Research Findings

Measuring results from cassava field experiment in Kalipare, East Java, Indonesia. Photo by IPI.

Response of Cassava (*Manihot esculenta* Crantz.) to Potassium Application on Various Soil Types in East and Central Java, Indonesia

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Abstract

East and Central Java are among the major cassava producers in Indonesia. Assuming that potassium (K) availability is a limiting factor for cassava cropping under the given conditions, the effects of K fertilizer at six seasonal doses (0, 30, 60, 90, 120, and 180 kg K_2O ha^{-1}) applied twice (one and three months after planting), and one treatment attributed to farmers' practice, were examined at four locations: Malang, Tulungagung, Wonogiri, and Karanganyar districts. The soils of the different regions vary from neutral (pH 6.2-6.8) silt loam to acid (pH 4.6-5.1) clay, and from high to very low exchangeable K (exch-K) contents. All K fertilizer treatments were combined with nitrogen (N) - 135 kg N ha^{-1}, and phosphorus (P) fertilizers - 36 kg P_2O_5 ha^{-1}, except one treatment with 200 kg N ha^{-1}, and 60 kg P_2O_5 ha^{-1}. Urea (46% N), SP36 (36 kg P_2O_5), and KCl (60% K_2O) were used as

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the source of N, P, and K fertilizer, respectively. Potassium doses hardly affected soil properties at harvest. Crop response to K dose was small to negligible at three sites, and significant only at Tulungagung, where tuber yield increased from 19 to 35 Mg ha^{-1}. The highest yields, 40-50 Mg ha^{-1}, were obtained at Malang on a rather fertile soil, but this is still below the recognized cassava yield potential. Nevertheless, some evidence indicates that there is considerable potential for K fertilization and other means to improve cassava production in these regions. The major problem of K nutrition, common to all four regions at varying significance, seemed to be the rapid depletion of the soluble K pool, including the applied fertilizer, from the rhizosphere before reaching the uptake zone of the roots. The tropical precipitation regime that promotes soil weathering and nutrient leaching must be taken into account. Measures such as division of the seasonal K dose into many frequent applications and supplementation of composted organic matter in order to enhance soil fertility and cassava crop performance are discussed.

Introduction

Cassava (*Manihot esculenta* Crantz) has multiple end-uses such as food, animal feed, and raw material for many industries. Hence, demand for this produce is likely to increase. In Indonesia, cassava has a strategic role for food security because 64% of total cassava consumption is for food. Recently, studies have been carried out to develop cassava as a raw material for biofuel.

Indonesia is the fourth cassava producer in the world after Brazil, Nigeria and Thailand. Sutyorini and Waryanto (2013) showed that during years 2009-2013, the harvested area of cassava declined by 3% (from 1.18 million ha in 2009 to 1.14 million ha in 2013), but the productivity increased by 12%, from 19.4 to 21.7 Mg ha^{-1}. In 2013, the cassava area in East and Central Java was 16% and 15% of the national area, respectively, with an average productivity of 23 Mg ha^{-1}. In East and Central Java, the cassava area declined by 15% during 2009-2013, however, the yields increased by 25% and 3%, respectively.

By using appropriate cultural practices, cassava yield could attain 25-40 Mg ha^{-1} (Wargiono *et al.* 2006). Taufiq *et al.* (2009) reported even higher yields of 63 Mg ha^{-1}, when 70, 30, and 115 kg ha^{-1} of nitrogen (N), P_2O_5, and K_2O, respectively, were applied. The amount of nutrient uptake by cassava is high. Howeler (1981) found that with a fresh tuber yield of 21 Mg ha^{-1} cassava absorbed 87, 37.6, and 117 kg ha^{-1} of N, phosphorus (P), and potassium (K), respectively. Wargiono *et al.* (2006) reported that, at a yield level of 30 Mg ha^{-1}, cassava absorbed 147.6, 20.7, and 148.8 kg ha^{-1} of N, P and K, respectively. Amanullah *et al.* (2007) showed that fresh tuber yields ranging from 20-35 Mg ha^{-1} required quite stable rates of about 6, 0.75, and 6 kg of N, P, and K, respectively, per Mg ha^{-1}. These data revealed that K uptake is as high as that of N. Putthacharoen *et al.* (1998) showed that K removed by cassava in the harvested product was as high as K removal by maize and peanut.

Cassava can be planted in various agroecosystems. The crop is adaptable to dry condition as well as marginal soil fertility. Lampung, East Java, and Central Java provinces are the main cassava producing regions in Indonesia. Soil type in the main area was dominated by Alfisol, Ultisol, and Inceptisol, which commonly had marginal soil fertility (Suryana, 2007). Until 15 years ago, the majority of cassava plantations in East and Central Java were cultivated as a monocrop. Nevertheless, due to low or unstable prices, farmers quite often tended to intercrop cassava with maize, upland rice, or with peanut.

The positive response of cassava yields to K application, particularly on poor soils, below the critical threshold of exchangeable K^+ at 0.15 meq per 100 g soil (Howeler, 1981), has been well documented (Maduakor, 1997; Suyamto, 1998; Nguyen *et al.*, 2002; Ispandi and Munip, 2005). Also, the significant reduction in cassava yield in the absence of K fertilization during five consecutive cropping years was clearly demonstrated (El-Sharkawy and Cadavid, 2000). Furthermore, this yield reduction was considerably restrained by K application. Nevertheless, cassava response to fertilizer application may largely depend on local soil properties and on farmers' practices. In the past, the majority of Indonesian cassava growers did not apply any fertilizer (FAO, 2005). Those who did, used to apply high levels of N, less P, and no K fertilizer. Almost all of cassava biomass is taken away from the field at harvest, thus soil fertility, especially K, is rapidly degraded. Therefore, it is important to optimize the K dose to the local soil properties and cassava plant requirements.

The objectives of the present three-year (2011/12 - 2013/14) study were: to examine cassava response to elevated K dose on four typical soils of East and Central Java, Indonesia; to demonstrate the contribution of K application to the cassava yield, as compared to the common K-deficient practices; and, to create awareness among farmers and extension workers on balanced nutrient management and cost:benefit ratio analyses. This paper focuses on the results obtained during the last two or three consecutive years of the experiment in relation to the previous years' results.

Materials and methods

Location and Planting Date

An on-farm trial was conducted at four sites (Map 1):

1. Sukowilangun village, Kalipare sub-district, Malang district, East Java Province (8°11'03" S, 112°26'51" E; 296 m asl). Planting date: 12 Nov, 2013. Harvest: 10 Sep, 2014. The trial on this site lasted three consecutive years with constant treatments and layout.

