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Evaluation of Phosphate Rock Sources and Rate of Application on Oil Palm Yield Grown on Peat Soils of Sarawak, Malaysia

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Abstract: Malaysia has 2.4 million ha of peat and this type of soil is very poor in phosphorus and needs P application. As there are various sources of P fertilizer in the Malaysian market, it is crucial for growers to apply the most effective source for their crops. In this research, two sources of phosphate rocks available in the local fertilizer market from Christmas Island (CIPR) and Morocco (MPR) at four rates were evaluated for maximum yields of Fresh Fruit Bunches (FFB) from oil palm grown on peat soils in Sarawak, Malaysia. The CIPR and MPR at the rates of 0, 500, 1000 and 2000 g plam^{-1} year^{-1} were applied annually. FFB ha^{-1}, average weight bunch^{-1} and leaf and soil nutrient concentrations were determined. Results showed that MPR treatments produced higher available soil P than CIPR treatments by average of 87% and also higher leaf P concentrations (up to 0.185%). Pearson's correlation indicated that available soil P was negatively correlated with K, Mg, B, Cu and Zn but positively correlated with Ca. In addition, P concentrations in leaves were positively correlated with Ca, Mg, B and Zn but were negatively correlated with K and Cu. Correlation of yield parameters and leaf nutrient concentrations revealed that bunch weights were negatively correlated with leaf P concentrations, Mg and B, whilst the total yield was negatively correlated with Mg and B. Maximum yields were obtained at CIPR-2000 and CIPR-1000 treatments. By interpolation maximum yields in MPR would be attained at MPR-750 treatment.

Key words: Phosphate rocks, oil palm, P fertilizer, fresh fruit bunches

INTRODUCTION

The demand for edible vegetable oil is expected to double from the present consumption around 120-240 Mt year^{-1} by 2050 and hence production must be increased. Malaysia has 2.4 million ha of peat out of 25 million ha of peat land in the oil palm growing countries of the World. In Sarawak, peat area covers approximately 1.6 million ha or 13% of the total land area in the state (Teng, 2003). Out of the 1.6 million ha of peat area in Sarawak, 1.48 million (92.5%) are deep peat and only 7.5% is classified as shallow peat. The original peat land in Sarawak is swampy and unsuitable for agricultural production. However, depletion of prime land for agriculture has led to new oil palm planting on marginal areas especially peat land. In 2009, a total of 666,038.03 ha of peat land in Malaysia were planted with oil palm which 437,174.27 ha (66%) were in Sarawak (Wahid *et al*., 2010).

Most of peat soils are classified as Tropofibrists or Tropohemists in the USDA soil order of histosols. Very low bulk density (100-200 kg m^{-3} compared with 1400-1800 kg m^{-3} for most mineral soils), very low nutrient contents except Nitrogen (N), poor nutrient retention capacity particularly potassium (K), rapid fixation of copper (Cu) and Zinc (Zn), low to very low pH (pH 2.8-4.5) and a large content of organic matter can be mentioned as the special characteristics of peat soils (Mutert *et al*., 1999).

Oil palm requires large amounts of chemical fertilizers to sustain the highest yield and P is one of the macronutrients, which is required for normal plant growth. Although oil palm requires less P as compared to N and K, P plays an important role in many aspects of plant physiology including photosynthesis, N fixation, maturation and root growth (Brady and Weil, 2010).

In Malaysia, phosphate rocks (PRs) have been widely used as a P source especially in oil palm plantation (Razman *et al*., 1999). Direct application of PRs is a very effective way in correcting P deficiency in most of the Malaysian soils which are highly weathered and poor in nutrient contents (Zin *et al*., 2001). The rapid PRs dissolution in acidic soils, high rainfall and temperature, present management practices and relative cost-effectiveness are the preferences of PRs as compared to soluble P fertilizers such as triple superphosphate (TSP) (Goh and Chew, 1995). Nevertheless, the performance of various PR sources depends on the characteristics of the PR and soil, type of crop and

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environmental conditions. Thus, PR sources have to be evaluated in the real field situation to determine the best source for each crop type and environmental conditions. Fertilizer costs constitute 30% of the total production costs of fresh fruit bunches (FFBs) of oil palm in Malaysia (Lee and Foong, 2003) and hence reducing the fertilizer costs by the use of the appropriate fertilizer type and rate for maximum FFB yields will lead to enormous economic benefits.

Since large scale planting of oil palms on deep peat is relatively new in Sarawak, the research on the most suitable PR sources and optimum phosphate fertilization is absent in this area. The available form of P in deep peat (0-25 cm) ranges from 30-200 mg kg^{-1}. Currently, in the commercial farming system, 500 g phosphate rock is applied in the planting hole at the time of planting. Generally, the phosphate is applied in the form of PRs at the rate of 1.0-1.2 kg palm^{-1} year^{-1} (Mutert *et al.*, 1999). However, Goh and Chew (1995) reported that the annual application of 1.0-1.5 kg PRs palm^{-1} is the best range for peat in Perak. Higher rates causes the reduction of Cu and Zn uptake, therefore, it is critical to determine the optimum fertilizer rates for maximum FFB production in the new peat lands.

This research was conducted to determine the most suitable PR source and the rate of application for maximum fresh fruit bunch (FFB) yields and to investigate the effect of the different P sources at various rates on the uptake of some selected nutrients by oil palm.

MATERIALS AND METHODS

Experimental design: The two PRs used in this study were Christmas Island Phosphate Rock (CIPR) and Moroccan Phosphate Rock (MPR). MPR is a medium reactive PR whilst, CIPR is low reactive. X-ray diffraction techniques were used to determine their mineralogical properties and standard methods were used for chemical and physical characterization of the PRs (Table 1). X-ray results showed that hydroxyl 1-apatite and calcite are contained in MPR while CIPR contained flour-apatite and quartz.

The experiment was conducted at Tradewinds Plantation Berhad in Sibu, Sarawak, 020°C 28' 33.9" N and 110°C 53' 35.3" E on six years old palms in a randomized complete block design (RCBD) with four replications. The peat was very deep (>300 cm), highly decomposed sapric in sub-surface tier (50-100 cm), very poorly drained over non-sulphidic marine clay and classified as *Sapric Ombrogambis*. The soil chemical and physical properties of the research area are shown in Table 2 and 3. Plot sizes were 6×4 (24) palms with recording core of 4×4 (16) palms. The two PRs were applied at three rates 500, 1000 and 2000 g palm^{-1} year^{-1}, hence designated as MPR-500, MPR-1000, MPR-2000, CIPR-500, CIPR-1000 and CIPR-2000. A control treatment without PR fertilizer was included in the experiment. All PR treatments were applied by broadcasting at the weeded palm circle (about 2.0 to 2.5 m from palm base). The trial was commenced in February 2005 and the treatments were applied in February every year. The normal type and rates were followed for all other fertilizers.

