Determination of optimum rate of phosphorus and potassium fertilizers for a four-year-old oil palm (*Elaeis guineensis* Jacq.)

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**Abstract.** Appropriate fertilizing rate of phosphorus (P) and potassium (K) plays an important role to increase growth and yield of oil palm as well as to minimize environmental pollution because of the residues of inorganic fertilizer. This study aimed to explain the effect of P and K fertilizers and determine the optimum rate for a four-year-old oil palm. Experimental design used in each of these experiments were one factor of randomized complete block design factor and consisted of five levels with three replications. The treatment levels used in experiment 1 were 0, 443.75, 887.5, 1331.25, and 1775 g P₂O₅ per palm per year. The treatment levels used in experiment 2 were 0, 1020.6, 2041.2, 3061.8, and 4082.4 g K₂O per palm per year. Application of P fertilizer significantly affected to palm height, trunk girth, stomatal density, leaf P content, bunch number and yield of FFB. The optimum rate of P fertilizer was 924 ± 88 g P₂O₅ per palm per year. Application of K fertilizer significantly affected to trunk girth, leaf area of frond 17, stomatal density, leaf K content, bunch number and yield of FFB. The optimum rate of K fertilizer was 2760 ± 107 g K₂O per palm per year.

**Keywords:** bunch number, growth, stomatal density, trunk girth, yield

**1. Introduction**

The productivity of palm oil in smallholder plantations is the lowest among 3.212 t CPO ha⁻¹ [1]. One of the factors causing the low productivity of oil palm in smallholder plantation is the cultivation management of less precise in the case of fertilization. Fertilization is one way and effort to increase the productivity of oil palm in Indonesia [2]. However, the recommended fertilizer rate of oil palm used by smallholder farmers is still general and not site specific even though land conditions in Indonesia so vary that nutrient availability for oil palm in each region will be different. Oil palm plantations in Indonesia around 60% are uplands with low pH and its soil type will affect to yield of fresh fruit bunches (FFB) [3]. Appropriate rate of fertilizer recommendation needs to be established in each region based on the land characteristics and the soil's ability to supply nutrients to the palm so that the productivity of oil palm in the smallholder plantations can increase.

Fertilization is an important aspect to increase the growth and yield of oil palm. However, inaccurate and excessive of inorganic fertilizer will cause a negative impact on environmental...
sustainability and cause an increase in production costs [4]. For examples, leaching of phosphorus (P) and potassium (K) in the soil will cause environmental pollution. Because of the excess of P application, leaching of P through run-off which was accumulated to water bodies lead to nutrient enrichment (eutrophication) and undesirable changes in their ecology as well as the balance of species of plants. Water pollution will be further exacerbated by the condition of sloping land and high intensity rainfall [5]. The retention and accumulation of K in soil depend on soil composition, physical and environmental factors influencing the adsorption and release of K as well as leaching through the soil profile [6]. Fertilization should be done with the appropriate rate based on palm age and land characteristics. The optimum nutrient requirements for maximum growth and yield of oil palm may differ depending on palm age, soil type and climate condition. Fertilization with the appropriate rate can improve the land fertility and increase the availability of nutrients for oil palm, so the oil palm can grow optimally with high productivity. Determination of the optimum fertilizer rates is needed to know an efficiency of optimal nutrient uptake for oil palm and minimize negative impacts for environment because of over-fertilization and the residues of inorganic fertilizer.

Determination of recommended fertilizer rate for oil palm can be done with soil analysis and leaf tissue analysis to identify the deficiency or excess of fertilizer provided and to know the nutrient balance [4], [7]. Soil P analysis is the best interpretation by comparing it with the response curve showing the relationship between the amount of P available in the soil and the plant response to P fertilization [8]. The need of P and K fertilizers for oil palm can be determined based on the palm response test to fertilization, principle of soil fertility and palm nutrients. The optimum rate of P and K fertilizers for oil palm is determined by soil nutrient status, nutrient requirements and fertilizer efficiency. Soil nutrient analysis, plant tissue analysis and nutrient balance can be used as a basis for determining recommended rate of oil palm fertilization [9]. Therefore, this research was conducted to explain the effect of P and K fertilizers for growth and yield of a four-year-old oil palm and determined optimum rate of P and K fertilizers.