2. Ngrejo village, Tanggunggunung sub-district, Tulungagung district, East Java Province (8º14'08" S, 111º53'04" E; 198 m asl). Planting date: 19 Nov, 2013. Harvest: 1 Sep, 2014. The trial on this site lasted three consecutive years with constant treatments and layout.

3. Molokokulon village, Ngadirojo sub-district, Wonogiri district (7º47'26.23'' S, 111º0'42.97" E; 325 m asl), Central Java Province. Planting date: 19 Nov, 2013. Harvest: 3 Nov, 2014. The trial in this area lasted two years, but not in the same field.

Map 1. A general map of Indonesia (A), with the regions of experimental work in the yellow square; the four experiment sites in Malang (1), Tulungagung (2), Wonogiri (3), and Karanganyar (4) districts in East and Central Java, Indonesia (B); Köppen-Geiger climate classification of Java: Eqatorial (Af, dark blue), Monsoon (Am, blue), and Tropical savanna (Aw, light blue). Yellow circles indicate experiment sites (C). *Sources:* Google Maps (A and B); derived from: World Koppen Classification.Svg, https://creativecommons.org/compatiblelicenses/by-sa/4.0/# (C).

4. Jatipuro village, Jatipuro sub-district, Karanganyar district, Central Java Province (7º44'31.22" S, 111º55'95" E; 430 m asl). Planting date: 20 Nov, 2013. Harvest: 5 Nov, 2014. The trial on this site lasted two consecutive years with constant treatments and layout.

Climate

The climate of Java island, Indonesia is tropical, however, significant differences occur between regions (Map 1C), particularly regarding precipitation (Fig. 1).

In all four regions, there is a clear distinction between the rainy (November - April) and the dry (May - October) seasons. Malang is the driest district, with about 1,300 mm yearly. The Central Java districts have significantly more rain, with more than 2,100 mm a year, while Tulungagung is intermediate with about 1,640 mm a year (Fig. 1).

Soil characteristics

Soil properties at the four experimental sites at the beginning of the last growing season are presented in Table 1. Soil texture differed significantly between sites, with silt-loam in Kalipare-Malang, light clay in Tulungagung, silty clay loam to clay in Wonogiri, and heavy clay in Karanganyar. Soil pH was slightly acidic to nearly neutral in the East Java sites, and quite acidic in the Central Java sites, but in all cases within the range suitable for cassava (4.5 - 7.0), as classified by Howeler (2002). Organic Carbon (C) and total N content were very low at all sites even in the topsoil layer, indicating that addition of organic matter and N fertilizer might have a positive effect on cassava growth. This was the reason why farmers usually applied high rates of N fertilizer. Critical levels of P and K for cassava were 8 ppm P (18 ppm P_2O_5) and 0.15 meq K 100 g^{-1} (Howeler, 1981). Phosphorous availability in the topsoil and in the subsoil layer in the East Java sites was high, except in the subsoil layer at Tulungagung. On the contrary, in the Central Java sites, P availability was below the critical level.

Potassium availability at Malang site was high in both layers, while at Tulungagung it was just above or at the critical level in the topsoil and subsoil layers, respectively. Exchangeable K (exch-K) was high in both sites of Central Java (Table 1).

Experimental set up

The trial consisted of seven treatments that were arranged in a randomized complete block design with three replications. The treatment consisted of six rates of K fertilizer (0, 30, 60, 90, 120, 180 kg K_2O ha^{-1}), and one treatment representing local farmers' practice. Detailed descriptions of the treatments at each region are given in Table 2. Urea (46% N), SP36 (36 kg P_2O_5), and KCl (60% K_2O) served as the source of N, P, and K, respectively. Nitrogen was applied one, three, and five months after planting (MAP) with proportionally 25%, 50%, and 25% of each dose, respectively. Phosphorus and K were applied one and three MAP, split into two equal doses. Phosphorus and K Fertilizers were dibbled at 7-10 cm distance (P) or next to the plant (K) and covered with soil. Fertilizer rates applied by farmers varied among individuals and sites (Table 3).