Measurements: FFB yield, bunch number, bunch weight and leaf and soil nutrient concentrations were determined. The FFB yield, bunch number and bunch weight were recorded at 15 days intervals. Frond 17 was sampled as the indicator for leaf nutrient concentrations at the end of each year. Soil samples were collected from two soil depths, 0-15 cm and 15-60 cm at about 2 meter from palm base.

Table 1: Some chemical and physical characteristics of the two applied phosphate rock fertilizers

Composition	MPR	CIPR (g kg^{-1})
P	144	145
CaO	468	311
Fe_2O_3	-	31
Al_2O_3	-	107
MgO	-	23
*Solubility in 2% citric acid	106	93
*Solubility in 2% formic acid	179	116

*: Solubility based on P_2O_5, -: Not determined

Table 2: Generalized chemical properties of the research area (0-25 cm)

pH	3.2-3.8	C (%)	40-52
%Ash	1.2-2.5	N (%)	1.5-1.8
Ex. Ca (cmol kg^{-1})	5.7-12.1	Av. P (mg kg^{-1})	30-200
Ex. Mg (cmol kg^{-1})	4.5-7.3	Av. B (mg kg^{-1})	0.1-6
Ex. K (cmol kg^{-1})	0.11-0.41	Av. Cu (mg kg^{-1})	2-12
CEC (cmol kg^{-1})	71-154	Av. Zn (mg kg^{-1})	15-48

Table 3: Correlation coefficients (in bold) and probabilities for leaf nutrient concentrations (frond 17) in oil palm treated with CIPR and MPR at different rates of application

Parameters	P	K	Ca	Mg	B	Cu	Zn
P	1.00000						
K	-**0.48270** (0.0016)	1.00000					
Ca	**0.69882** (<0.001)	-**0.49531** (0.0012)	1.00000				
Mg	**0.75825** (<0.0001)	-**0.22859** (0.1560)	**0.31051** (0.0512)	1.00000			
B	**0.68512** (<0.0001)	-**0.21200** (0.1891)	**0.26412** (0.0996)	**0.88530** (<0.0001)	1.00000		
Cu	-**0.33379** (0.0353)	**0.61471** (<0.0001)	-**0.40066** (0.0104)	-**0.08776** (0.5902)	**0.05470** (0.7374)	1.00000	
Zn	**0.35941** (0.0227)	**0.21709** (0.1784)	**0.24711** (0.1242)	**0.25253** (0.1159)	**0.07950** (0.6258)	**0.22331** (0.1660)	1.00000

Bold values: Pearson's correlation coefficients

Rainfall distribution in the trial areas was generally at optimum levels, i.e., above 100 mm month^{-1} throughout the year (except in August 2006, 2009 and September 2008) during the study period (Not shown).

Calculations and statistical analysis: All the data were analyzed using SAS 9.2 software (SAS institute, Cary, NC, USA). Analysis of Variance (ANOVA) was performed on the combined data using PROC MIXED procedure. Harvests and blocks were considered as random variables while, the various treatments were considered as fixed effects in the model.

RESULTS AND DISCUSSION

Effect of different types and rates of phosphate rocks on available soil phosphorus (Bray 2) and interactions: The overall analysis indicated that the type of PRs had no significant effects on available soil P but the PRs rates ($p<0.01$), time ($p<0.01$), P type×P rate ($p = 2.35$), P type×time ($p = 0.37$) and P type×P rate×time ($p<0.01$) interactions had significant effects on available soil P. A positive quadratic relationship was observed between average available P concentrations versus the PRs application rates (Fig. 1a). The curve reveals that from 0-1000 g PR palm^{-1} year^{-1}, the relationship between PRs rate and amount of available P are almost linear but becomes curvilinear above that rate. Partitioning the effects of the two PRs revealed that MPR application resulted in higher available soil P levels in soil than CIPR but the differences were only significant at the rate of 1000 g palm^{-1} year^{-1} (Fig. 1b). Available soil P is 187% higher in MPR treatments as compared to CIPR treatments at this rate. This is related to the higher solubility or reactivity of MPR in comparison to CIPR (Table 1). However, reduction in dissolution for both PRs at the higher PR rates resulted in the non-significant difference of available soil P levels (Fig. 1b).

The available soil P was dependent on the PR type×PR rate×time interactions (Fig. 1c). Since available soil P showed extremely high increment from the previous year and a reduction from the following year in the year 2007, it could be considered to be an outlier. This trend was also observed in the control which is very unlikely. It seems the available soil P levels remained almost constant over time for most of the treatments. Generally, trends of available soil P were not very distinct but the lower PR rates seemed to release the lower available P which were not different from control in the years 4 and 5 (Fig. 1c). While available soil P increased with increasing P rates in CIPR, it was notable that available soil P of MPR-2000 treatment was lower than MPR-1000 treatment. This is probably due to the decreased MPR solubility at the highest rate and therefore, releasing less available soil P. However, the whole scenario was complex due to the many factors acting together. For instance, as applied PR

