Recommendations for Field Crops. Ministry of Agriculture and Cooperatives, Bangkok, Thailand.

Sogbedji, J. M., L. K. Agboyi, K. S. Detchinli, R. Atchoglo, and M. Mazinagou. 2015. Sustaining improved cassava production on west African ferrasols through appropriate varieties and optimal potassium fertilization schemes. Journal of Plant Sciences. 3: 117-122.

Sowcharoensuk, C. 2023. Industry Outlook 2023-2025: Cassava industry. Available: https://www.krungsri.com/en/research/industry/industry-outlook/agriculture/cassava/io/cassava-2023-2025. Accessed Jul.16, 2024.

Sukyankij, S., S. Sukyankij, C. Khongsud and T. Panich-pat. 2022. Effects of foliar phosphorus fertilizer on yield and phosphorus use efficiency in rice RD61 variety. Journal of Agriculture. 38: 305-318.

Taufiq, A., Subandi, and Suyamto. 2013. Response of Cassava (*Manihot esculenta* Crantz.) to potassium on acidic dry land in Indonesia. Project Report, Indonesian Legumes and Tuber Crops Research Institute, Malang, Indonesia.

Thomas, G. W. 1982. Exchangeable cations, pp. 159–165. In: A.L. Page (ed.). Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties, 2nd ed. Agronomy Monograph No. 9. American Society of Agronomy and Soil Science Society of America, Madison, WI, USA.

Traithipchawalit. P., S. Anusontpornperm, I. Kheoruenromne, and S. Thanachit. 2018. Growth and yield response of virgin cane, K95-84 variety, to potassium chloride and potassium thiosulfate. Khon Kaen Agriculture Journal. 46: 991-1000.

Ukaoma, A. A., and C.I. Ogbonnaya. 2013. Effect of inorganic mineral nutrition on tuber yield of cassava (*Manihot esculenta* Crantz) on marginal ultisol of South Eastern Nigeria. Academia Journal of Agricultural Research. 1: 172-179.

Umeh, S. I., C. C. Onyeonagu, and B. U. Umeh. 2015. Potassium nutrition and translocation in cassava (*Manihot esculenta* Crantz) intercropped with soybean. American Journal of Experimental Agriculture. 5: 281-286.

Uwah, D. F., E. B. Effa, L. E. Ekpenyong, and I. E. Akpan. 2013. Cassava (*Manihot esculenta* Crantz) performance as influenced by nitrogen and potassium fertilizers in Uyo, Nigeria. The Journal of Animal and Plant Sciences. 23: 550-555.

Vanlauwe, B., P. Pypers, and N. Sanginga. 2008. The potential of integrated soil fertility management to improve the productivity of cassava-based systems. In: Cassava: Meeting of the Challenges of the New Millennium: Proceedings of the First Scientific Meeting of the Global Cassava Partnership. International Plant Biotechnology Outreach (IPBO), Ghent University, Ghent, Belgium.

Walkley, A., and C. A. Black. 1934. An examination of Degtjareff method for determining soil organic matter: A proposed modification of the chromic acid titration method. Soil Science. 37: 29–38.

Westerman, R. L. 1990. Soil Testing and Plant Analysis, 3rd ed. American Society of Agronomy and Soil Science Society of America. Madison, WI, USA.

Wilson, H., and A. Ovid. 1994. Influence of fertilizers on cassava production under rainfed conditions. Journal of Plant Nutrition. 17: 1127-1135.