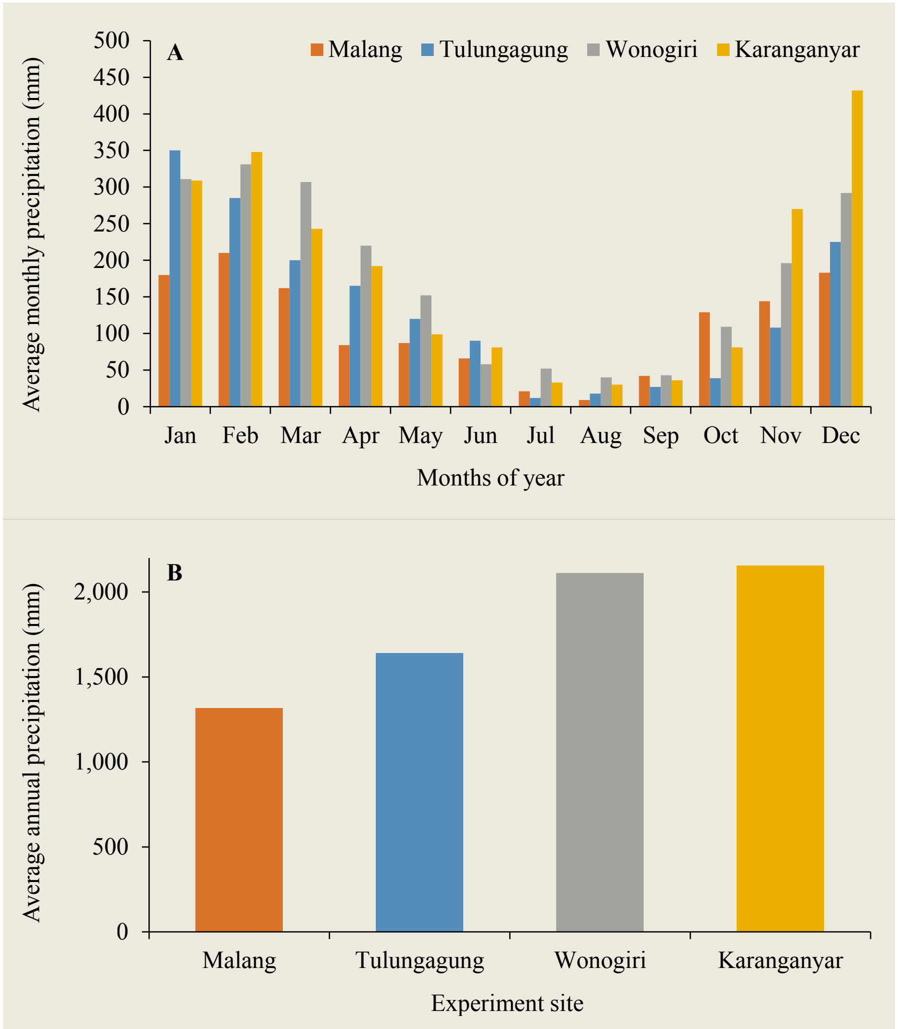

Fig. 1. Average monthly (A) and average annual (B) precipitation in the four experiment sites during years 2000-2012 in East and Central Java, Indonesia. Source: http://www.worldweatheronline.com/.

Table 1. Soil characteristics at four sites in East and Central Java at the beginning of the experiments.

Soil variables	East Java				Central Java			
	Kalipare-Malang		Tanggunggunung-Tulungagung		Ngadirojo-Wonogiri		Jatipuro-Karanganyar	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Sand (%)	28	35	19	17	14	5	8	6
Silt (%)	55	54	39	27	54	33	39	35
Clay (%)	17	19	42	44	32	62	53	59
Texture	Silt loam	Silt loam	Clay	Clay	Silty clay loam	Clay	Clay	Clay
pH-H_2O (1:2.5)	6.6	6.8	6.2	6.2	4.6	5.0	5.1	5.2
C-organic (%)	1.09	1.39	1.67	1.66	1.46	1.40	1.06	1.08
N-total (%)	0.08	0.07	0.12	0.12	0.11	0.09	0.07	0.07
P_2O_5 (ppm)	26.9	30.3	28.5	4.78	13.5	3.20	5.05	4.78
Exch-K ($cmol^+ kg^{-1}$)	0.98	0.93	0.21	0.15	0.27	0.28	0.34	0.38
Exch-Ca ($cmol^+ kg^{-1}$)	2.03	13.1	28.6	29.4	2.31	2.34	3.94	2.02
Exch-Mg ($cmol^+ kg^{-1}$)	3.65	3.30	7.30	7.11	0.72	0.75	0.60	0.63

Table 2. Detailed description of the experiment treatments in East and Central Java, 2013/2014.

Treatment	Fertilizer dose			
	N	P_2O_5		K_2O
		East	Central	
	-----------------------*kg ha*$^{-1}$-----------------------			
T_1 Farmer's practices[(1)]				
T_2	135	36	60	0
T_3	135	36	60	30
T_4	135	36	60	60
T_5	135	36	60	90
T_6	135	36	60	120
T_7	200	60	60	180

[(1)]Farmer's practices are described in Table 3.

Implementation

After soil cultivation and ridging, cassava stem cuttings (cultivar Malang-4) were planted along the ridge, spaced at 100 cm between rows and 100 cm within a row (plant density 10,000 plants ha^{-1}), excluding Kalipare site, where 125 x 100 cm (8,000 plants ha^{-1}) spacing was performed. Plot size at all sites was 5 x 8 m, except in Kalipare, which was 6.25 x 8 m (5 rows of 8 m length). Cassava was planted as a monocrop.

Bud reductions to maintain two buds per plant was carried out one MAP. Hand weeding was executed at one, two, and three MAP (depending on weed condition). Insect and disease control included the use of chemical pesticides as required. The crop was harvested at about 10 MAP.

Data collection

1. Initial soil analyses, 0-20 and 20-40 cm deep, consisted of pH (soil:water 1:2.5), P (Bray-1 extraction method), K, Ca, and Mg (extraction using 1 N NH_4-acetate pH 7), and C-organic (Kurmis method). Nine soil subsamples were taken systematically from the plots using a soil auger. The sub samples at each depth were merged and taken for analyses at the Soil and Plant Laboratory of ILETRI.
2. Leaf, stem, and tuber dry matter contents (three plants per plot) were determined at harvest. Samples were oven-dried at 105°C (for leaf and stem) and at 60°C (for tuber) till reaching a constant weight.
3. Leaf (including petiole), stem and tuber K concentration were determined at harvest.
4. Soil samples (0-20 cm deep at the root zone) were taken from each plot at harvest and K concentration was determined.
5. Fresh tuber yields were determined for each plot at harvest.
6. Tuber starch content was determined at harvest at the Food Science Laboratory of ILETRI, employing the hydrolysis method.

Table 3. Fertilizer applied in farmer's practice treatment at the four experimental sites in 2013/2014.

Site	Fertilizer rate			Equivalent to		
	Urea (46% N)	SP36 (36% P_2O_5)	Phonska 15-15-15	N	P_2O_5	K_2O
	---*kg ha*$^{-1}$---					
Malang	400	0	200	214	30	30
Tulungagung	500	0	200	260	30	30
Wonogiri	600	300	0	276	108	0
Karanganyar	0	0	550	83	83	83

Analysis of variance and mean comparison of collected data were performed using Statistix 3.0 statistical software and MSTAT-C.

Soil analyses at the 2013/14 harvest revealed interesting changes that had occurred in the top soil fertility during the experimental years as a result of the different K doses applied (Fig. 2). In the

East Java sites, the exch-K remained constant or even slightly decreased under K doses less than 60 kg K_2O ha^{-1}, this parameter tended to increase or remain constantly high under higher K doses. Despite any fertilization management, exch-K in Tulungagung was much lower than in Malang. In Karanganyar, Central Java, exch-K increased considerably in the first year of the experiment (2012/13) from 0.17 to 0.46 $cmol^+$ kg^{-1}, but declined in the second year to 0.15-0.29 $cmol^+$ kg^{-1} and was much less responsive to K fertilization (Fig. 2). In the second site of Central Java, Wonogiri, two different fields were employed, each in a season, thus no comparison could be made between consecutive years. However, in the 2013/14 trial, exch-K at harvest increased linearly from 0.22 to 0.66 $cmol^+$ kg^{-1}, under no K and 180 kg K_2O ha^{-1}, respectively. In 2012/13, on a much more fertile soil, exch-K ranged at 0.83-1.08 $cmol^+$ kg^{-1}, with a very slight response to K application dose.