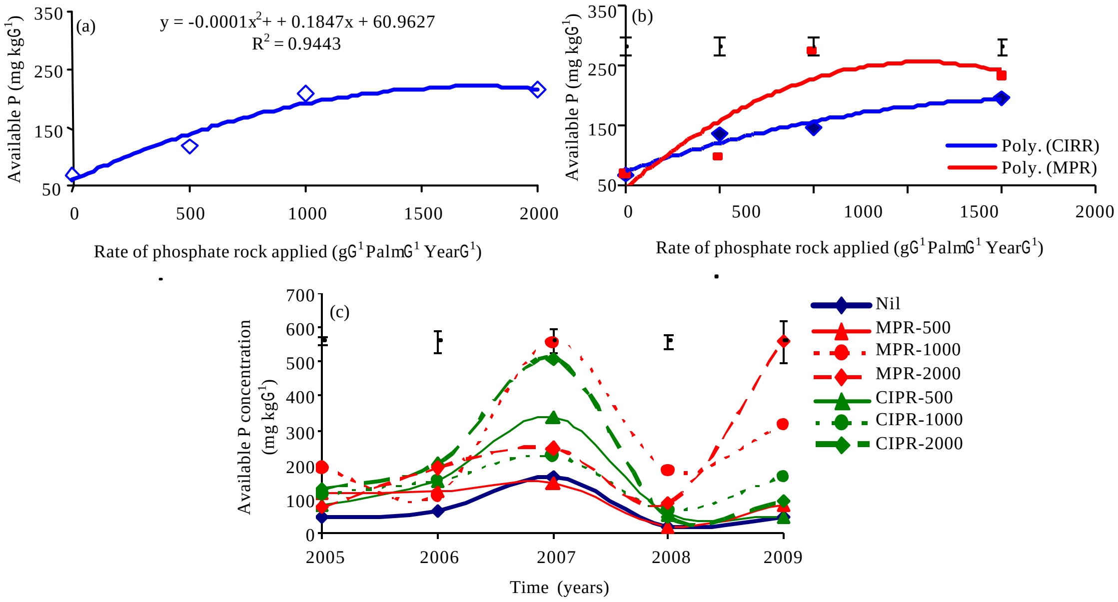

Fig. 1(a-c): Average available soil P in soil as influenced by: (a) PR fertilizer rate, (b) Rates of CIPR and MPR, (c) PR type×rate over time NB: Bars denote SE

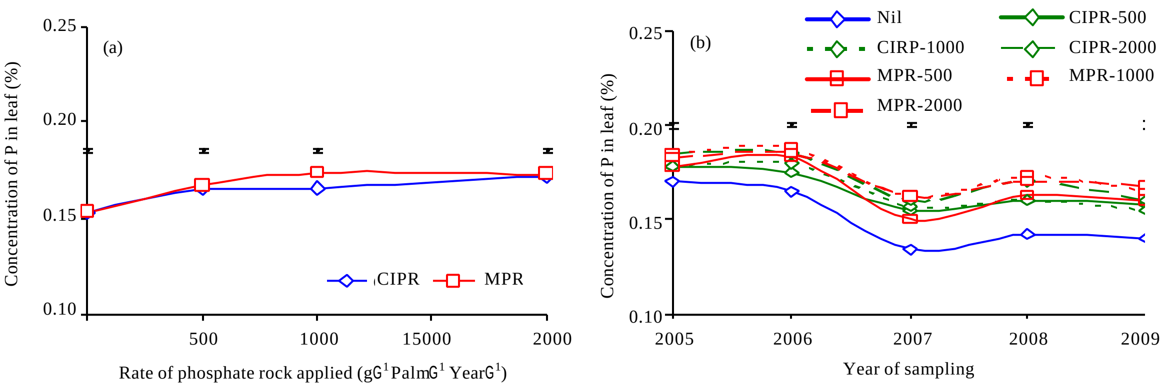

Fig. 2(a-b): Leaf P concentration as influenced by: (a) PR type×rate, (b) PR type×rate×time (years) NB: The bars denote SE

dissolved to release P, more PR was added annually and depressed dissolution of PR with considering the absorption of the solubilized P.

Pearson's correlation indicated that available soil P was negatively correlated to K, Mg, B, Cu and Zn with r = -0.42**, -0.31,-0.31*, -0.37* and -0.32* respectively but positively related to Ca (r = 0.39*).

Effect of PR treatments on leaf nutrient concentrations (Frond No. 17)

Phosphorus (P): Leaf P concentration was significantly influenced by the type of phosphate rock ($p = 0.37$), rate of applied fertilizer ($p<0.01$) and the interaction of PR type×rate ($p = 1.1$). Average leaf P concentration increased with increasing P rates from 0.15% (control) to 0.175% (2000 g PR palm^{-1} year^{-1}) and this is related to the increasing of available soil P as demonstrated in Fig 1a. Leaf P concentration was higher in MPR treatments as compared to CIPR treatments and it was more remarkable at 1000 g PR palm^{-1} year^{-1} treatments (Fig. 2a). MPR was more soluble or reactive than CIPR hence resulted in the higher soil P concentrations at corresponding rates (Fig 1b) and consequently, more P was taken up by the plants at MPR treatments and resulted in the higher leaf P concentrations. Interaction of PR type×fertilizer rate×time revealed that CIPR and MPR applications had a significant effect on leaf P concentrations in comparison to control (Fig. 2b). Leaf P concentrations increased with increasing the rate of PRs application with an exception of MPR-1000 which showed the highest leaf P concentration (Fig. 2b). Results also showed that leaf P concentrations in MPR treatments were higher than CIPR treatments at corresponding fertilizer rates (Fig. 2b).

The leaf P concentrations were gradually declined over time except the sudden decline between 2006 and 2007 in all the treatments. The leaf P concentrations then increased gently in 2008 and continued to decline gradually in 2009 (Fig. 2b). The decline in leaf P concentrations over time could be attributed to the yearly P application and plant age. Nevertheless, leaf P concentration in all the treatments except in control (from 2007-2009) ranged between 0.15-0.189% which is within optimal foliar P levels (0.15-0.19%) according to Foster and Prabowo (1996). Leaf P concentrations showed some positive correlation with available soil P but it is not significant at $p = 0.05$ (Table 3).

Table 4: Pearson's correlation coefficients (bold) and probability for the leaf nutrient concentrations by the yield characteristics

Parameter	Bunch weight	Total yield	Bunch No.
P	**-0.46701** (0.0024)	**-0.21334** (0.1862)	**0.10100** (0.5352)
K	**0.25671** (0.1098)	**-0.01193** (0.9418)	**-0.18510** (0.2528)
Ca	**-0.10866** (0.5045)	**-0.14535** (0.3708)	**-0.05547** (0.7339)
Mg	**-0.70658** (<0.0001)	**-0.55559** (0.0002)	**-0.14316** (0.3782)
B	**-0.81558** (<0.0001)	**-0.60352** (<0.0001)	**-0.08705** (0.5933)
Cu	**-0.09973** (0.5404)	**0.03582** (0.8263)	**0.18460** (0.2541)
Zn	**0.23568** (0.1432)	**0.10994** (0.4995)	**-0.05112** (0.7541)