2. Materials and methods

This research was conducted from March 2016 to March 2017 at IPB-Cargill Teaching Farm located in Jonggol, Bogor, West Java, Indonesia. The materials used were Tenera oil palm aged four years, Dami Mas variety. Palm was planted with an equilateral triangle planting system (9.2 m x 9.2 m x 9.2 m). This research consisted of two separate experiments that were determination of optimum rate of P fertilizer (experiment 1) and determination of optimum rate of K fertilizer (experiment 2). Experimental design used in each experiment was one factor of randomized complete block design with three replications. In experiment 1, this experiment used five levels of P rate that were 0, 443.75, 887.5, 1331.25, and 1775 g P\(_2\)O\(_5\) palm\(^{-1}\) year\(^{-1}\). The basic standard of fertilizer rate used in, except the fertilizer treatment, was 2 kg urea and 3 kg KCl palm\(^{-1}\) year\(^{-1}\). In experiment 2, this experiment used five levels of K rate that were 0, 1020.6, 2041.2, 3061.8, and 4082.4 g K\(_2\)O palm\(^{-1}\) year\(^{-1}\). The basic standard of fertilizer rate used in, except the fertilizer treatment, was 2 kg urea and 1.5 kg SP-36 palm\(^{-1}\) year\(^{-1}\). Each experiment consisted of 15 experimental units. Each experimental unit consisted of 5 palms so that the number of palm used was 75 palms. The application of fertilizer was done twice in April 2016 (37 months after planting (MAP)) and November 2016 (44 MAP) with application rate of 40\% (1st application) and 60\% (2nd application) of all fertilizer rate per year. Fertilization method was done manually which fertilizers were spread evenly circular on the disk of palm.

Soil analysis was conducted in March 2016 before the first fertilizer application and was taken with a depth of 30 cm using auger drill. Observations of growth variables were performed on variables such as palm height, trunk girth and leaf area of frond 17. Observations of the physiological variables were done on leaf chlorophyll content, stomatal density and leaf nutrient content by taking samples of leaflets on frond 17. Observations of the production variables were performed on variables such as bunch number, average bunch weight, and yield of FFB. Data were statistically analyzed at significant level of P <0.01 and P <0.05 using analysis of variance and was continued by contrast polynomial orthogonal test and regression analysis.
3. Results and discussion

3.1. Climate and soil condition

The research was located at an altitude of about 113 m above sea level with a slope of land ranging from 9% to 11%. Climatic conditions of the study sites from April 2016 to March 2017 showed that temperatures ranged from 26-31 °C, humidity 78-80% and rainfall 3211 mm per year with an average rainfall 268 mm per month. Rainfall was evenly distributed throughout the year with rainy days over 123 days and based on Schmidt-Ferguson climatic classification there was no dry month at the study site. The criteria of soil physical and chemical properties [10] showed that the soil texture was considered clay which consisted of sand (19.70%), dust (25.10%) and clay (55.21%), pH (H₂O) was classified as very acid (4.42) and C-organic was considered moderate level (2.36%). The substance of total N was considered moderate level (0.28%), while the availability of P substance was considered low level (6.83 ppm). Exchangeable cations such as Ca (5.76 cmol+/kg), K (0.25 cmol+/kg) and Na (0.10 cmol+/kg) were considered low level, while the substance of exchangeable Mg was considered moderate level (1.79 cmol+/kg). Cation exchange capacity (CEC) was considered high level (25.53 cmol+/kg), while base saturation was considered low level (30.95%). Exchangeable Al and H were 7.91 cmol+/kg and 0.80 cmol+/kg, respectively.

3.2. Determination of optimum rate of P fertilizer for a four-year-old oil palm (experiment 1)

3.2.1. Growth response. Application of P fertilizer had significant effect on palm height and trunk girth, but didn’t have significantly effect on the leaf area of frond (Table 1). Palm height increased quadratically with application of P fertilizer up to 1775 g P₂O₅ palm⁻¹ year⁻¹ at 42, 45 and 48 MAP. The highest increase of palm height was found in the treatment of P fertilizer with application rate of 887.5 g P₂O₅ palm⁻¹ year⁻¹. Response pattern of palm height was seen decreased with treatment of P fertilizer rate at 1331.25 g P₂O₅ palm⁻¹ year⁻¹ and decreased significantly at treatment of P fertilizer with application rate of 1775 g P₂O₅ palm⁻¹ year⁻¹. This indicated that P in the soil was absorbed by palm within a certain range until P was sufficient to increase the growth of palm height. Treatment of P fertilizer with rate 887.5 g P₂O₅ palm⁻¹ year⁻¹ could increase the palm height by 15.82% compared to control at 48 MAP.

