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Roles and optimisation rate of potassium fertiliser for immature oil palm (*Elaeis guineensis* Jacq.) on an Ultisol soil in Indonesia

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Abstract

Potassium (K) is an essential macronutrient needed in large amounts by oil palm as it is directly involved in physiological processes. This research focused on the influence of K fertiliser on the vegetative growth of oil palm and determined the optimum rate of K fertiliser for immature plants (aged 1 to 3 years). The study was conducted at IPB-Cargill Oil Palm Teaching Farm, Jonggol, Bogor, Indonesia, from March 2013 to March 2016. The application rates were 0, 196, 392, 588, and 784 g K_2O plant^{-1} year^{-1} during the first year; 0, 384, 768, 1152, and 1536 g K_2O plant^{-1} year^{-1} during the second year; and 0, 450, 900, 1350, and 1800 g K_2O plant^{-1} year^{-1} during the third year of the immature oil palms. This experiment used a randomized complete block design with three replications. The optimum fertiliser rate was calculated by differentiating the regression equation of the quadratic response curve for variable growth. Potassium fertiliser significantly affected plant morphology, and increased plant height, stem girth, frond number, frond length, and leaf area of frond 17. Potassium application also significantly increased chlorophyll content, stomatal density, and K nutrient content of the leaves of immature oil palm. The optimum K fertilizer rate for 1-, 2-, and 3-year-old immature oil palm was 512, 966, and 1430 g K_2O plant^{-1} year^{-1}, respectively. Application of K fertiliser provided the amount of K needed to support oil palm growth.

Keywords: fertiliser, fronds number, growth, macronutrient, potassium, stem girth

1 Introduction

Potassium plays important roles in photosynthesis, regulation of osmotic balance, and phloem transport in plants (Tripler *et al.*, 2006; Harris & Nazari, 2011). It also activates enzymes, regulates transpiration, transports assimilates, controls transport through the cell membrane, aids in the formation of proteins and carbohydrates, and strengthens plant tissues (Marschner, 2012). Potassium also supports resistance to abiotic and biotic stresses, such as drought, pests, and diseases (Wang *et al.*, 2013).

Potassium deficiency is usually found in plants grown on peat soil, sandy soil, and acid soils with low cation exchange capacity. This deficiency is due to low exchangeable K in the soil and the lack of K fertiliser application. In contrast, excessive K can cause nutrient imbalances and deficiencies of Ca and Mg (Reddy *et al.*, 1997; Roggatz *et al.*, 1999). Potassium is a highly mobile element in plants, and it is translocated from older to younger tissue (Selvaraja *et al.*, 2013). The presence of adequate levels of nutrients in plants is important for normal growth and high production. Fertiliser application can help to meet the nutrient needs of plants. The rate, manner, and timing of application, as well as the type of fertiliser, should be based on the age of the plants and soil characteristics.

Oil palm (*Elaeis guineensis* Jacq.) is an agricultural commodity that has a high economic value. Indonesia is the largest palm oil producer in the world, and it accounts for 45 % of global crude palm oil production (Pusdatin Pertanian, 2014). From 2004 to 2014, the oil palm plantation area in Indonesia grew by 7.7 % annually on average, and palm oil production increased by an average of 11.1 % per year (Ditjenbun, 2015). However, the available land for

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the cultivation of oil palm generally has low fertility levels. These lands need to be restored through the application of appropriate technical cultivation (intensification of land use) to enable plant growth.