Bold values: Pearson's correlation coefficients

Calcium (Ca): Leaf Ca concentrations increased with increasing PRs application rates by about 13% at the highest P level in comparison to control at both CIPR and MPR treatments. Leaf Ca concentrations at MPR treatments were generally higher than CIPR treatments, particularly at the higher PR rates i.e., 1000 and 2000 g PR Palm^{-1} year^{-1} whilst they were not different at 500 g PR Palm^{-1} year^{-1} (Fig. 3a). Ca is a major constituent of the PRs and is released by the dissolution of these fertilizers (Table 1). Ca content is about 150% higher in MPR as compared to CIPR (Table 1) and therefore, leaf Ca concentrations are higher in MPR treatments. There was a positive correlation ($p<0.01$) between leaf P and leaf Ca concentrations ($r = 0.70$) as shown in Table 4. Leaf Ca

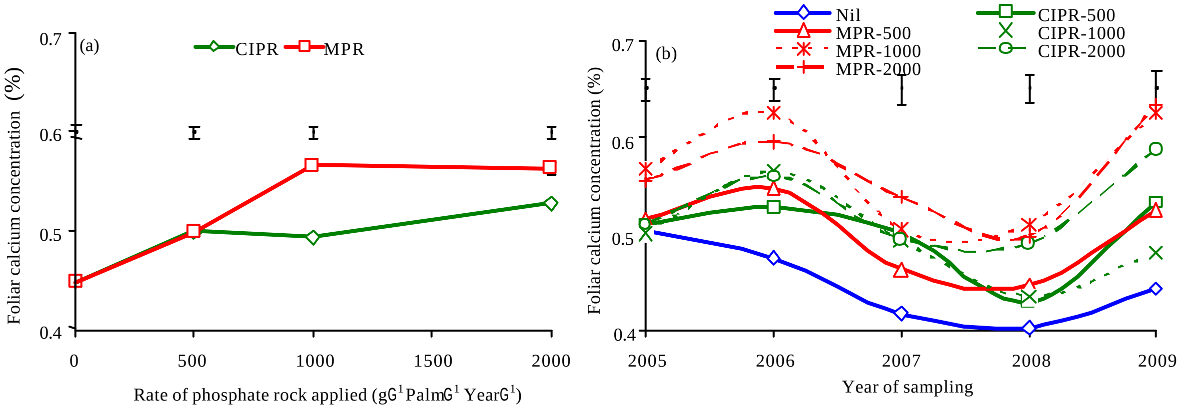

Fig. 3(a-b): Leaf Ca concentrations as influenced by, (a) PR type×rate and (b) PR type×rate×time (years), The bars denote SE

concentrations were not different at MPR and CIPR treatments when they were applied at the rate of 500 g Palm^{-1} year^{-1} because the two PRs dissolved entirely at this rate but at higher rates, MPR dissolved more than CIPR because it is inherently more soluble than CIPR and in addition PRs solubility decreases with the increase in rate. Leaf Ca concentrations were higher in all the fertilized palms compared to the non-fertilized one. In the first year, only the two highest rates of MPR showed the higher leaf Ca concentrations compared to the control while, all other fertilizer rates did not show differences probably because dissolution takes time and therefore only the highly soluble PR at the high rates could release high Ca amounts (Fig. 3b). Nevertheless, in subsequent years there were more significant differences between treatments. Leaf Ca concentrations were almost constant over time except a decline in the third and fourth years. Leaf Ca concentrations increased with increasing MPR rates but CIPR did not show same trend except in the last year (2009), where it was lower at CIPR-1000 treatments compared to CIPR-500 treatments (Fig. 3b). On the other hand, MPR-1000 and MPR-2000 resulted in the higher leaf Ca concentrations in comparison to MPR-500 throughout the experimental period (2005-2009) as shown in Fig. 3b. The optimum leaf Ca concentrations for mature palms are 0.5-0.75% (Goh and Hardter, 2003) and, therefore, the plants in some of the treatments such as CIPR-500, MPR-500 and CIPR-1000 might suffer from Ca deficiency from the third year, when the leaf Ca concentrations were less than 0.5%. Accordingly, the control would suffer from deficiency from the year two (2006), when the leaf Ca concentration was 0.475% (Fig. 3b).

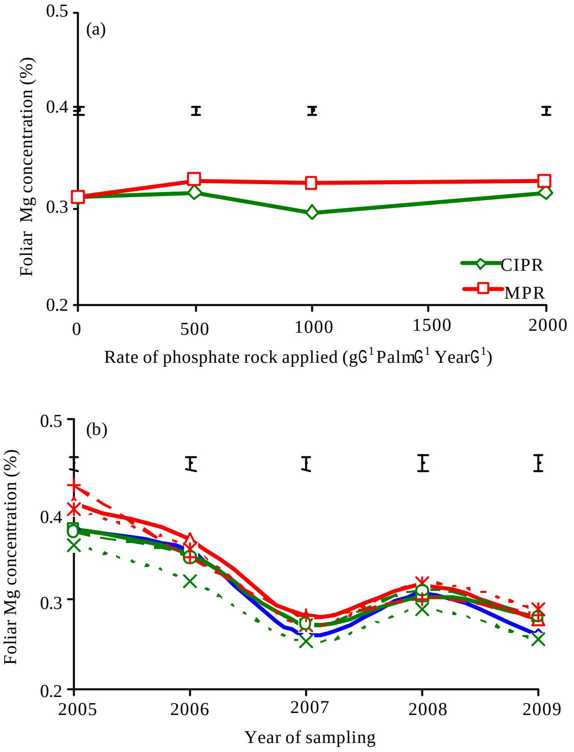

Fig. 4(a-b): Leaf Mg concentrations as influenced by: (a) PR type×rate, (b) PR type×rate×time (years) The bars denote SE

Magnesium (Mg): Leaf Mg concentrations increased very slightly with fertilization and generally did not show significant differences between the different PR application rates. Leaf Mg concentrations were higher in MPR fertilized palms as compared to CIPR fertilized palms at all rates probably due to the higher dissolution of MPR relative to CIPR (Fig. 4a). Leaf Mg concentrations showed a strong correlation ($p<0.01$) with leaf P concentrations