The trunk girth increased quadratically at 39, 42, 45 and 48 MAP with the treatment of P fertilizer rate up to 1775 g P₂O₅ palm⁻¹ year⁻¹. The response pattern of trunk girth continued to increase in line with the increasing rate of P fertilizer up to 1331.25 g P₂O₅ palm⁻¹ year⁻¹ and decreased in response pattern of the trunk girth on the treatment of P fertilizer rate 1775 g P₂O₅ palm⁻¹ year⁻¹. This indicated that the nutrient requirement of P for growth of trunk girth was very high. The addition of P nutrient in soil with a rate range 1331.25 g P₂O₅ palm⁻¹ year⁻¹ was still capable of being absorbed by palm for growth of trunk girth. The trunk on young palm is areas of accumulation for palm growth, especially trunk girth [11] because the trunk is the plant organ which was classified as an active sink [12],[13]. Treatment of P fertilizer with rate 1331.25 g P₂O₅ palm⁻¹ year⁻¹ could increase the trunk girth by 6.92% compared to control at 48 MAP.

3.2.2. Physiological response. Application of P fertilizer significantly affected to stomatal density and P content in leaf tissue, but didn’t significantly affect to leaf chlorophyll content. Stomata density quadratically increased with application of P fertilizer rate up to 1775 g P₂O₅ palm⁻¹ year⁻¹ at 42 and 48 MAP (Table 2). Stomatal plays an important role in the process of CO₂ gas exchange into the leaf mesophyll required to sustain photosynthesis process and plant nutrient uptake through mass flow in the transpiration process [14], [15]. Optimum stomatal density would increase the rate of photosynthesis so that the formation of assimilate could go well.
Table 1. Growth response of oil palm on application of P fertilizer

| Phosphorus rate (g P₂O₅ palm⁻¹ year⁻¹) | Growth response at months | 39 MAP | 42 MAP | 45 MAP | 48 MAP |
|----------------------------------------|---------------------------|--------|--------|--------|--------|
| 0 (control)                            | Palm height (m)           | 7.02   | 7.23   | 7.41   | 7.52   |
| 443.75                                 |                           | 7.07   | 7.48   | 7.87   | 8.17   |
| 887.5                                  |                           | 7.39   | 7.90   | 8.35   | 8.71   |
| 1331.25                                |                           | 7.36   | 7.74   | 8.07   | 8.37   |
| 1775                                   |                           | 7.02   | 7.36   | 7.65   | 7.93   |
| F-value ^                               |                           | 2.57m  | 5.34*  | 6.93*  | 5.38*  |
| Response pattern ^                     |                           | -      | Q**    | Q**    | Q**    |
| 0 (control)                            | Trunk girth (cm)          | 260.6  | 266.6  | 272.7  | 275.9  |
| 443.75                                 |                           | 271.3  | 276.7  | 283.2  | 286.0  |
| 887.5                                  |                           | 278.0  | 284.1  | 289.2  | 293.1  |
| 1331.25                                |                           | 278.4  | 285.0  | 291.0  | 295.0  |
| 1775                                   |                           | 271.1  | 277.6  | 281.3  | 284.2  |
| F-value ^                               |                           | 5.76*  | 4.69*  | 4.50*  | 4.36*  |
| Response pattern ^                     |                           | Q**    | Q*     | Q**    | Q**    |
| 0 (control)                            | Leaf area of frond 17 (m²) | 4.84   | 5.21   | 5.39   | 5.55   |
| 443.75                                 |                           | 5.13   | 5.71   | 5.88   | 5.95   |
| 887.5                                  |                           | 4.93   | 5.67   | 5.73   | 5.84   |
| 1331.25                                |                           | 5.05   | 5.69   | 5.81   | 5.88   |
| 1775                                   |                           | 4.98   | 5.41   | 5.53   | 5.58   |
| F-value ^                               |                           | 0.59m  | 1.28m  | 0.90m  | 0.85m  |

Notes: ^: ANOVA test, ^: contrast polynomial orthogonal test; **: significant effect at P < 0.01, *: significant effect at P < 0.05, ns: not significant, MAP: months after planting, Q: quadratic response pattern.