However, fertilisation of oil palm is expensive, and it accounts for about 30 % of the production costs and 60 % of the maintenance costs. Therefore, appropriate recommendations for fertiliser application are needed to keep the cost of fertiliser to a minimum, while providing the maximum benefit (Sugiyono *et al.*, 2005). Optimising the rate of fertilisation is intended to ensure that enough fertiliser is applied to meet crop needs, while limiting the amount of residues. The basic theory for determining the optimum rate relies on a quadratic function. This function can help determine the state of nutrients in deficient, replete, and toxic conditions (Corley & Tinker, 2003; Webb, 2009). The Indonesian Oil Palm Research Institute has formulated a general standard fertilisation rate for oil palm (Sutarta *et al.*, 2007). However, this standard rate is not appropriate for ensuring maximum productivity at each location or for every soil type. Today, Indonesia has more than 11.9 million ha of oil palm plantations grown on various soil types, including Ultisols, Andisols, Entisols, Vertisols, Inceptisols, Spodosols, and Oxisols. Ultisols are classified as marginal soils, especially in tropical regions, and these soils have a low pH (pH < 5.5), low cation exchange capacity, low base saturation, and deep profiles (high leaching losses). As Ultisols are mostly found in high rainfall areas with more than 200 mm month^{-1}, high leaching losses and erosion occur. Marginal soils need special techniques or best management practices to reach maximum productivity (Paramananthan, 2013). Therefore, appropriate fertilisation rates for specific locations need to be identified so that oil palm can grow and reach maximum production, thus improving the potential of existing land. Efforts to increase the productivity of oil palm should be done as early as possible, ideally when the plants are still immature so that potential production will be high when the plants reach maturity. Therefore, the effects of K fertiliser on a marginal soil, Ultisol, were studied to identify the optimum fertiliser rate for immature oil palms during their first 3 years of development.

2 Materials and methods

Research was conducted at IPB-Cargill Oil Palm Teaching Farm, Jonggol, Bogor, Indonesia, on an Ultisol at an altitude of ca. 113 m asl. Analysis of fertiliser, soil, leaf tissue, and frond tissue was carried out at the Laboratory of Chemistry and Soil Fertility, Department of Soil Science and Land Resources, Bogor Agricultural University. The study was conducted from March 2013 to March 2016 (year 1–3).

Plant materials used in this study were immature oil palms aged 1 month of the Tenera type, Dami Mas variety. These palms were planted at a density of 136 plants hectare^{-1} with a spacing of 9.2 m × 9.2 m × 9.2 m; the planting system was an equilateral triangle. Holes of 60 cm × 60 cm × 60 cm were dug before planting, and basic fertiliser was added to each hole at the following amounts: 60 kg of manure, 500 g of rock phosphate, and 500 g of dolomite. This experiment used a randomized complete block design with one factor: five levels of K fertiliser. Each treatment consisted of five plants, and was repeated thriceleading to a total of 75 plants.

Fertiliser was broadcast spread in a circle around the oil palm twice a year, once at the beginning and once at the end of the rainy season. Fertiliser application in the first year was performed at 4 and 9 months after planting (MAP), in the second year at 14 and 20 MAP, and in the third year at 25 and 32 MAP. Each application was one half of the yearly fertiliser rate. In addition to the K fertiliser treatments (Table 1), each oil palm received standard fertiliser with nitrogen (N) and phosphorus (P) at 250 g N and 255 g P_2O_5 plant^{-1} year^{-1} in the first year; 630 g N and 450 g P_2O_5 plant^{-1} year^{-1} in the second year, and 960 g N and 720 g P_2O_5 plant^{-1} year^{-1} in the third year of the experiment.

Table 1: *K fertiliser treatments on immature oil palm plants during the 3 years of the experiment (n = 15 per treatment).*

K rate	*Rate of fertilizers* (g K_2O plant^{-1} year^{-1})		
	First year	*Second year*	*Third year*
Level 0 (control)	0	0	0
Level 1	196	384	450
Level 2	392	768	900
Level 3	588	1152	1350
Level 4	784	1536	1800

Plant morphological responses were evaluated based on the variables plant height, stem girth, frond number, frond length, and leaf area. Plant height was measured from the base of the stem to the youngest unfolded leaf and stem girth was determined at approximately 20 cm above the ground. The number of fronds that were still fresh and the leaflets of fronds that had completely opened were counted. The youngest leaf that was completely open was designated as the first leaf following Legros *et al.* (2009).

Frond lengths were measured from the frond base that was attached to the stem to the tip of fronds 9 (first-year immature oil palm) and fronds 17 (second-year and third-year immature oil palm). Leaf area measurements were made at the leaf midrib of frond 9 (first-year immature oil palm) and frond 17 (second-year and third-year immature oil palm). Leaf area was calculated using the following formula: leaf area $= \left((\sum_{(i=1)}^{2} l_i \times w_i)/2\right) \times 2n \times k$, where l_i was the length of leaflets (m), w_i was the width of the leaflets (m), n was the number of leaflets left or right, and k was a constant (0.57 for immature oil palm) (Hardon *et al.*, 1969; Sutarta *et al.*, 2007).