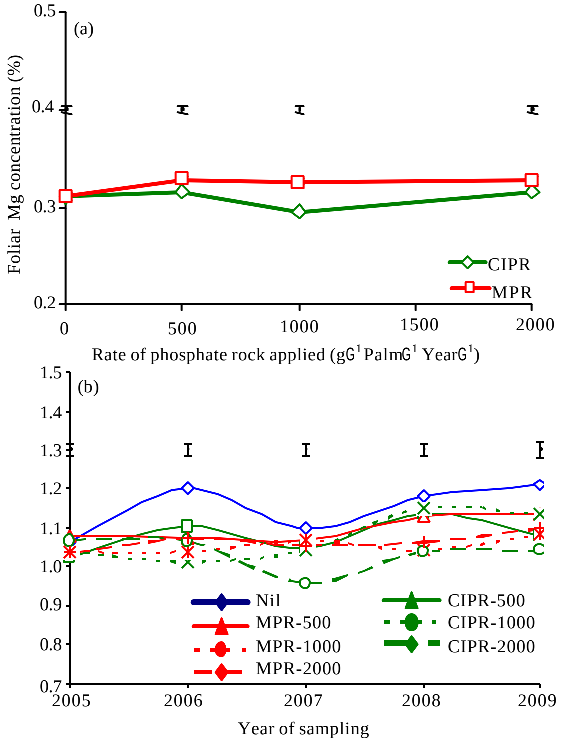

Fig. 5(a-b): Leaf K concentrations as influenced by PR type×rate×time (years). The bars denote SE

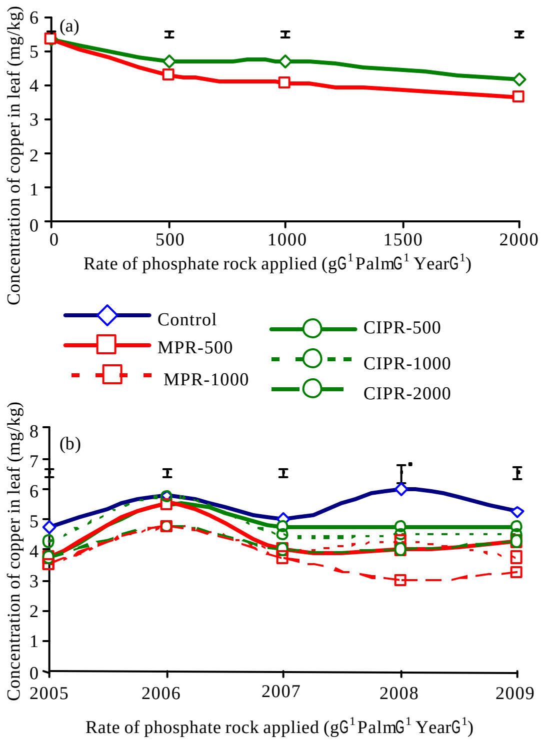

Fig. 6(a-b): Leaf Cu concentrations as influenced by: (a) PR type×rate, (b) PR type×rate×time (years). The bars denote SE

(r = 0.76) (Table 3). Leaf Mg concentrations gradually declined over time except between 2006-2007 which seemed abrupt (Fig. 4b). In the first year (2005), leaf Mg concentrations in MPR treatments were higher than control whilst in CIPR treatments these concentrations were lower particularly at CIPR-1000 treatment. Leaf Mg concentrations were within the optimal range (0.25-0.30%) as stated by Goh and Hardter (2003) in all the treatments including control.

Potassium (K): Leaf K concentrations seemed to decline gradually with increasing the PR rates but the two PRs did not have a significant effect on this parameter. In general, application of the PRs led to a decline of leaf K concentrations at most rates over the experimental period. Leaf K and P concentrations exhibited an antagonistic interaction as shown by a negative correlation (r = -0.48, p = 0.16) between them (Table 3). Generally, the leaf K concentrations remained relatively constant (1.0-1.2% in almost all treatments) in this experiment (Fig. 5) in agreement with report by Ng *et al.* (1968) which reported that K remains constant throughout maturity at 1.0-1.3%.

Copper (Cu): Leaf Cu concentrations was influenced significantly by the PRs type (p = 0.08), rate of fertilizer application (p<0.01) and time (p<0.01) but the interactions were not significant. Nevertheless, investigation of the type of PRs×fertilizer rate interaction revealed that average leaf Cu concentration declined gradually with the rate of applied PR. It also revealed that average leaf Cu concentrations in CIPR treatments were higher than MPR treatments at all corresponding PR rates (Fig. 6a). There was a linear relationship between PRs type×fertilizer rate×time with leaf Cu concentrations with an exception of slight increases in leaf Cu concentration in 2006 for all the treatments and for two treatments in 2008 (MPR-2000 and control which decreased and increased, respectively) as shown in Fig. 6b. Leaf Cu concentrations declined with increasing the rate of applied PRs. Consequently, the highest leaf Cu concentration was observed in the control treatment whilst the lowest one was detected in MPR-2000 treatment (Fig. 6b). A negative correlation (p = 3.5) was observed between leaf Cu and P concentrations with r = -0.33 (Table 3). Generally, CIPR treatments had a comparatively higher leaf Cu concentrations as compared

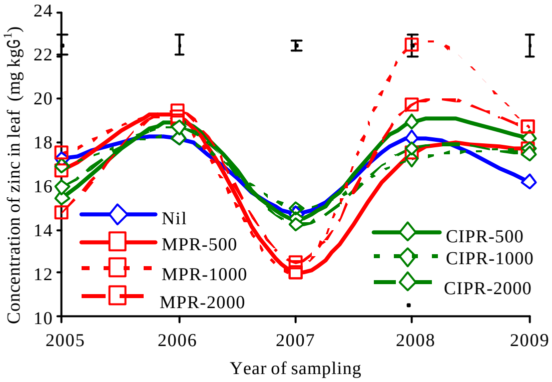

Fig. 7: Leaf Zn concentrations as influenced by PR type×rate×time (years). The bars denote SE

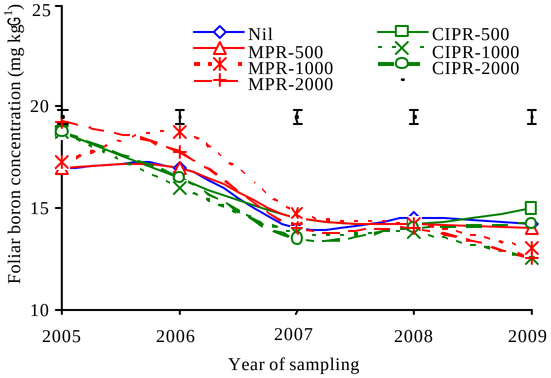

Fig. 8: Leaf B concentrations as influenced by PR type×rate×time (years) The bars denote SE

to MPR treatments and this is explained by the fact that Cu and P are negatively correlated and MPR releases higher P concentrations in the soil leading to the higher leaf P concentrations and consequently, depressing the leaf Cu concentrations more than CIPR. This is in agreement with the findings of Goh and Hardter (2003) that excess P have been known to induce Cu deficiency in very sandy soils and peat soils in North Sumatra, Indonesia and Malaysia.