Table 2. Chlorophyll content, stomatal density, and leaf P content of oil palm on application of P fertilizer

| Phosphorus rate (g P₂O₅ palm⁻¹ year⁻¹) | Chlorophyll content (mg cm⁻²) | Stomatal density (stomatal mm⁻²) | Leaf P content (%) |
|----------------------------------------|------------------------------|---------------------------------|-------------------|
|                                        | 42 MAP | 48 MAP | 42 MAP | 48 MAP | 48 MAP | 48 MAP |
| 0 (control)                            | 0.045  | 0.046  | 189.6  | 182.6  | 0.21   |       |
| 443.75                                 | 0.046  | 0.047  | 232.0  | 194.3  | 0.23   |       |
| 887.5                                  | 0.046  | 0.048  | 251.0  | 217.7  | 0.24   |       |
| 1331.25                                | 0.047  | 0.049  | 231.5  | 188.5  | 0.23   |       |
| 1775                                   | 0.047  | 0.048  | 217.0  | 172.9  | 0.25   |       |
| F-value ^                               | 1.43m  | 3.00m  | 6.77*  | 16.64** | 4.59*  |       |
| Response pattern ^                     | -      | -      | Q**    | Q**    | L**    |       |

Notes: ^: ANOVA test, ^: contrast polynomial orthogonal test; **: significant effect at P < 0.01, *: significant effect at P < 0.05, ns: not significant, MAP: months after planting, L: linear response pattern, Q: quadratic response pattern.
The results of leaf tissue analysis could be used as an indicator of nutrient adequacy status in plants, but the leaf analysis results should be integrated and supported with other observational data such as nutrient deficiency symptoms on leaves, vegetative growth, yield and land vegetation [16]. The results of leaf analysis in this experiment showed that the P content in the leaf increased linearly on application of P fertilizer rate up to 1775 g P₂O₅ palm⁻¹ year⁻¹ at 48 MAP. This suggested that the palm was still capable of absorbing P in the soil by the highest rate P treatment in this experiment. The optimum leaf P concentration on young palm (<6 years old) was ranging from 0.16-0.19% [17] and critical value was 0.15% [18]. The response pattern of growth and yield of oil palm showed that significant decrease with P content of 0.25% in the highest rate treatment in this experiment.

### 3.2.3. Yield response

Statistical analysis showed that some of yield responses were affected to P fertilization. Application of P fertilizer significantly affected to the bunch number and yield of FFB, but didn’t significantly affect to average bunch weight (Table 3).

| Phosphorus rate (g P₂O₅ palm⁻¹ year⁻¹) | Bunch number (bunch palm⁻¹ year⁻¹) | Average bunch weight (kg bunch⁻¹) | Productivity (t FFB ha⁻¹ year⁻¹) |
|---------------------------------------|------------------------------------|----------------------------------|----------------------------------|
| 0 (control)                           | 9.2                                | 10.6                             | 13.0                             |
| 443.75                                | 17.6                               | 8.6                              | 20.2                             |
| 887.5                                 | 15.0                               | 10.3                             | 20.0                             |
| 1331.25                               | 13.7                               | 10.7                             | 19.1                             |
| 1775                                  | 12.3                               | 11.0                             | 17.4                             |
| F-value                               | 5.03*                              | 1.06**                           | 4.76*                            |
| Response pattern                      | Q**                                |                                  |                                  |

^: ANOVA test, ‡: contrast polynomial orthogonal test; **: significant effect at \( P < 0.01 \), *: significant effect at \( P < 0.05 \), ns: not significant, Q: quadratic response pattern.

Phosphorus fertilization would add the availability of nutrients in the soil and then the optimum rate of P would increase to the bunch number and yield of FFB. Application of P fertilizer at rate of 443.75 g P₂O₅ palm⁻¹ year⁻¹ could increase the harvested yield i.e. bunch number and yield of FFB by 91.30% and 55.38%, respectively, compared to control. Optimum availability of P nutrient could increase palm growth and yield. The palm wouldn’t reach its yield potential if the supply of P nutrient wasn’t sufficient [19].