Evaluations of physiological plant response were based on the variables chlorophyll content, stomatal density, and K nutrient content in the leaves. Analysis of chlorophyll content and nutrient content of K in the leaves was done on leaf samples of frond 9 in first-year immature oil palm and leaf samples of frond 17 in second-year and third-year immature oil palm (Chapman & Gray, 1949; Ochs & Olivin, 1977; von Uexkull & Fairhurst, 1991). Stomatal density was determined by applying cellulose acetate to the lower surface of the cut leaves and leaving it to dry; then these leaves were affixed with transparent insulation and placed on object glass. Stomata were observed using a microscope with a magnification of 10×40.

Study of K dynamics is essential because K is mobile in soil. The measurement of K dynamics in the soil was carried out at three soil-layer depths (0–20, 20–40, and 40–60 cm) within the radius of fertiliser application around each oil palm at 12 MAP (first year), 24 MAP (second year), and 36 MAP (third year). These measurements were done for the level 3 K rate only (Table 1), as this was assumed to be the optimum rate.

Nutrient balance calculation was done using the following method:

(1) *Potassium source*
K total in the soil before fertilisation (g) =
K content in the soil (%) × soil dry weight.
K in fertiliser (g) =
K content in the fertiliser (%) × the amount of fertiliser applied.

(2) *K Recovered*
K in the soil one year after fertiliser application (g) =
K content in the soil after fertilisation (%) × soil dry weight.
Plant uptake (g) = K content in the rachis and leaflets of frond 17 × dry weight of plant tissue.

The plant nutrient contents used in calculating the nutrient balance only in the rachis and leaflets referred to the formula of Aholoukpe *et al.* (2013):
Dry weight (DW) frond =
1.147 + 2.135 × DW rachis (kg)

(3) *Fertiliser efficiency* (%) =
$$\frac{\text{plant uptake}}{\text{the amount of K in the fertiliser}} \times 100\,\%$$

(4) *Unmeasured fertiliser* (%) =
$$\frac{\text{the amount of K in the fertiliser–plant uptake}}{\text{the amount of K in the fertiliser}} \times 100\,\%$$

Data were analysed by analysis of variance (ANOVA) at the level $P < 0.05$, using SAS Proprietary Software 9.4 (TS 1M3). If a significant effect was found, then analysis proceeded with a test of the orthogonal polynomial at level $P < 0.01$ and $P < 0.05$. In addition, regression analyses were done to determine the optimum rate of fertilisers (Mattjik & Sumertajaya, 2006).

3 Results

3.1 Soil characteristics and climatic conditions

Soil from the research site underwent initial analysis in March 2013 for the circle of fertiliser application and the area between two oil palm rows (dead pathway; Table 2).

The average annual rainfall during the experimental period (April 2013 to March 2016) was 2734 mm year^{-1} with an average of 227.8 mm month^{-1}. Rain occurred on 140 days year^{-1} on average, the average temperature ranged from 26 to 32 °C, and the average humidity was 73.8 %.

Based on the Schmidt-Ferguson climate criteria, the rainfall distribution in year 1 was evenly distributed throughout the year without dry months, and there was no water deficit. During the second experimental year, two dry months occurred (September and October 2014). Extended droughts occurred in the third year, with a dry period of six months from May to October 2015.

3.2 Morphological responses

Potassium fertiliser had a significant effect on plant height of oil palm at 12 MAP, but not at 24 MAP and 36 MAP (Table 3). In addition, the long dry period of six months in the third year resulted in a water deficit that affected plant morphology, especially plant height. Plant growth in the second year was approximately 193 cm but only 149 cm in the third year (mean overall treatments).

Application of K fertiliser yielded a quadratic response for stem girth of oil palm at 6 and 12 MAP, 24 MAP, and 30 and 36 MAP, but not at 18 MAP. Application of K fertiliser at level 2 increased the stem girth up to 23 % at 12 MAP, 7.9 % at 24 MAP, and 9.7 % at 36 MAP compared to the control.