Zinc (Zn): The leaf Zn concentrations were not significantly influenced by Prs type or rate but were strongly influenced by the interaction of PR type×time ($p<0.01$) and Prs type×fertilizer rate×time ($p = 1.45$). However, there was a significant correlation between the leaf Zn and P concentrations ($p = 2.3$) with $r = 0.36$ (Table 3). This probably implies that Zn was not a constituent of the PRs but the influence of the PRs is most probably through interaction effects between Zn and the amounts of P released from the PRs as demonstrated by the positive correlation between leaf Zn and P concentrations (Table 3).

The investigation of the PRs type×fertilizer rate×time interactions (Fig. 7) revealed that in general, leaf Zn concentrations increased from year one (2005) to almost a constant level in all other years except 2007, where a sudden decline was observed. In this year (2007), MPR treatments showed the lowest leaf Zn concentrations (not significantly different between the three rates of MPR) while CIPR treatments had the higher leaf Zn concentrations but also not significantly different between the CIPR rates (Fig. 7). The leaf Zn concentrations ranged from 12-22.5 mg kg^{-1}, which implied that Zn was still not a limiting factor, although it was higher than the optimum range (12-18 mg kg^{-1} according to Goh and Hardter (2003) in some treatments.

Boron: The leaf B concentrations were not influenced by the type or rates of applied PRs and their interactions showed that B is not a constituent of the PRs. However, leaf B concentrations declined over time. The PRs type×fertilizer rate×time interaction (Fig. 8) revealed that in general, leaf B concentrations declined gradually from 2005 to 2009 with an exception of the rapid decline observed between 2006 and 2007 (Fig. 8), probably due to

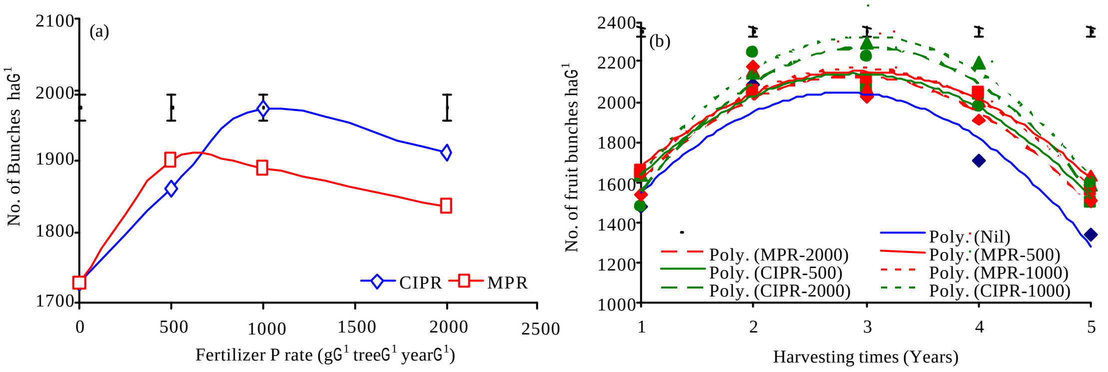

Fig. 9(a-b): Number of oil palm fruit bunches as influenced by : (a) PR type×rate, (b) PR type×rate over a period of five years (2005-2009). The bars denote SE

the continuous plant B uptake. It was noteworthy that after the second year (2006), all the treatments exhibited leaf B concentrations below the critical range (15-25 mg kg^{-1}) according to Goh and Hardter (2003).

Oil palm yield parameters

Number of fruit bunches per hectare: The average number of Fresh Fruit Bunches (FFB) increased over time up to a maximum number and then declined ($p<0.01$). The average number of FFB also increased with increasing the rates of applied PRs up to 1000 g palm^{-1} year^{-1} as CIPR and above this rate, CIPR application led to a lower number of FFBs as shown in Fig 9a. Number of FFBs were lower at the rate of 2000 g palm^{-1} year^{-1} when applied as MPR while the number of FFBs produced in the other MPR rates (MPR-500 and MPR-2000) were not significantly different (Fig. 9a). The disparity between the number of FFBs from CIPR and MPR treatments could be attributed to the differences between amounts of available soil P released by the two PRs at corresponding rates of application. According to the relationship between available soil P and rates of PRs application (Fig. 1b), it was demonstrated that at the rate of 1000 g palm^{-1} year^{-1}, MPR released higher available soil P (280 mg P kg^{-1} soil) as compared to CIPR (˜150 mg P kg^{-1} soil) although the differences were not significant at 500 and 2000 g palm^{-1} year^{-1}. As discussed earlier, at the rates of 500 and 2000 g palm^{-1} year^{-1}, solubility of the two PRs were enhanced and depressed, respectively thus released amounts of available soil P were not significantly different for the two PRs at corresponding rates. However, from Fig. 9a, the highest numbers of FFBs were attained at CIPR-1000 treatment which released ˜150 mg P kg^{-1} consequently, at MPR-1000 treatments corresponding to 280 mg P kg^{-1}, there was a depression in the number of FFBs due to high available soil P. This was probably associated with the antagonistic interaction of P with Cu and K discussed earlier. This is proven by the fact that MPR-1000 which released the highest available soil P (280 mg P kg^{-1} soil) was one on the treatments that exhibited the lowest leaf Cu concentrations (about 4 mg kg^{-1} soil) over time (Fig. 6). This level is below the optimum Cu concentrations needed for normal plant growth and, therefore, could result in the lower number of FFBs observed in this study. The MPR-1000 treatment was also one of the MPR treatments that released the lowest level of K (˜1.04%). According to the previous literatures, Cu did not have any effects on the number of FFBs but leaf K concentrations was positively correlated with oil palm yield components (bunch number and bunch weight) (Nair and Sreedharan, 1983; Kusnu *et al*., 1996). Thus, CIPR-1000 treatments produced more fruit bunches than MPR-1000 treatments (Fig. 9a).