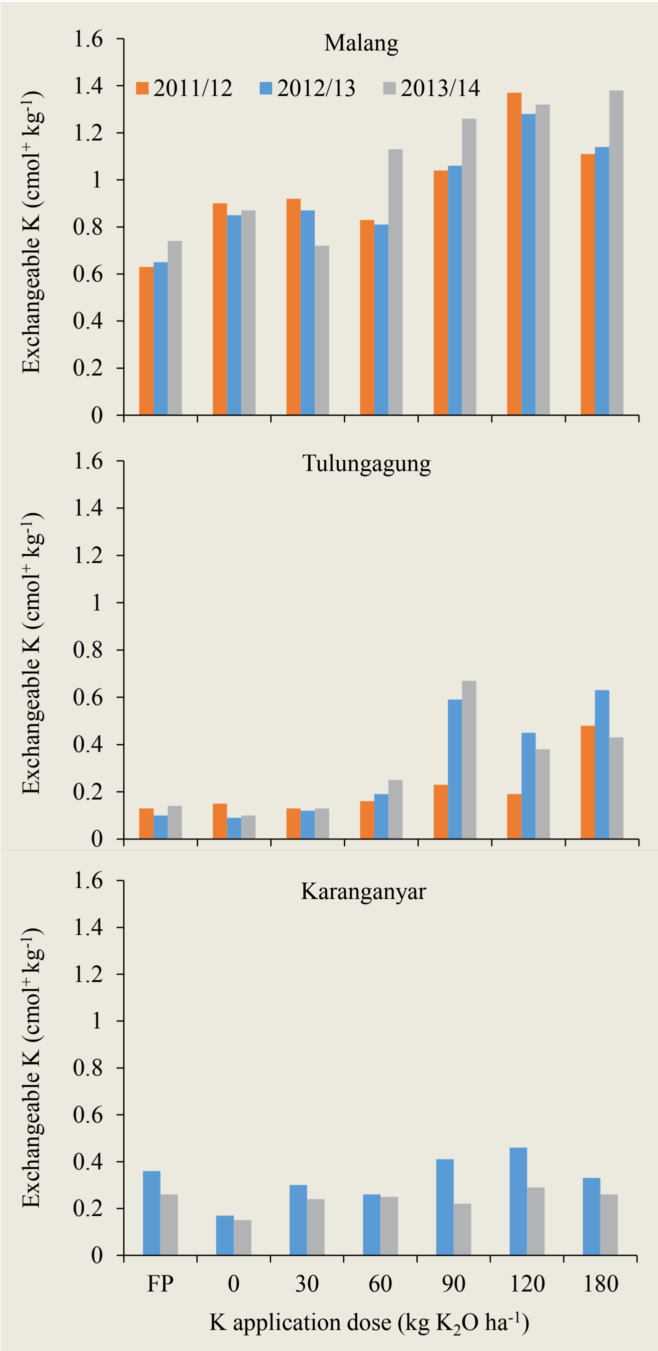

Fig. 2. Effects of K application dose on the exch-K of the top soil at root zone (0-20 cm) during the experimental years in three sites in East and Central Java, Indonesia.

Plant growth and production

Cassava dry matter production during the 2013/14 season was the highest at Malang and Wonogiri, ranging from 17 to 22.5 Mg ha^{-1}, intermediate in Karanganyar (14-16 Mg ha^{-1}), and the lowest at Tulungagung (7-15 Mg ha^{-1}) (Fig. 3A). With the exception of Tulungagung, cassava dry matter production did not display any consistent response to K application dose. In Tulungagung, however, dry matter production increased steadily with increasing K dose (Fig. 3A).

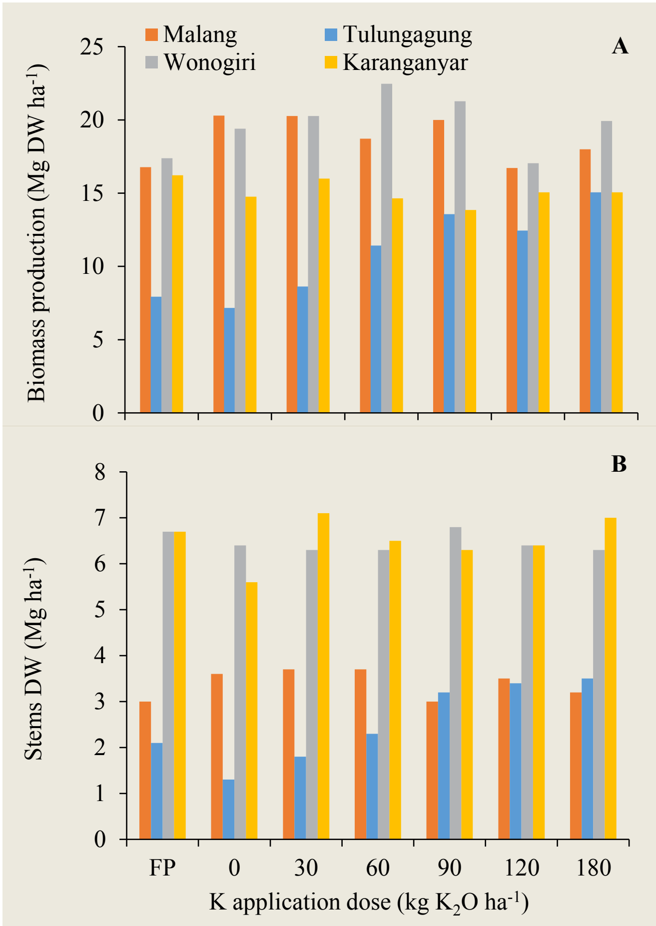

Fig. 3. Total dry matter (A) and stems dry weight (B) in response to K application dose at the four sites of the experiment at the 2013/14 harvest.

Stems biomass at harvest was significantly greater at the Central Java sites, ranging from 6-7 Mg ha^{-1}, while at Malang and Tulungagung in East Java, it ranged from 3-3.7 and 1.3-3.5 Mg ha^{-1}, respectively (Fig. 3B). A clear response of stems biomass to K dose was observed only in Tulungagung.