### 3.2.4. Determination of optimum rate of P fertilizer

The quadratic response pattern generated from the observed variables could be used to determine the optimum rate of P fertilizer by decreasing the regression equation (Table 4). The optimum rate of P fertilizer in this experiment was determined based on variables of palm height, trunk girth, bunch number and yield of FFB that had a significant effect and quadratic response pattern up to 48 MAP. The result of optimum rate of P fertilizer in this experiment was 924 ± 88 g P₂O₅ palm⁻¹ year⁻¹.

### 3.3. Determination of optimum rate of K fertilizer for a four-year-old oil palm (experiment 2)

#### 3.3.1. Growth response

Application of K fertilizer significantly affected to trunk girth and leaf area of frond 17, but it didn’t significantly affect to palm height (Table 5). Trunk girth increased quadratically at 39, 42, 45 and 48 MAP by treatment of K fertilizer rate up to 4082.4 g K₂O palm⁻¹ year⁻¹. The trunk girth increased by 8.52% on the treatment of K rate 3061.8 g K₂O palm⁻¹ year⁻¹ compared to control at 48 MAP. However, the response pattern of trunk girth showed a significant decrease in the treatment of K fertilizer rate 4082.4 g K₂O palm⁻¹ year⁻¹. This showed that the treatment of K fertilizer rate...
4082.4 g K₂O palm⁻¹ year⁻¹ exceeded the nutrient adequacy limit for the growth of oil palm, especially trunk girth.

**Table 4. Regression equation and optimum rate of P fertilizer on a four-year-old oil palm**

| Variables            | Age (MAP) | Regression equation | R²  | Optimum rate |
|----------------------|-----------|---------------------|-----|--------------|
| Palm height          | 42        | y = -0.00000007x² + 0.0013x + 7.1777 | 0.90 | 929          |
|                      | 45        | y = -0.00000009x² + 0.0018x + 7.376 | 0.94 | 1000         |
|                      | 48        | y = -0.000001x² + 0.0022x + 7.4988  | 0.96 | 1100         |
|                      | 39        | y = -0.00002x² + 0.0335x + 260.21   | 0.99 | 838          |
| Trunk girth          | 42        | y = -0.00002x² + 0.0335x + 266.01   | 0.98 | 838          |
|                      | 45        | y = -0.00002x² + 0.0344x + 272.11   | 0.97 | 860          |
|                      | 48        | y = -0.00002x² + 0.0361x + 275.01   | 0.96 | 903          |
| Bunch number         | 48        | y = -0.000007x² + 0.0122x + 10.506  | 0.62 | 871          |
| Productivity         | 48        | y = -0.000007x² + 0.0137x + 13.741  | 0.86 | 979          |

Average of optimum rate (g P₂O₅ palm⁻¹ year⁻¹) 924 ± 88

Note: MAP: months after planting

**Table 5. Growth response of oil palm on application of K fertilizer**

| Potassium rate (g K₂O palm⁻¹ year⁻¹) | 39 MAP | 42 MAP | 45 MAP | 48 MAP |
|--------------------------------------|--------|--------|--------|--------|
| 0 (control)                          | 7.02   | 7.23   | 7.41   | 7.52   |
| 1020.6                                | 7.49   | 7.51   | 7.73   | 8.05   |
| 2041.2                                | 7.10   | 7.37   | 7.66   | 8.31   |
| 3061.8                                | 7.31   | 7.57   | 7.83   | 8.28   |
| 4082.4                                | 7.09   | 7.29   | 7.51   | 7.72   |
| F-value ^                             | 0.51*  | 0.34*  | 0.47m  | 2.72m  |

|--------------------------------------|--------|--------|--------|--------|
| 0 (control)                          | 260.6  | 266.6  | 272.7  | 275.9  |
| 1020.6                                | 272.2  | 277.4  | 284.5  | 290.2  |
| 2041.2                                | 278.5  | 284.8  | 290.8  | 294.3  |
| 3061.8                                | 280.6  | 286.6  | 294.4  | 299.4  |
| 4082.4                                | 270.2  | 276.9  | 282.4  | 288.0  |
| F-value ^                             | 4.67*  | 5.74*  | 7.50** | 5.67*  |