The number of FFBs depended on the fertilizer type, rate of fertilizer and the time of harvest. The relationship between the number of FFBs ha^{-1} and the time of harvest for the two fertilizer types at different rates of PRs application can be plotted as the quadratic function (Fig. 1b). The quadratic equations exhibited high regression coefficients (equal to or more than 0.91) except one treatment (MPR-2000). The equations were as follows:

- **Control (Nil):** $Y = -156.3X^2+871.9X+831$, $R^2 = 0.91$
- **CIPR-500:** $Y = -140.0X^2+811.8X+864.8$, $R^2 = 0.97$
- **CIPR-1000:** $Y = -176.1X^2+1051.5X+756.8$, $R^2 = 0.99$
- **CIPR-2000:** $Y = -180.6X^2+1082.0X+650.8$, $R^2 = 0.91$
- **MPR-500:** $Y = -126.5X^2+744.3X+1058.8$, $R^2 = 0.91$
- **MPR-1000:** $Y = -138.1X^2+807.7X+985.8$, $R^2 = 0.99$
- **MPR-2000:** $Y = -146.9X^2+846.9X+909.2$, $R^2 = 0.88$,

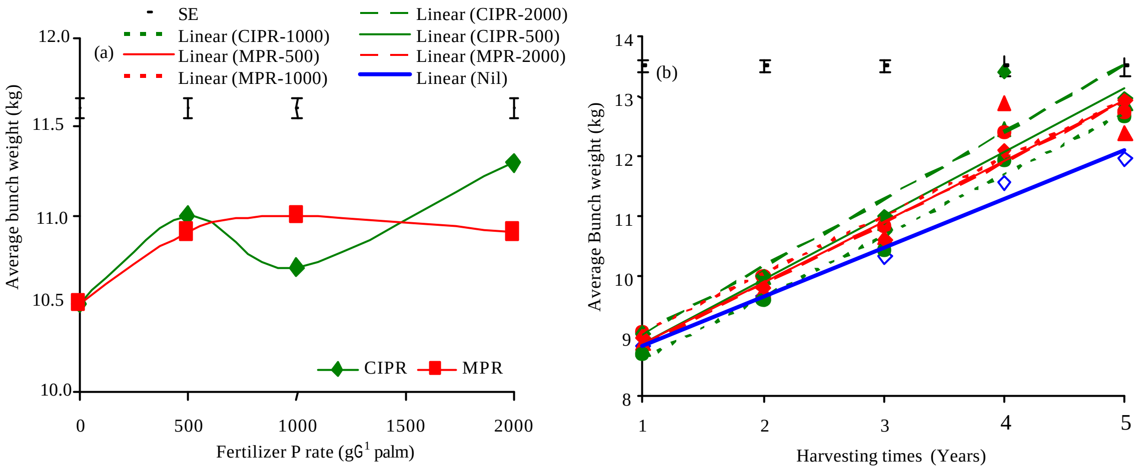

Fig. 10(a-b): Average weight of oil palm fruit bunches as influenced by: (a) PR type×rate, (b) PR type×rate over a period of five years (2005-2009). The bars denote SE

where, Y is the number of FFBs ha^{-1} and X is the year of harvest i.e., year 1, 2, 3, 4 and 5 representing 2005, 2006, 2007, 2008 and 2009, respectively.

From the equations, it appeared that the highest number of FFBs were all obtained in the third year (2007) and declined, thereafter (Fig. 9b). Control (nil or zero P treatment) exhibited the lowest number of FFBs which were significantly lower than all the fertilizer treatments. Among the fertilizer treatments, CIPR-1000 treatment produced the maximum number of FFBs ha^{-1} while CIPR-2000 treatment led to a decline in the number of produced FFBs probably due to the slightly higher available soil P at the latter rate. However, the number of FFBs produced by the aforementioned rates of CIPR was not significantly different but they were significantly higher than the number of FFBs harvested from the three MPR rates (Fig. 1b). Different levels of MPR application (MPR-500, MPR-1000 and MPR-2000) did not have a significant effect on the number of produced FFBs. MPR application above 500 g palm^{-1} year^{-1} led to the depression of the number of fruit bunches while in CIPR, depression of the number of FFBs occurred at the rate of 2000 g palm^{-1} year^{-1}. It is not clear why the highest number of FFBs were attained in the third year (2007) and declined after that time but the continuous yearly application of PRs leading to the accumulation of P in the soil in excess of the plant needs after the third year could be detected as the reason.

Size of fruit bunches: The rate of applied PRs and time ($p<0.01$) had a significant effect on the size of FFBs. In MPR treatments, the average weight of FFBs increased with increasing P rates from 10.5 kg bunch^{-1} in the control up to a maximum of 11.0 kg bunch^{-1} at the rate of 1000 g PR palm^{-1} year^{-1}. However, the bunch weights were not significantly different between the three MPR rates (Fig 10a). Similarly, in CIPR treatments, the bunch weights increased from 10.5 kg bunch^{-1} year^{-1} at nil P fertilizer rate to a maximum of 11.3 kg bunch^{-1} year^{-1} at the rate of 2000 g PR Palm^{-1} year^{-1} equivalent to about 197 mg kg^{-1} available P as shown in Fig. 1b. However, there was a significant decline in the bunch weights to 10.7 kg bunch^{-1} at the rate of 1000 g palm^{-1} year^{-1} (Fig. 10a) and this was the only rate which MPR treatment produced heavier bunches as compared to CIPR treatments. The low weight of fruit bunches at CIPR-1000 treatments may be attributed to the fact that, this treatment produced the highest number of FFBs and consequently may have resulted in correspondingly smaller fruit bunches.

A correlation between the bunch weights and some selected leaf nutrient concentrations revealed that they were negatively correlated with P (P = -0.48**), Mg (r = -0.71***) and B (r = -0.82***) as shown in Table 4. The maximum average bunch weight in this study was 11.3 kg at 2000 g PR palm^{-1} year^{-1} treatments which can possibly be explained by a combination of the interaction effects and the number of FFBs. This maximum weight obtained at the highest leaf P concentration (0.173%) and moderate leaf B concentration (15.45 mg kg^{-1}) as compared to the other treatments. Leaf P concentrations seems to be the most important nutrient affecting the bunch weights and that is related to the available soil P.