Tuber yields and dry matter allocation

Large differences in tuber yield occurred between the experimental sites (Fig. 4). The highest fresh weight yields, above 40 Mg ha^{-1}, were obtained at Malang. Here, despite some significant differences between treatments, no consistent response to K dose could be observed. Fresh tuber yield at Wonogiri ranged from 31 to 47 Mg ha^{-1}, second to Malang, and again, showed no significant response to K dose. A significant and positive response was observed at Tulungagung, where fresh tuber yield increased from 19-35 Mg ha^{-1}, as K dose rose from 0-180 kg K_2O ha^{-1}. On the contrary, at Karanganyar, fresh tuber yields were at the lowest level and tended to decline in response to elevated K dose (Fig. 4A).

Examination of the dry tuber yields does not change the impression arising from the fresh tuber yield results. However, a clearer response could be observed in Wonogiri, where dry tuber yield increased as the K dose rose up to 60 kg ha^{-1}, but declined with further increase in K dose (Fig. 4B).

The harvest index (HI) expresses the allocation of dry matter between the product (tubers) and other plant organs (stems and leaves), calculated as: $HI = Tuber_{DM} / (Stems + Leaves + Tubers)_{DM}$. There were significant differences in HI between the districts, nevertheless, no certain effect of K dose on HI could be elucidated from the present results (Fig. 4C).

Tuber yields over consecutive years of the experiment provide a better insight into the influence of K application on both short and long-term perspectives (Fig. 5). Yields from the first year were higher, reaching even 89 and 38 Mg ha^{-1} under 90 K_2O ha^{-1}, at Malang and Tulungagung, respectively. Nevertheless, in the second year yields declined in Malang by 16% and dropped further in the third year to about 66% of the first year. Yield reduction in the second year in Tulungagung was even sharper (28%), but it slightly recovered in the third year. Also in Karanganyar, tuber yields were high in the first year and declined by 13% in the second (Fig. 5). Throughout the experiment, significant tuber yield response to K dose was obvious only in Tulungagung.

Starch and K concentrations

Starch accumulation in cassava tubers averaged 28-30% of fresh weight (Fig. 6). While no significant effect of K dose could be observed at Malang, starch concentration in tubers harvested at Tulungagung and Wonogiri tended to increase with the rising K dose up to 120 kg K_2O ha^{-1} reaching 32-37%, but usually declined

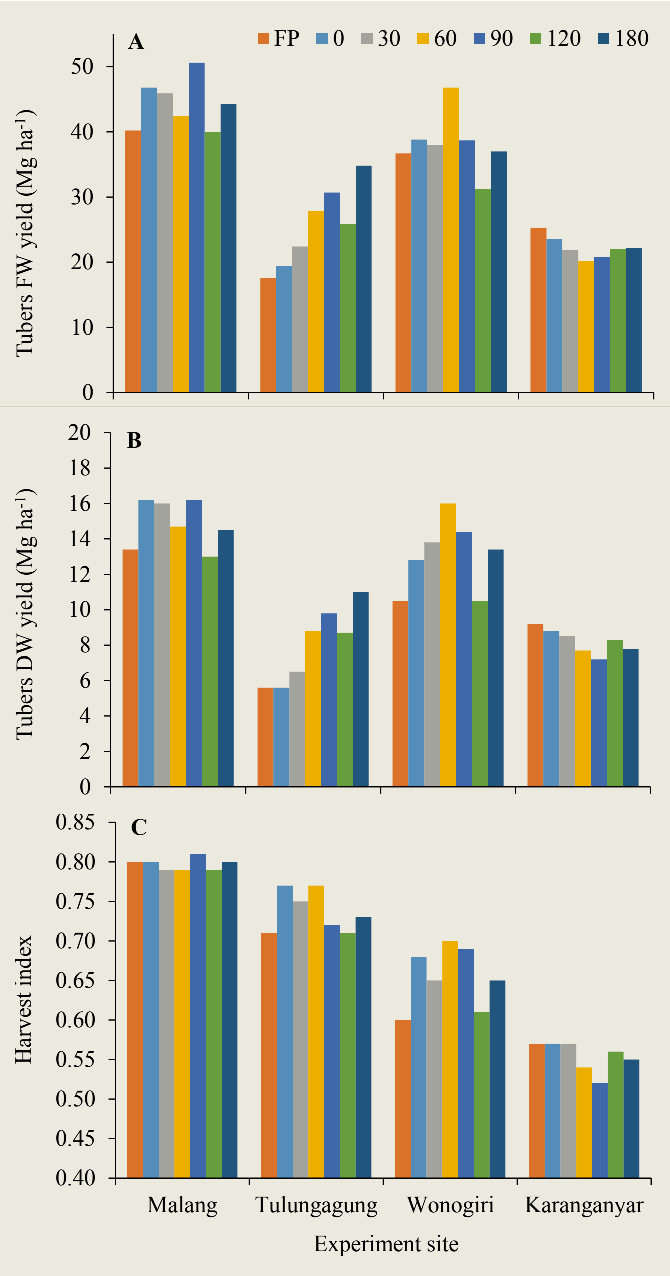

Fig. 4. Tubers, fresh (A) and dry (B) weight yields, and harvest index (C), as affected by K application dose at the four sites of the experiment in the 2013/14 harvest.

back to 28-30% under the highest K dose. Despite significant differences in starch concentration between treatments at Karanganyar, no consistent effect of K dose could be clarified (Fig. 6).

Potassium concentrations in the above-ground organs varied significantly among the experimental sites (Fig. 7). In the leaves, Potassium concentration varied from 0.35-2.31% and from 0.26-