Application of K fertiliser increased the frond number of oil palm at 12, 18, 24, 30 and 36 MAP. At level 2, it increased the number of fronds of oil palm up to 59.4 % at

Table 2: *Analysis of physical and chemical soil properties before the start of the experiment.*

Soil characteristics	*Value* †	*Criteria* *	*Value* ‡	*Criteria* *
Texture				
Sand (%)	17.34		18.63	
Dust (%)	28.67		22.75	
Clay (%)	53.99		58.63	
pH_{H_2O}	4.55	Acid	4.55	Acid
pH_{KCl}	3.85		3.85	
C-organic (%)	2.15	Moderate	2.19	Moderate
N-total	0.19	Low	0.20	Low
P-available (ppm)	10.15	Low	11.15	Low
P-total (ppm)	88.30	Very low	92.75	Very low
Cation exchange value				
Ca (meq/100 g)	4.14	Low	3.68	Low
Mg (meq/100 g)	1.86	Moderate	1.56	Moderate
K (meq/100 g)	0.38	Moderate	0.32	Moderate
Na (meq/100 g)	0.28	Low	0.24	Low
CEC (meq/100 g)	34.38	High	34.18	High
Alkali saturation (%)	19.39	Very low	16.81	Very low
Acidity				
Al (meq/100 g)	10.84		10.65	
H (meq/100 g)	2.34		3.03	

†: analysis sample on oil palm circle. ‡: analysis sample on oil palm dead pathway.
*: based on general criteria of soil chemical properties (Balittanah, 2005).

12 MAP, 30.0 % at 24 MAP, and 40.0 % at 36 MAP as compared to the control.

Potassium fertiliser application affected quadratically the leaf area in the second-year immature oil palm (18 and 24 MAP) and the third-year immature oil palm (30 and 36 MAP), but it had no effect in the first year. Potassium fertiliser application at level 3 increased the leaf area of oil palm up to 25.8 % at 24 MAP and 11.1 % at 36 MAP compared to the control.

3.3 *Physiological response*

Potassium fertiliser application linearly affected the chlorophyll content at 6 and 12 MAP, but it did not affect the chlorophyll content in the second-year and third-year immature oil palm (Table 4). Potassium fertiliser at the level 3 rate was associated with an increase in the chlorophyll content of 9.3 % compared to controls at 12 MAP. Potassium fertiliser application quadratically affected the stomatal density at 12 and 24 MAP, but linearly affected it at 36 MAP. Potassium fertiliser at the level 3 rate increased the stomatal density of leaves by 7.4 % compared to controls at 12 MAP, while the rate level 2 increased the density of leaf stomata by 15.2 % compared to controls at 24 MAP.

Potassium fertiliser application linearly affected the nutrient content of K in the leaves at 6, 12, and 18 MAP, but not at 24 and 36 MAP. This result suggests that the K nutrient at 6, 12, and 18 MAP was absorbed and was needed by the plants for growth, although it is possible that the K was not yet optimally absorbed. The K nutrient content in the leaf tissue was suspected to be below the critical nutrient levels.

3.4 *Potassium nutrient content in the soil*

Measurement of K nutrient content in the soil in the first year (Fig. 1a) was performed at 12 MAP, in the second year (Fig. 1b) at 24 MAP, and in the third year at 36 MAP (Fig. 1c). Figure 1 shows that K nutrient content in the soil for oil palm at 12, 24, and 36 MAP decreased with increasing soil depth. The movement of the K nutrient accumulated at a depth of 0–20 cm, while the content was the lowest at a depth of 40–60 cm. This finding suggests that some of the K from fertilisers did not reach deeper soil layers. Potassium

Table 3: *The effect of K fertiliser application on the morphological responses of immature oil palm aged 1 to 3 years.*