The interactions of the P sources×P rates×time revealed that the bunch weights resulting from different P fertilizers at different rates increased linearly with time over a period of five years (Fig. 10b). The data were best plotted as the linear functions with high regression

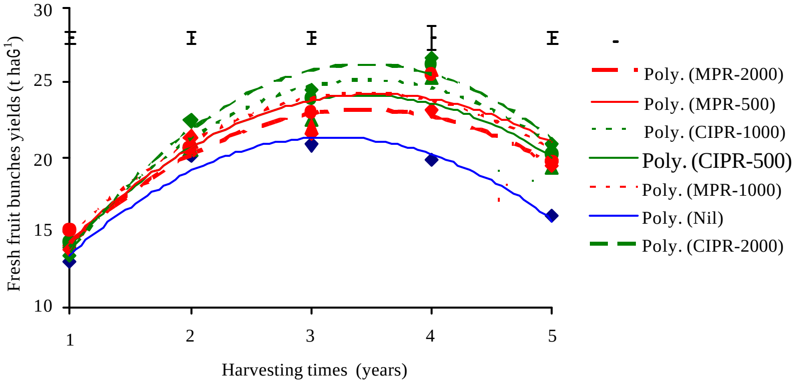

Fig. 11: Total yields of oil palm fruit bunches as influenced by: (a) PR type×rate, (b) PR type×rate over a period of five years (2005-2009). The bars denote SE

coefficients (p = 0.90) except MPR-500 treatment. The bunch weights in every specific year can be estimated by the equations when the best PRs rate and PRs type are applied. An increment of bunch weights with palm age has also been reported by other workers.

The equations were as follows:

- **Control (Nil):** $Y = 0.82X+8.02$, $R^2 = 0.98$
- **CIPR-500:** $Y = 1.07X+7.80$, $R^2 = 0.98$
- **CIPR-1000:** $Y = 1.03X+7.59$, $R^2 = 0.99$
- **CIPR-2000:** $Y = 1.12X+7.92$, $R^2 = 0.90$
- **MPR-500:** $Y = 1.02X+7.87$, $R^2 = 0.89$
- **MPR-1000:** $Y = 0.97X+8.10$, $R^2 = 0.97$
- **MPR-2000:** $Y = 1.02X+7.84$, $R^2 = 0.98$

where Y is the weight of fresh fruits bunch^{-1} and X is the year of harvest i.e. year 1, 2, 3, 4 and 5 represent years 2005, 2006, 2007, 2008 and 2009, respectively.

Fruit bunches from the unfertilized plots had the lowest weights, while CIPR-2000 treatment produced the highest weights in all five years (Fig. 10b). Fruit bunch weights were not significantly different in all three MPR treatments and CIPR-500 treatment. It was remarkable that CIPR-1000 treatment resulted in a very low bunch weights in comparison to the nil (control) treatment in all five years (Fig. 10b). This may partly be attributed to the higher number of FFBs yielded in CIPR-1000 treatment and partly to the nutrient interactions.

Total yields of oil palm fresh fruit bunches: Generally, the FFB yields (a factor of bunch number and bunch weight) varied with the P rates from year to year. The yields increased over time from a minimum of 13.07 t ha^{-1} in year one (2005) to maximum yields attained in year four (2008) for all the treatments except the control which reached the maximum in year three (2007). The FFB yields varied with the PRs type, the application rates and also with the year of harvest (Fig. 11). These variations were described by quadratic equations (Fig. 11). The equations exhibited high regression coefficients that were = 0.92 except for MPR-500 treatment. The yields in every specific year can be predicted accurately by the equations when the best PRs rate and PRs type are applied. The equations are listed below:

- **Control (Nil):** $Y = -1.67X^2+10.56X+4.60$, $R^2 = 0.96$
- **CIPR-500:** $Y = -1.68X^2+11.56X+4.24$, $R^2 = 0.92$
- **CIPR-1000:** $Y = -1.85X^2+12.82X+2.94$, $R^2 = 0.95$
- **CIPR-2000:** $Y = -2.11X^2+14.57X+1.10$, $R^2 = 0.97$
- **MPR-500:** $Y = -1.53X^2+10.83X+5.09$, $R^2 = 0.88$
- **MPR-1000:** $Y = -1.60X^2+11.00X+5.32$, $R^2 = 0.92$
- **MPR-2000:** $Y = -1.50X^2+10.28X+5.49$, $R^2 = 0.93$

where Y is the oil palm FFB yields in t ha^{-1}and X is the year of harvest i.e. year 1, 2, 3, 4 and 5 representing 2005, 2006, 2007, 2008 and 2009, respectively.

CIPR-2000 treatment exhibited the highest FFB yields with a maximum of 26.64 t ha^{-1} in year four (2008) and thereafter, the yield declined. However, CIPR-2000 treatment did not show significant difference with FFB yields of CIPR-1000 treatment and yields in CIPR-500, MPR-500 and MPR-1000 treatments were not significantly different (Fig. 11). Nonetheless, MPR-2000 showed the lowest FFB yields among all the fertilizer treatments. The total FFB yields seemed to depend mainly on the available soil P released from the Prs and maximum yields were attained at CIPR-2000 treatment equivalent to 197 mg P kg^{-1} soil. Therefore, by interpolation of the amounts of available soil P released by the two Prs (Fig. 1b), this amount (197 mg P kg^{-1} soil) of available soil P required for maximum yields would be released from 750 g MPR palm^{-1} year^{-1}. Thus, in MPR-1000 and MPR-2000 treatments, the yields were depressed due to excess available soil P and nutrient interactions. In MPR-500 treatment, available soil P was below the amounts needed for maximum yields.

Correlation of FFB yields and the leaf nutrient concentrations showed significant negative relationships with Mg (r = -0.56**) and B (r = -0.60***).

CONCLUSION

The highest FFB yields were attained at 2000 g CIPR palm^{-1}year^{-1} treatment although it was not significantly different from the yields at 1000 g CIPR palm^{-1}year^{-1} treatment despite the doubling in the fertilizer cost involved. In addition palms from the high CIPR rate (2000 g CIPR palm^{-1}year^{-})^{1} had lower foliar concentrations of Cu, Ca and K as compared to palms grown with 1000 g CIPR palm^{-1}year^{-1}. Consequently, we would recommend application of CIPR at the rate of 1000 g CIPR palm^{-1}year^{-1}. Although, MPR treatments produced lower yields than CIPR treatments at the rates tested in this experiment, it was evident from this work that MPR could attain yields comparable to CIPR if applied at about 750 g palm^{-1} year^{-1}. However, the choice of the two PRs would therefore be depended on the cost and accessibility of the two. Nevertheless, we would recommend further research on the frequency of the PRs application to avoid excessive accumulation of available P that would depress yields. More attention should be paid to the levels of the other nutrients particularly Mg and B that seems to be declining over time.

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