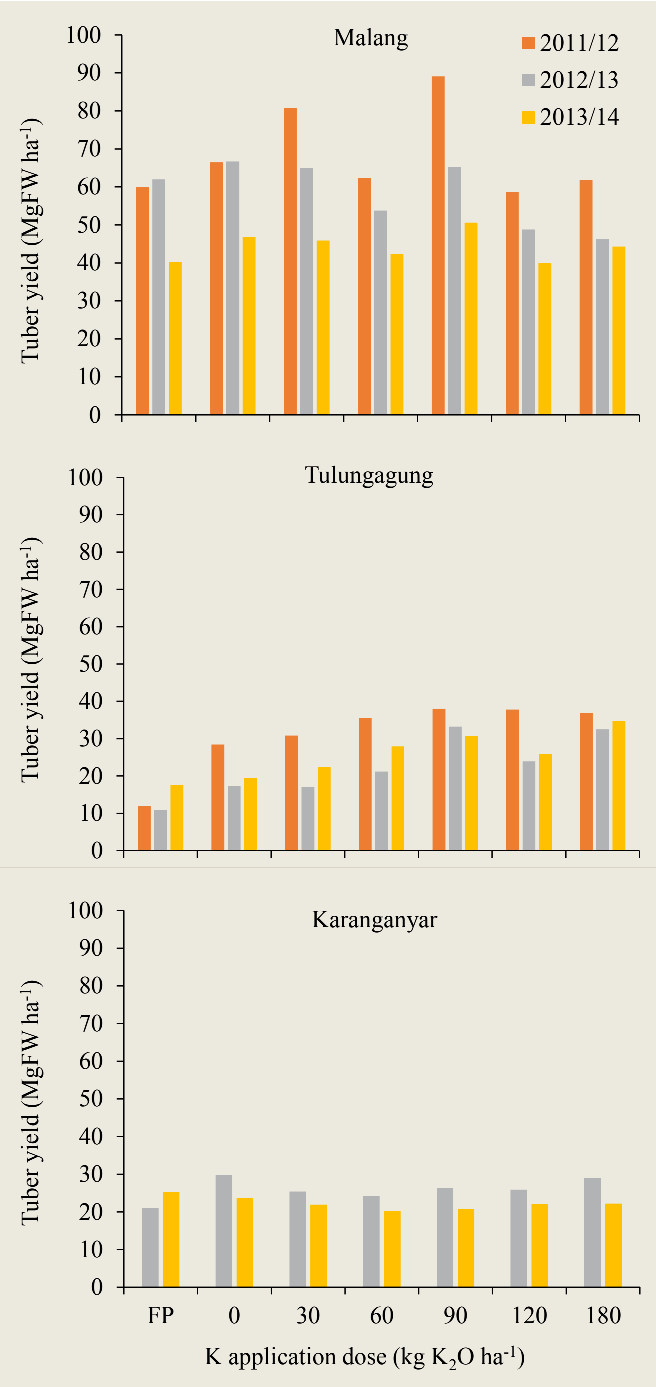

Fig. 5. Effects of K application dose on fresh tuber yields over three (or two) consecutive years of experiment at East Java (Malang and Tulungagung) or Central Java (Karanganyar), respectively.

1.89 in the leaves and the stem, respectively. The highest leaf K concentrations, above 2%, were obtained at Malang under K dose ranging from 0-60 kg K_2O ha^{-1} but those dropped to about 1.5% under higher K doses. The lowest leaf K concentrations were

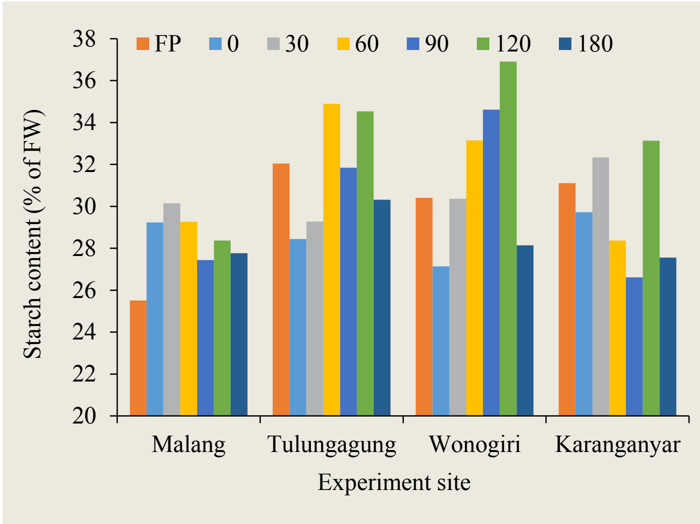

Fig. 6. Influence of K application dose on starch concentration in tubers at the four sites of experiment in 2013/14.

recorded at Tulungagung (0.31-0.56%) displaying a significant tendency to increase in response to the rising K dose above 60 kg K_2O ha^{-1}. In Wonogiri, the differences in leaf K were very small (1.4-1.56%), with a slight but significant tendency to rise with the K dose. A similar trend, but at a much lower range (0.83-1.07), was observed at Karanganyar (Fig. 7). The differences in stem K concentration among the experiment sites were quite similar to those shown for leaf K (Fig. 7). Noteworthy was the significant decline in stem K concentration observed at Malang in response to elevated K dose at the lower range.

Tuber K concentration ranged from 0.2 to 0.77% (Fig. 7). The highest values were recorded at Malang, with a very slight response to K application dose. At the other three sites, tuber K was lower but increased significantly in response to elevated K application dose. That response was clear at Tulungagung above 90 kg K_2O ha^{-1}, slighter at Wonogiri under 30-60 kg K_2O ha^{-1}, and dramatic at 30 kg K_2O ha^{-1}, at Karanganyar.

Potassium removal by the crop

The crop biomass and K concentration measurements in the different plant organs provided a rough calculation of K removal by the cassava crop (Table 4). Obviously, K removal at Malang was significantly higher than K inputs under most of the K application doses. Furthermore, K removal even tended to decline with the rising K dose. On the contrary, at Tulungagung, where K removal under zero K was about 17 kg K ha^{-1}, only 10% of the removal at the respective situation in Malang, it steadily increased with rising K doses up to 59 kg K ha^{-1}, about 40% of K input. Also at the Central Java sites, K removal by the cassava crops exceeded inputs at most K application doses; only at 120 kg K_2O ha^{-1} or above did K application exceed K removal. At