Rate level of K	*Plant height* (cm)						
	0 MAP	*6 MAP*	*12 MAP*	*18 MAP*	*24 MAP*	*30 MAP*	*36 MAP*
Level 0 (control)	158.7	240.3	292.0	431.4	496.4	533.6	623.4
Level 1	162.5	246.7	310.2	431.7	500.0	556.4	652.1
Level 2	165.8	248.1	308.8	431.5	497.5	561.5	667.5
Level 3	167.7	257.9	318.0	434.4	513.8	568.2	654.2
Level 4	166.3	248.1	313.0	431.6	500.2	557.6	656.9
Response pattern ¢	*ns*	*ns*	Q^{*}	*ns*	*ns*	*ns*	*ns*
	Stem girth (cm)						
Level 0 (control)	25.2	44.2	79.0	134.4	167.0	222.8	239.6
Level 1	28.9	47.7	86.4	137.2	170.0	233.7	256.3
Level 2	28.7	48.9	90.3	140.1	176.6	238.0	258.2
Level 3	29.7	51.8	97.2	140.2	180.1	240.2	262.8
Level 4	30.5	50.2	84.1	137.1	178.7	236.3	257.5
Response pattern ¢	*ns*	Q^{**}	Q^{**}	*ns*	Q^{*}	Q^{*}	Q^{*}
	Frond number						
Level 0 (control)	14	24	32	52	70	45	60
Level 1	16	26	42	70	88	65	82
Level 2	16	27	47	66	86	63	80
Level 3	17	29	51	71	91	66	84
Level 4	16	29	48	69	89	63	80
Response pattern ¢	*ns*	*ns*	Q^{**}	Q^{**}	Q^{*}	Q^{**}	Q^{**}
	Frond length (cm)						
Level 0 (control)	118.1	147.3	200.9	301.1	374.2	384.9	439.1
Level 1	121.3	152.1	207.3	280.4	374.4	411.9	468.0
Level 2	123.5	153.4	205.7	287.8	374.9	416.5	464.5
Level 3	123.4	154.9	215.8	306.5	377.2	420.2	470.8
Level 4	122.9	153.5	207.2	291.9	375.4	416.6	464.9
Response pattern ¢	*ns*	*ns*	*ns*	Q^{**}	*ns*	Q^{*}	Q^{*}
	Leaf area (m^2)						
Level 0 (control)	0.38	1.04	1.85	2.46	2.87	3.80	4.69
Level 1	0.39	1.17	1.93	2.38	3.49	4.12	5.42
Level 2	0.43	1.13	1.94	2.26	3.51	4.18	5.34
Level 3	0.45	1.17	2.11	2.72	3.61	4.27	5.21
Level 4	0.43	1.26	1.93	2.48	3.56	4.08	5.26
Response pattern ¢	*ns*	*ns*	*ns*	L^{*}	Q^{**}	Q^{**}	Q^{*}

¢: based on contrast test. **: significance of treatment effect at level $P < 0.01$. *: significance of treatment effect at level $P < 0.05$. *ns*: not significant. *L*: linear response. *Q*: quadratic response. MAP: month after planting.

Table 4: *The effect of K fertiliser on physiological response on immature oil palm aged 1 to 3 years.*

Rate level of K	*Chlorophyll content* (mg cm^{-2})					
	6 MAP	*12 MAP*	*18 MAP*	*24 MAP*	*30 MAP*	*36 MAP*
Level 0 (control)	0.041	0.043	0.043	0.044	0.034	0.043
Level 1	0.043	0.044	0.044	0.045	0.036	0.044
Level 2	0.043	0.044	0.043	0.047	0.037	0.043
Level 3	0.045	0.046	0.044	0.047	0.039	0.044
Level 4	0.046	0.047	0.044	0.046	0.036	0.043
Response pattern ¢	*L***	*L***	*ns*	*ns*	*ns*	*ns*
	Stomatal density (unit mm^{-1})					
Level 0 (control)	188.90	210.60	217.69	245.75		189.6
Level 1	207.80	216.70	227.04	259.35		215.0
Level 2	213.40	218.70	249.15	283.16		226.9
Level 3	216.90	226.20	250.00	279.76		205.0
Level 4	211.60	215.40	238.95	270.41		225.3
Response pattern ¢	*ns*	*Q**	*ns*	*Q**		*L**
	Leaf nutrient content of K (%)					
Level 0 (control)	0.82	0.85	0.96	0.65		0.49
Level 1	0.97	0.88	0.93	0.59		0.51
Level 2	1.10	1.08	1.07	0.63		0.60
Level 3	0.99	0.91	1.08	0.67		0.57
Level 4	1.06	1.01	1.05	0.65		0.52
Response pattern ¢	*L**	*L**	*L**	*ns*		*ns*

¢: based on polynomial orthogonal test. **: significance of treatment effect at level $P < 0.01$.
*: significance of treatment effect at level $P < 0.05$. *ns*: not significant.
L: linear response. *Q*: quadratic response. MAP: months after planting.