Response pattern ^

|--------------------------------------|--------|--------|--------|--------|
| 0 (control)                          | 4.84   | 5.21   | 5.39   | 5.55   |
| 1020.6                                | 5.16   | 5.45   | 5.71   | 5.86   |
| 2041.2                                | 5.31   | 5.61   | 5.83   | 6.02   |
| 3061.8                                | 5.33   | 5.68   | 5.79   | 5.91   |
| 4082.4                                | 5.31   | 5.58   | 5.73   | 5.83   |
| F-value ^                             | 3.31m  | 2.53m  | 3.20m  | 5.45*  |

Response pattern ^

Notes: ^: ANOVA test, ^: contrast polynomial orthogonal test; **: significant effect at P < 0.01, *: significant effect at P < 0.05, ns: not significant, Q: quadratic response pattern.
Leaf area in this experiment increased quadratically at 48 MAP on the treatment of K fertilizer rate up to 4082.4 g K$_2$O palm$^{-1}$ year$^{-1}$. Potassium application increased leaf area of oil palms [20]. Leaf area related to the amount of sunlight that could be captured by the leaves in the process of photosynthesis. The optimum leaf area would increase the assimilate formed so that it would affect the yield of oil palm [21].

3.3.2. Physiological response. Application of K fertilizer significantly affected stomatal density and leaf K content, but didn’t significantly affected leaf chlorophyll content. Response pattern of stomatal density increased linearly at 42 MAP on the application of K fertilizer rate up to 4082.4 g K$_2$O palm$^{-1}$ year$^{-1}$ (Table 6). Potassium was still absorbed by plant until the highest level of the treatment at 42 MAP. However, the response pattern of stomatal density at 48 MAP showed a quadratic response pattern to the application of fertilizer K rate at level of treatment 4082.4 g K$_2$O palm$^{-1}$ year$^{-1}$.

| Table 6. Chlorophyll content, stomatal density, and leaf K content of oil palm on application of K fertilizer |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Potassium rate (g K$_2$O palm$^{-1}$ year$^{-1}$) | Chlorophyll content (mg cm$^{-2}$) | Stomatal density (stomatal mm$^{-2}$) | Leaf K content (%) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0 (control) | 0.045 | 0.046 | 189.6 | 182.6 | 0.77 |
| 1020.6 | 0.045 | 0.047 | 215.0 | 220.1 | 0.98 |
| 2041.2 | 0.046 | 0.047 | 226.9 | 213.2 | 1.03 |
| 3061.8 | 0.045 | 0.047 | 205.0 | 197.9 | 1.07 |
| 4082.4 | 0.045 | 0.046 | 225.3 | 176.9 | 1.06 |
| F-value $^\wedge$ | 0.77ns | 1.69ns | 6.55* | 38.62** | 7.76** |
| Response pattern $^\dagger$ | - | - | L* | Q** | Q* |

Notes: $^\wedge$: ANOVA test, $^\dagger$: contrast polynomial orthogonal test; **: significant effect at $P < 0.01$, *: significant effect at $P < 0.05$, ns: not significant, Q: quadratic response pattern, L: linear response pattern.

Result of leaf tissue analysis in this experiment showed that leaf K content at 48 MAP quadratically increased to treatment of K fertilizer rate up to 4082.4 g K$_2$O palm$^{-1}$ year$^{-1}$. Leaf K content in this experiment was considered low level and had not reached optimum. The nutrient K status was considered to be optimum for the palm if the K concentration in the leaf was 1.1-1.30% [17] while a critical nutrient level was 1% [22]. Many factors affected the nutrient content in leaf tissues such as water availability, amount of fertilizer, palm age, vegetative growth and climatic factors including rainfall [23]. The K nutrient concentration in leaf tissue would be higher in sufficient water conditions than in water deficit conditions [24].

3.3.3. Yield Response. Application of K fertilizer had significant effect to yield component such as bunch number and productivity, but didn’t significantly affect average bunch weight (Table 7). Bunch number and yield of FFB increased quadratically by treatment of K fertilizer rate up to 4082.4 g K$_2$O palm$^{-1}$ year$^{-1}$. The treatment of K fertilizer rate at level 2041.2 g K$_2$O palm$^{-1}$ year$^{-1}$ showed the highest response to the bunch number and yield of FFB. Bunch number was increased by 68.48%, while productivity was increased by 59.23% compared to control.