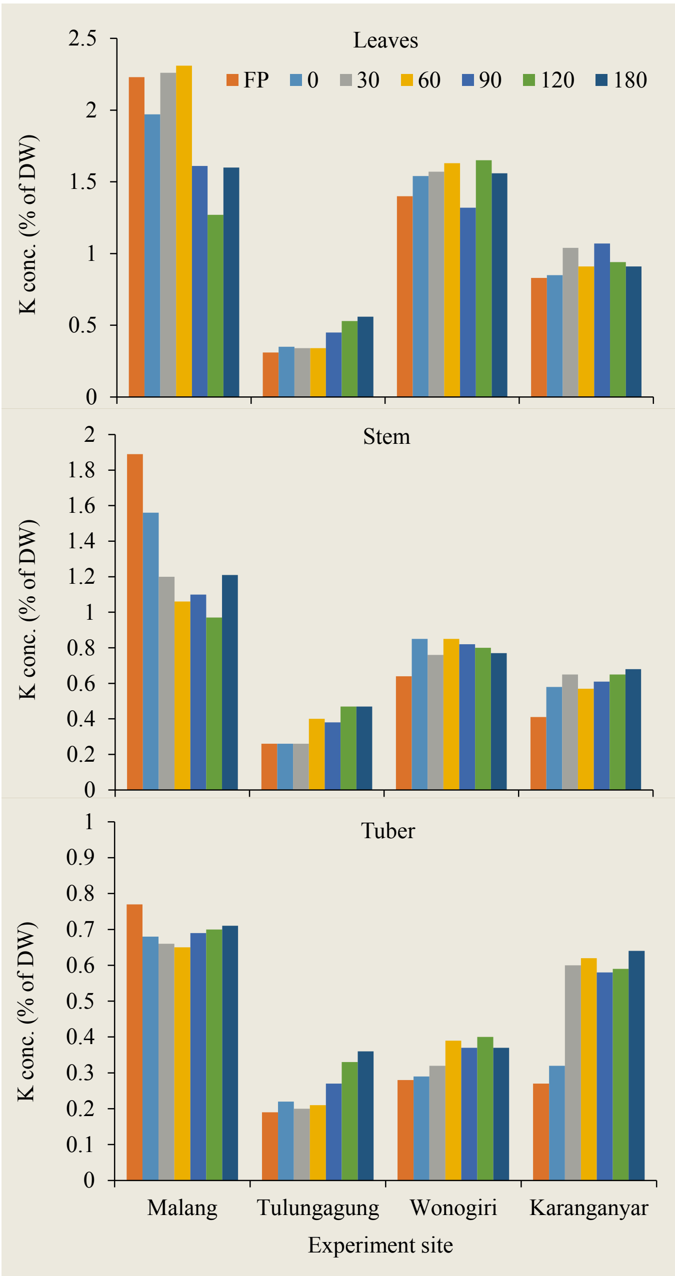

Fig. 7. Effects of K application dose on K concentrations in the leaves, stem, and tubers at harvest.

both sites, K removal rate seemed to respond only at the lower K application range of 30 or 60 kg K_2O ha^{-1} (Table 4).

Discussion

Indonesia is an important cassava producer, however, the average yields obtained are lower than the potential production for this crop. It was hypothesized that farmers' practices that frequently ignore cassava K requirements were responsible for the poor performance of this crop in many regions of Indonesia. Hence, optimizing K supply should result in higher yields. In the present study, a wide range of K application doses, up to 180 kg K_2O ha^{-1}, were examined during two to three consecutive years on various soil types and climate conditions. The maximum cassava yields that were obtained on the third consecutive crop season (2013/14) at Malang, East Java, ranged at 40-50 Mg ha^{-1} (Fig. 4). These are generally within the upper range of yields reported for cassava under various conditions of soil and fertilization regimes (Wargiono *et al.*, 2006). Nevertheless, reports of much higher yields (Taufiq *et al.*, 2009), and yields obtained in the present study on the first or second years of the experiment (Fig. 5) point to reasonably higher potential. Furthermore, tuber yields at the other three sites were fairly small (Wonogiri, Central Java), or significantly low (Tulungagung and Karanganyar, Fig. 4). Apparently, among the four experimental sites, K application was found to be effective and economically beneficial only at Tulungagung, and even there, tuber yields remained relatively poor. Can K application still be a considerable solution and what measures should be taken to realize its potential?

Potassium is essential for plant growth and development (Marschner, 1995). If not provided by a fertile soil, K must be supplied to ensure satisfactory crop performance and yield. Potassium plays a major role in sugar transport and starch accumulation in plants (Zörb *et al.*, 2014). Therefore, starch accumulating crop plants such as potato, wheat, and maize (Pettigrew, 2008), as well as cassava, are significant K consumers. Indeed, K requirements of cassava are high, as indicated by the K removal rates calculated in the present study (Table 4), and are expected to further increase in the future, in case the expectations for higher yields come true. Yet, K removal rates were often much higher than K applied; there were huge differences among sites in crop performance and yield under similar fertilization regimes, and; crop response to K application dose was very poor or unsatisfactory. These discrepancies require further in-depth explanation.

Potassium uptake by plants is strongly determined by soil properties, climate (temperature and precipitation regime), and fertilization management. The availability of K differs greatly with soil type and is affected by physico-chemical properties of the soil. To simplify the complex K dynamics in the soil, K in soil is often classified into four groups depending on its availability to plants: water-soluble, exchangeable, non-exchangeable and structural forms (Zörb *et al.*, 2014). Water-soluble K is directly available to plants, and potentially susceptible to leaching. Exchangeable K is electrostatically bound as an outer-sphere complex to the surfaces of clay minerals and humic substances (Barre *et al.*, 2008). Both fractions are often considered to be easily available to crops. However, the size of both pools is very small, only about 0.1-0.2% and 1–2% of the total K in soil,

Table 4. Estimated K removal by cassava crop during the 2013/14 season, as affected by K application dose and experiment site.

Treatment	K_2O input	Equivalent K input	Experiment site			
			Malang	Tulungagung	Wonogiri	Karanganyar
	--kg ha^{-1}--					
T_1	FP[(1)]	FP[(1)]	168.4	16.8	74.8	55.0
T_2	0	0	176.0	16.6	94.6	63.7
T_3	30	24.9	162.9	18.8	94.7	101.2
T_4	60	49.8	142.2	28.8	118.7	88.8
T_5	90	74.7	157.7	41.2	110.0	83.9
T_6	120	99.6	127.6	46.5	95.5	94.0
T_7	180	149.4	146.3	59.2	101.7	99.8

[(1)]FP = farmers' practices that differed among sites. K_2O inputs were: 30, 30, 0, and 83 kg ha^{-1} (equivalent to: 24.9, 24.9, 0, and 69 kg K ha^{-1}) at Malang, Tulungagung, Wonogiri, and Karanganyar sites, respectively.

respectively (Sparks, 1987). Non-exchangeable and structural forms are considered to be slowly- or non-available K sources for plants. However, these pools may also contribute significantly to the plant supply in the long term (Pal *et al.*, 2001).

The quantities of plant-available and non-available K in the soil varies greatly among soil types, and dynamic equilibrium reactions exist between the different soil K pools. Thus, a number of soil physical and chemical properties as well as plant-soil interactions and soil microbial activities affect the fixation and release of K in soils.