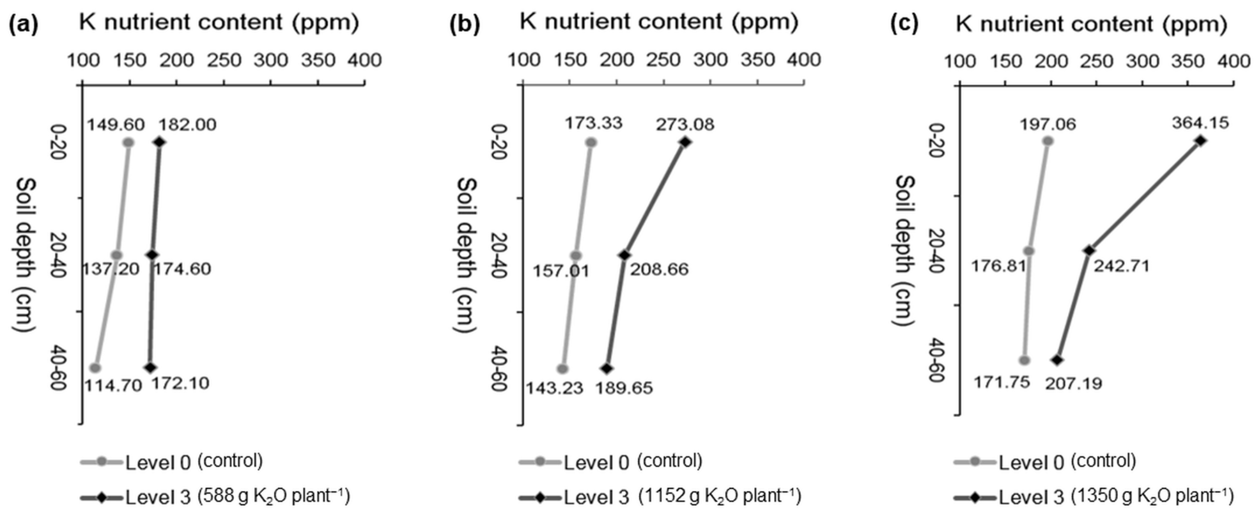

Fig. 1: *Potassium nutrient content of palm circle at various depths of the soil layers.for first-year* ***(a)****, second-year* ***(b)****, and third-year* ***(c)****.*

availability in the soil is influenced by weathering of minerals, K fixation by clay, leaching, erosion, and plant uptake. When the temperature increases, the movement of K also increases through diffusion (Korb *et al.*, 2002).

3.5 *Optimization rate of K fertiliser on immature oil palm aged 1, 2, and 3 years*

The effect of fertiliser optimisation was assessed for the variables stem girth and frond number. Siallagan *et al.* (2014) stated that the optimum rate could be obtained by lowering the quadratic curve regression equation on variables of morphology that were significantly affected, while Sudradjat *et al.* (2014a) stated that the optimum rate could be seen from the morphology variable that was the most responsive. The results of optimum rate in the first-year immature oil palm, the second-year immature oil palm, and the third-year immature oil palm were 512, 966, and 1431 g K_2O ha^{-1} year^{-1}, respectively (Table 5).

3.6 *Potassium nutrient balance*

Nutrient balance of K in this experiment was investigated to determine the optimum rate range. Fertiliser efficiency, which shows that nutrients derived from fertilisers can be absorbed by plants, was 26 to 27 % in this research (Table 6), while the fertiliser efficiency of previous research (Busyra, 2010) was 17 to 39 %. Unmeasured fertiliser in the current study reached 73 %. This fertiliser may have been in other plant tissues (fruits, seeds, roots) or partially lost because of leaching and adsorption to soil (clay type 1 : 2) (Havlin *et al.*, 2005).