3.3.4. Determination of optimum rate of K fertilizer. The optimum rate of K fertilizer in this study was determined based on trunk girth, leaf area of frond 17, bunch number and yield of FFB that showed the quadratic response pattern up to 48 MAP (Table 8). The optimum rate of K fertilizer in this experiment was $2760 \pm 107$ g K$_2$O palm$^{-1}$ year$^{-1}$. Nutrient requirement could be seen based on optimum nutrient status in leaf tissue and yield response by considering interaction among various nutrients on plant tissue [16].
Table 7. Yield response of oil palm on application of K fertilizer

| Potassium rate (g K₂O palm⁻¹ year⁻¹) | Bunch number (bunch palm⁻¹ year⁻¹) | Average bunch weight (kg bunch⁻¹) | Productivity (t FFB ha⁻¹ year⁻¹) |
|--------------------------------------|------------------------------------|-----------------------------------|----------------------------------|
| 0 (control)                          | 9.2                                | 10.6                              | 13.0                             |
| 1020.6                               | 14.3                               | 9.8                               | 18.6                             |
| 2041.2                               | 15.5                               | 10.0                              | 20.7                             |
| 3061.8                               | 14.4                               | 9.6                               | 18.2                             |
| 4082.4                               | 13.9                               | 9.9                               | 17.9                             |

F-value * 4.28 0.27 4.34 *

Response pattern * Q* 0.27ns 4.34 *

Notes: *: ANOVA test, *: contrast polynomial orthogonal test; *: significant effect at P < 0.05, ns: not significant, BN: bunch number (bunch palm⁻¹ year⁻¹), ABW: average bunch weight (kg bunch⁻¹), PRD: productivity (t FFB ha⁻¹ year⁻¹), Q: quadratic response pattern.

Table 8. Regression equation and optimum rate of K fertilizer on a four-year-old oil palm

| Variables                  | Age (MAP) | Regression equation | R²  | Optimum rate (g K₂O palm⁻¹ year⁻¹) |
|----------------------------|-----------|---------------------|-----|----------------------------------|
| Trunk girth                | 39        | y = -0.0000003x² + 0.0162x + 260.02 | 0.98 | 2700  |
|                           | 42        | y = -0.000003x² + 0.016x + 265.84   | 0.97 | 2667  |
|                           | 45        | y = -0.000003x² + 0.017x + 271.92   | 0.95 | 2833  |
|                           | 48        | y = -0.000003x² + 0.0174x + 275.68  | 0.95 | 2900  |
| Leaf area of frond 17     | 48        | y = -0.00000007x² + 0.0004x + 5.5602 | 0.95 | 2857  |
| Bunch number              | 48        | y = -0.0000009x² + 0.0047x + 9.6448 | 0.92 | 2611  |
| Productivity              | 48        | y = -0.000001x² + 0.0055x + 13.426  | 0.88 | 2750  |

Average of optimum rate (g K₂O palm⁻¹ year⁻¹) 2760 ± 107

Note: MAP: months after planting

4. Conclusions
Phosphorus fertilizer significantly affected to palm height at 42, 45 and 48 MAP, trunk girth at 39, 42, 45 and 48 MAP as well as leaf P content at 48 MAP. Phosphorus fertilizer significantly affected bunch number and yield of FFB of a four-year-old oil palm. Application of P fertilizer at rate of 443.75 g P₂O₅ palm⁻¹ year⁻¹ could increase the yield of FFB by 7.2 t ha⁻¹ year⁻¹ (55.38%) compared to control. The optimum rate of P fertilizer for a four-year-old oil palm was 924 ± 88 g P₂O₅ palm⁻¹ year⁻¹.

Potassium fertilizer significantly affected to trunk girth at 39, 42, 45 and 48 MAP, stomatal density at 42 and 48 MAP, leaf area of frond 17 and leaf K content at 48 MAP. Potassium fertilizer significantly affected bunch number and yield of FFB of a four-year-old oil palm. Application of K fertilizer at rate of 2041.2 g K₂O palm⁻¹ year⁻¹ could increase yield of FFB by 7.7 t ha⁻¹ year⁻¹ (59.23%) compared to control. The optimum rate of K fertilizer for a four-year-old oil palm was 2760 ± 107 g K₂O palm⁻¹ year⁻¹.

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