The degree of K fixation or release in soils depends on the type of clay mineral and its charge density, moisture content, competing ions, and soil pH. Wet soil, and moreover, frequent cycles of soil wetting may enhance soil weathering and K release. The H^+ concentration in soil solution (via soil pH) seems to play a key role in K release from clay minerals by enhancing the exchange of H^+ for K^+. The combination of heavy precipitation regime, high temperature, and acidic soils facilitates soil weathering and K release and availability to plants, but also promotes rapid K loss through leaching. These conditions also enhance the degradation and mineralization of soil organic material. Organic acids, exuded by plant roots and certain microbial flora, are known to facilitate weathering of soil minerals through the formation of metal-organic complexes, and by enhancing the exchange of H^+ for K^+ (Hinsinger and Jaillard, 1993; Wang *et al.*, 2011). The depletion of K in rhizosphere soil solution below a threshold level (10-20 µM) has been reported to be a key signal which activates the root exudation mechanisms (Hosseinpur *et al.*, 2012; Schneider *et al.*, 2013).

Photo 2. The highest fresh tuber weight of cassava at Wonogiri site in 2013/2014 . Photo by A. Taufiq.

Fertilizer application is required not only to ensure but also to sustain an adequate supply of soluble K to crops. Thus, for optimized K fertilizer management practices, it is crucial to recognize and understand the dynamic factors regulating soil K availability, as well as the shifting crop requirements that occur under specific local conditions. Therefore, and due to the large differences in yields and in crop response to fertilizers application, the results of each experiment site are discussed separately, as case studies.

The Kalipare-Malang site is characterized by a silt loam soil with neutral pH, relatively high exch-K (Table 1), and the lowest annual precipitation, only 1317 mm (Fig. 1). The high, K-irresponsive tuber yields obtained here (Fig. 4), the high HI, and the very high K removal rates (Table 4) indicate that soil fertility can provide most of the crop K requirements and only a small dose (30 kg K_2O ha^{-1}) would be required to maintain this situation. Presumably, with the dose applied twice, in December and February, at the beginning of the crop cycle and at the middle of the rainy season (Fig. 1), most of the excess K fertilizer had been leached away from the rhizosphere before reaching the plant. Moreover, the declining rates of K removal with the rising K application dose may suggest that excess concentrated K fertilizer, the way it has been applied, interrupts the fragile balance between soil-K release and K uptake by the crop. However, in order to further increase cassava tuber yields under these conditions a higher K dose, divided and applied 5-6 times during the season, should be considered. Noteworthy is the limited stem fraction in the crop biomass (Fig. 3) under the high K availability at Malang (Fig. 2) demonstrating K role in governing dry matter production and allocation.

On the contrary, the soil of Tanggunggunung-Tulungagung site is clayish, more acidic (pH 6.2), very low exch-K (Table 1), and receives 1640 mm of annual precipitation. In this site, the lowest tuber yields were obtained. However, the response to K application dose was significant and positive for all parameters, including biomass production (Fig. 2), tuber yield and HI (Fig. 4), and starch (Fig. 6) and K contents (Fig. 7). Potassium removal was in close correlation with K application dose, indicating significant crop dependence on fertilization. Nevertheless, K use efficiency declined steeply from 75 to 39% with increasing K dose (Table 4). These results suggest that the opportunity the crop has to utilize applied K is very limited, and a large proportion of fertilizer is wasted. The same as the previous case study, distribution of the K dose during the cropping season might broaden the opportunity for K uptake, thus increasing K use efficiency, and furthermore, enhancing crop performance and yields.

The low soil pH (4.6-5.2) in Central Java, combined with high annual precipitation (2150 mm) promote rapid weathering of the clay soil, releasing significant K from the fixed to the soluble pool. Thus, with relying on soil available K, considerable (though unsatisfactory) tuber yields are obtained (Fig. 4). Large proportions of the soluble K pool are prone to be leached away during the rainy season. Moreover, any additional K applied during that period (November-April, Fig. 1) is presumably washed away before reaching plant roots (Lambin and Meyfroidt, 2010), explaining the poor response to K application dose. High imbalanced N/K nutrition ratio might have promoted stem growth (Fig. 3) at the expense of tubers, leading to the declining HI (Fig. 4). Undoubtedly, more efficient K supply should improve cassava crop performance. Under the Central Java circumstances, first K application should take place about 30 days after planting, when the new fibrous roots penetrate into the soil and begin functioning (Alves, 2002). The rest of the annual dose should be divided into small portions and applied frequently throughout the season, preferably during April to June, under an intermediate precipitation regime.

Careful attention to two issues, not necessarily associated with K nutrition, may contribute to improving cassava cultivation in the tropics: soil amendment and crop rotation. Lack of organic material is often associated with loosening of soil particles and consequent soil erosion and poor cation exchange capacity (Don *et al.*, 2010; Prabowo and Nelson, 2015). The common practice to remove all above ground residues from cassava fields after harvest, although done for phytosanitary reasons, accelerates soil degradation processes. In cassava, organic manurial treatments were shown to result in higher nutrient uptake by plants, higher tuber yields, and the least depletion of soil nutrients (Amanullah *et al.*, 2007). Embedding composted organic matter in ridges along the rows and application of supplemental fertilizers and soil amendments (e.g. gypsum to reduce soil acidity) directly to that strip would enhance root expansion into the new fertile soil space, thus improving nutrient uptake and crop performance. In the long term, reiteration of such practices is expected to restore soil properties.

Cassava is often grown as a monocrop system in consecutive years. Evidence of exch-K buildup, whenever it occurs at the high K dose treatments (Fig. 2) requires further examination; soil sampling is necessary also during the cropping season. The consistent reduction in tuber yields after the first year (Fig. 5) should give rise to significant concerns. Crop species, including cassava, might have specific requirements, and essential nutrients might be depleted during consecutive monocropping, causing suppressed crop performance. Therefore, crop rotation, whenever possible, is recommended.

In conclusion, cassava response to elevated K dose was rather disappointing in three of the four experimental sites in East and Central Java. In most cases, tuber yields were far below the potential, and yield increases compared to the farmers' practices were too small or negligible. However, there were considerable indications that K application, if appropriately carried out, might result in substantial enhancement of cassava performance and yield. Cost and benefit ratio analyses of K application programs are premature, as further research is still required. A fundamental principle of plant K nutrition must be obeyed: maintenance of the soil's exch-K pool at a constant available level to match the current crop requirements. Thus, the annual K dose should be divided and distributed throughout the season taking into account precipitation regime, crop phenology (e.g., tuber growth), and soil properties. Special care should be paid to acid soils (Taufiq *et al.*, 2015) where K depletion rates are rapid.

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