Table 5: *Optimum rate of K fertiliser based on regression function on immature oil palm.*

Variable	*Age of plants* (MAP[†])	*Regression function*	R^2	*Optimum rate* (g K_2O plant^{-1} year^{-1})
Stem girth	6	$y = -0.00002x^2 + 0.020x + 44.13$	0.95	500
	12	$y = -0.00007x^2 + 0.065x + 77.80$	0.77	464
Fronds number	10	$y = -0.00001x^2 + 0.0118x + 22.116$	0.99	590
	12	$y = -0.00003x^2 + 0.0297x + 28.625$	0.96	495
			Average on the first-year immature oil palm	512 ± 54
Stem girth	20	$y = -0.00001x^2 + 0.0221x + 146.72$	0.91	1105
	24	$y = -0.000006x^2 + 0.0173x + 166.09$	0.94	1442
Fronds number	14	$y = -0.00002x^2 + 0.0347x + 41.891$	0.83	868
	16	$y = -0.00002x^2 + 0.0355x + 47.598$	0.81	888
	18	$y = -0.00002x^2 + 0.034x + 53.598$	0.81	850
	20	$y = -0.00002x^2 + 0.0331x + 58.264$	0.84	828
	22	$y = -0.00002x^2 + 0.0344x + 64.154$	0.84	860
	24	$y = -0.00002x^2 + 0.0354x + 72.176$	0.82	885
			Average on second-year immature oil palm	966 ± 211
Stem girth	26	$y = -0.000009x^2 + 0.0234x + 215.18$	0.94	1300
	28	$y = -0.00001x^2 + 0.0254x + 219.63$	0.97	1270
	30	$y = -0.00001x^2 + 0.0277x + 222.93$	0.99	1385
	36	$y = -0.00001x^2 + 0.0357x + 240.49$	0.95	1785
Fronds number	26	$y = -0.00001x^2 + 0.0323x + 41.054$	0.83	1615
	28	$y = -0.00001x^2 + 0.0338x + 44.932$	0.85	1690
	30	$y = -0.00001x^2 + 0.0339x + 47.224$	0.85	1695
	32	$y = -0.00001x^2 + 0.0342x + 50.761$	0.84	1710
	34	$y = -0.00002x^2 + 0.037x + 56.805$	0.85	925
	36	$y = -0.00002x^2 + 0.0375x + 62.542$	0.85	938
			Average on third-year immature oil palm	1431 ± 319

[†]MAP: months after planting.

Table 6: *Nutrient balance of potassium in immature oil palm aged 1 to 3 years.*

Analysis	per plant		
	First-year	*Second-year*	*Third-year*
Potassium source			
Soil prior to fertiliser (g)	147.7	672.1	1194.8
Fertiliser (g)	488.0	955.9	1120.2
Recovered nutrient			
Soil after fertiliser (g)	224.5	545.7	1991.2
Plant uptake (g)	132.4	259.9	285.5
Fertiliser efficiency (%)	27.0	27.2	26.2
Unmeasured fertiliser (%)	73.0	72.8	73.8

4 Discussion

For 3-year-old oil palm, K has a significant effect on the morphological variables stem girth, frond number, frond length, and leaf area, but it has no effect on plant height (Table 3). The stem girth is closely correlated with production (Corley & Tinker, 2003, 2016) likely because it is very closely related to the stem function of oil palm. The stem contains carrier systems for water, plant nutrients, and the results of photosynthesis, and it is also the largest site of food storage in plants (Corley & Tinker, 2003). Muhdi *et al.* (2015) explained that the oil palm stem has the highest proportion of biomass compared with other organs, such as the midrib and leaves. The oil palm stem is also suspected to be an active sink, which would explain the increase in stem girth in response to K fertiliser (Goh & Hardter, 2003). One of the roles of K is to support transfer of the results of photosynthesis to the tissues that need these, and sufficient K content in plant tissues assists in this transfer process within stems.

Morphological variables such as girth stem, frond number, frond length, and leaf area were strongly affected by water shortage (Table 3). Water deficit occurred during the period 26–31 MAP, with an average rainfall of only 19 mm month^{-1} (against 325 mm per month during the rest of the experimental period). Sudradjat *et al.* (2014b) explained that a long dry period can affect the amount of oil palm fronds as the uptake of nutrients is blocked. In the current study, young fronds did not unfold (leaf spear) during the water deficit period (30 MAP), but the number of fronds significantly increased at 36 MAP when rainfall was adequate. Young midribs (leaf spears) were inhibited and growth was restrained during drought stress, but the midribs began to reopen when rainfall returned to normal.

The rate of growth of oil palm is related to water availability, especially rainfall during periods of growth. Taiz & Zeiger (1998) explained that drought reduces growth and photosynthesis. The process of growth of oil palm needs nutrients that are absorbed by the soil, such as K which plays a role in cell osmotic regulation and regulation of enzymes. Water deficit conditions decrease the effectiveness of mineral nutrient uptake and translocation of photosynthate into plant tissue and cause plants to exhibit stunted growth (Darmosarkoro *et al.*, 2001).

Application of K fertiliser had no effect on the frond length at 12 and 24 MAP, but had a significant effect on the frond length at 36 MAP. Greater frond length could increase the leaf area index, which could in turn potentially increase yield components such as fruit weight (Prayitno *et al.*, 2008). Table 3 shows that K has a linear effect at 18 MAP and a quadratic effect at 24, 30, and 36 MAP on the leaf area of oil palm. Leaf area increases with increasing age of oil palm, and the ability of photosynthesis is related to leaf area (Cha-um *et al.*, 2013). Arsyad *et al.* (2012) explained that improving nutrient uptake requires a sufficient quantity of groundwater as well as optimum leaf surface area. The more photosynthate produced, the higher the effectiveness of photosynthesis.

Potassium is directly involved in several physiological processes (Table 4), and it plays important roles in the biochemical and physiological processes that are vital to plant growth (Cakmak & Kirkby, 2008). The chlorophyll content in first-year immature oil palm seemed to increase along with the amount of K fertiliser applied. High chlorophyll content indicates that photosynthesis is efficient and the plants have energy for growth (Suharno *et al.*, 2007). In this study, K only affected leaf chlorophyll content in first-year immature oil palm. Leaf chlorophyll content in second-year and third-year immature oil palm was assumed to have reached the maximum.

This study showed that stomatal density had an inconsistent response to application of K fertiliser from first-year to third-year immature oil palm. Table 4 shows that K affected the stomatal density at 12 to 36 MAP, with the exception of 18 MAP. The inconsistent stomatal density response might be closely related to K mobility in plant tissue. Potassium is involved in maintaining the osmotic potential of plants, including setting the opening and closing of stomata, which allow the CO_2 needed for photosynthesis to enter plants (Corley & Tinker, 2003). Stomata have several characteristics that control the rate of photosynthesis, such as density, size, and conductance. Stomatal density can increase the activity of the gas exchange through the stomata, which can increase photosynthesis, transpiration, and respiration in the leaves (Khazaei *et al.*, 2010).

Potassium content in leaf tissue at 24 and 36 MAP was lower compared to previous time points. This decrease was presumably because of the phase change from vegetative to generative plants at 24 and 36 MAP, which resulted in nutrients being transferred to the seeds and fruit that were forming (Schwab *et al.*, 2007). The critical nutrient potassium level of leaf frond 9 is 1.25 % (Ochs & Olivin, 1977) and that of the leaf midrib frond 17 is 1 % in young oil palm less than 6 years after transplanting (Ochs & Olivin, 1977; von Uexkull & Fairhurst, 1991; IFIA, 1992). Table 4 indicates that the leaf K content (average over five treatments) at 12, 24, and 36 MAP was 0.95, 0.64, and 0.54 %, respectively. Therefore, the value of leaf K content was 24 % (the first-year), 36 % (the second-year), and 46 % (the third-year) lower as compared to this critical level.

5 Conclusion

Potassium consistently increases morphological variables such as girth stem, frond number, frond length, and leaf area at the age of one to three years of oil palm. Based on the response of morphological variables on potassium fertilisation we obtained the quadratic equation to determine the optimum rate according to the age of the plant. This study has determined the optimum rate for one, two and three years old of oil palm planted on Ultisol soils, i.e. 512, 966 and 1430 g K_2O plant^{-1} year^{-1}. Potassium is needed in large quantity by oil palm for vegetative growth during immature period (0 to 36 months). The optimum rate of K fertiliser obtained from this research can be recommended to accelerate the productive period and to increase the overall productivity of oil palms cultivated in Indonesia.

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